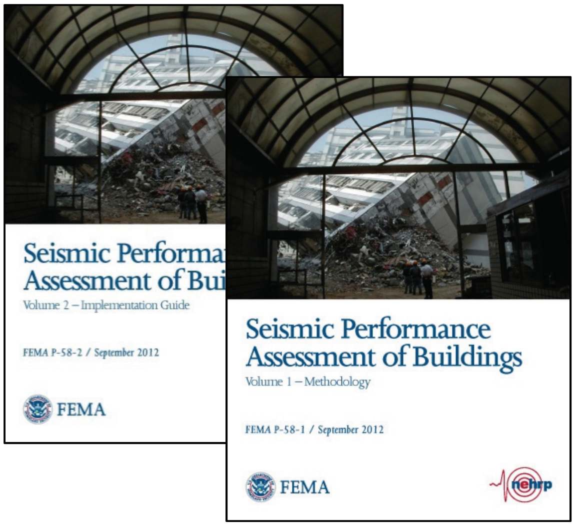

Background Document

FEMA P-58/BD-3.9.1

Architectural Glass Seismic Behavior Fragility Curve Development

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FEMA

nehrp

Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Specifically in the case of certain nonstructural component fragilities, the NISTIR fragility classification numbering scheme was modified over the course of the project, and the fragility classification number assigned in this document might be different from numbers assigned in the final fragility database. Users of information in this document assume all liability arising from such use.

Notice

Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

ATC-58 Project

Architectural Glass Seismic Behavior Fragility Curve Development

Final Report

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SUMMARY

This report was prepared for the Applied Technology Council (ATC) as part of the ATC-58 project that is developing Next Generation Performance-Based Design criteria for seismic performance assessment of building structural and Nonstructural components. The main objective of this report is to provide the information needed to evaluate the response of curtain wall (CW) and storefront (SF) wall systems to earthquake-induced movements in terms of the probability of different types of glazing damage. The main tasks in this work included processing of full-scale laboratory experimental data obtained through cyclic racking tests on a variety of CW and SF systems to develop fragility curves and document behavioral observations from laboratory experiments.

Cyclic racking test results on CW and SF wall systems consisting of dry-glazed stick-built systems or unitized Structural Sealant Glazing (SSG) systems were employed in this work. The test specimens included a variety of Annealed (AN), Heat-Strengthened (HS), and Fully-Tempered (FT) glass in different configuration including monolithic, insulating glass units (IGU), asymmetric IGUs with an interior monolithic pane and an exterior laminated pane, and single thickness laminated glass units. Furthermore, the configurations varied by glass size, glass-to-frame clearance, framing type, and glass thickness. All of the glass configurations included in this report had square corner geometry. The number of specimens tested for each glass configuration type ranged from one to twenty-four. Overall, the test results on 44 different CW and SF configurations were used to develop the fragility information in this report. These configuration types were chosen based on the amount of experimental data available, being most common CW and SF systems used on buildings, and representing a range of glazing options available.

The fragility information was generated using the fragility calculator software developed by ATC as part of the ATC-58 project. The derived fragilities are used in the software Performance Assessment Calculation Tool (PACT). The details and characteristics for the 44 different system configurations were organized and typed into Excel worksheets presented in Appendix A. The categories for the worksheet were created to essentially match the "common data" input area in the *Fragility Function Calculator version 1.02* software. The worksheet was split up into Serviceability type failures and Ultimate type failures applicable to each glass configuration. The drift values and drift index or ratios (D.I.) for all relevant damage state failures were then organized in a separate worksheet listed in Appendix B. This worksheet includes glass specimen characteristics, cracking drift values, glass fallout damage state values, gasket damage state values for some data sets, and other data values that were thought to be useful in future analysis.

The detailed information from the tables in Appendix A and data from Appendix B for each configuration was then input into the *Fragility Function Calculator Version 1.2* software. The "Method A" analysis option was used for most of the configurations and damage limit states. This is the analysis option to be used when actual damage state parameters are known for all specimens tested. For configurations where some of the

specimens did not reach failure and the facility drift capacity was used as their failure drift, "Method B" was the analysis option used. The program then produces an output containing the values of M (# of specimens), θ (median), β_r (dispersion value), and whether the fragility function passes the Lilliefors goodness-of-fit test at a 5% significance level. The complete results are included in Appendix C. It was noted that for select configurations where Method B was chosen, the calculator did not determine realistic θ and β_r values. Once the two fragility parameters of θ and β_r were computed, the dispersion parameter β was determined for fragility function development using $\beta = (\beta_r^2 + \beta_u^2)^{1/2}$ assuming $\beta_u = 0.25$. The resulting dispersion values along with the median and additional information related to consequences of failure and cost of repair are presented in Appendix D. With the parameters determined, the fragility curves were plotted using the provided software through the available "plot" function. The plotted fragilities from the software can be seen in Appendix E-1. Because of skew in some curves, fragility curves were also plotted using Excel software and shown in Appendix E-2.

In order to enhance the usability and applicability of the fragility information developed to real world construction, several practical issues were also addressed. Issues such as variability of glazing frame systems, extrapolation of laboratory panel test results to whole building façade, variability of glass-to-frame clearances, aspect ratios, and relating the results from laboratory panel size to panel sizes actually constructed on buildings are addressed. Furthermore, a few other issues related to practical application of the results are discussed. The additional topics addressed include an investigation of how a professional can identify specific characteristics of a glazing system, a data lumping analysis, whether a glass-to-frame clearance should be made a random variable, an expanded discussion on the glass fallout, and ratings of data used to develop the report. Finally, the results of a survey to reflect the views of curtain wall installers and designers on reasons for seismic glass damage is presented. At the end of the report, some conclusions derived from the study are presented.

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1. Introduction

This report is developed to support the prediction of probable earthquake performance of glazing systems within the context of seismic performance assessment of buildings including structural and nonstructural components as part of a Performance-Based Design (PBD) approach. This report is prepared for the Applied Technology Council (ATC) as part of the ATC-58 project to develop next-generation performance-based seismic design criteria. This sub-project provides the means to evaluate the response of curtain wall (CW) and storefront (SF) wall systems to earthquake-induced movements in terms of the probability of damage, the amount of damage, and the consequences of such damage. Types of damage to glazing systems in a given earthquake and associated repair costs are presented. The document is also intended to help design professionals gain a better understanding of the expected seismic behavior of modern CW and SF glazing systems. These tasks were undertaken through processing of full-scale laboratory experimental data on testing several different configuration types of glazing systems in the form of fragility curves and behavioral observations from laboratory experiments. Application of experimental data and results collected from the laboratory CW and SF specimen racking tests to the industry and field projects is discussed to enhance the usability of the fragility information on the glazing systems. Fragility information is useful for the assessment of the probability that a given glazing system will be damaged in a given earthquake event. This information when combined with estimated repair costs can help designers evaluate the performance of the glazing systems in meeting the selected objective of the PBD process of specific projects. Furthermore, fragility information can be analyzed as a tool to help designers select the appropriate CW or SF system during the preliminary design process.

The main objectives of this report are to: identify probable damage states for several types of glazing systems in earthquakes, develop fragilities associated with the defined damage states using the available experimental data, and estimate repair costs for each type of damage. The fragility information in this report was generated using the fragility calculator software developed by ATC as part of the ATC-58 project. The derived fragilities are used in the software Performance Assessment Calculation Tool (PACT) that has been developed by ATC to perform loss assessment calculations. PACT software computes losses, which may be defined in terms of direct economic loss, downtime, and casualties based on: (1) user-provided building structural, nonstructural, and content description (e.g., number and height of stories, floor areas, structural system type, distribution of walls in the building, etc.); (2) a determination of the earthquake hazard at the building site; (3) a structural seismic analysis to obtain predicted building responses (e.g., floor accelerations and story drifts); and (4) relating predicted building responses to damage and loss estimates through the specification of component damage vulnerabilities relating to such predicted responses.

For glazing fragility specification, structural responses (story drift ratios) associated with each damage state are expressed in probabilistic terms. Laboratory data from previous cyclic racking tests and some recent tests carried out to measure the drift capacity of various architectural glass CW and SF configurations were analyzed to develop fragility functions for several defined serviceability and ultimate damage states. These damage states included glass cracking, glass fallout, loss of dry-glazed gasket seal, and vertical and horizontal joint movements in unitized systems and associated potential frame damage.

The following sections discuss the background of seismic performance of glazing in earthquakes, followed by the experimental program, which includes the test facility, test procedure and specimens, and also the typical experimental test results and observations. The damage states and the procedure to develop fragility data are then explained. This is followed by a discussion on practical issues with respect to application of fragility information. The appendices will include the details of the data and plotted fragility curves in addition to completed information that will be available in the PACT software glazing assessment part, including the fragility tables.

2. Background

Curtain walls, storefronts, and windows have been vulnerable to damage in past earthquakes (EERI 1990, 1995a, 1995b, 2001, Evans et al. 1998, Lingnell 1994, FGMAJ 1995, Selvaduray and Tran 2003, Tucker and Lagos 2007). Reconnaissance reports have shown that earthquake damage can occur to these glazing systems even on buildings exhibiting little or no damage to the primary structural system. For example, the Northridge reconnaissance report (EERI 1995a) indicated that glazing system damage was extensive and extended to areas well beyond where most other nonstructural damage was quite limited (e.g., to suspended ceilings) and structural damage was rare. Glass breakage in glazing system can pose life safety hazards to pedestrian and building occupants. Examples of recent earthquake damage to glass panels are shown in Figure 1.

Figure 1: Glass failures documented during the 6.8 M Nisqually earthquake. Photo by Tom Reese/ Seattle Times March 2001.

To address life-safety concerns with respect to glazing failure, IBC 2006 (ICC 2006) refers to ASCE 7-05 (ASCE 2006) and requires glazing systems to accommodate the building design drift. The provisions require satisfaction of the following equation:

$$\left.\begin{array}{ll}\Delta_{fallout} & \geq 1.25\ I\ D_p \\ \text{or} & \geq 0.5\ \text{in.}\end{array}\right\}\ \text{whichever is greater} \qquad (1)$$

where I is the importance factor and $\Delta_{fallout}$ is the drift at which glass fallout from the CW or SF wall system under consideration occurs. D_p is the drift that the glazing component must be designed to accommodate. D_p is defined as the relative displacement over the height of the component and results from the building structural analysis for seismic loads based on ASCE 7-05 with the consideration of displacement amplification factor.

Satisfaction of the ASCE 7-05 provision requires determination of $\Delta_{fallout}$, which must be obtained using engineering analysis or by the test method prescribed in AAMA 501.6 (AAMA 2001). At this time, engineering analysis guidelines for dry-glazed glazing systems are not sufficiently developed; therefore, use of mockup testing is the only practical approach.

ASCE 7-05 also provides a way to avoid determination of $\Delta_{fallout}$ by requiring that

$$D_{clear} \geq 1.25\ D_p \qquad (2)$$

where D_{clear} is the lateral drift that occurs relative to the height of the glass panel and causes initial glass-to-frame contact in dry-glazed systems. For rectangular glass panels within a rectangular glazing frame in dry-glazed systems, D_{clear} can be estimated using the fallowing equation:

$$D_{clear} = 2c_1[1 + (h_p c_2)/(b_p c_1)] \qquad (3)$$

where h_p and b_p are, respectively, the height and width of the rectangular glass panel, c_1 is the clearance (gap) between the vertical glass edges and the glazing frame, and c_2 is the clearance between the horizontal glass edges and the glazing frame as shown in the drawing illustrated in Figure 2. Figure 3 shows an example of clearances used in an actual dry-glazed glazing construction.

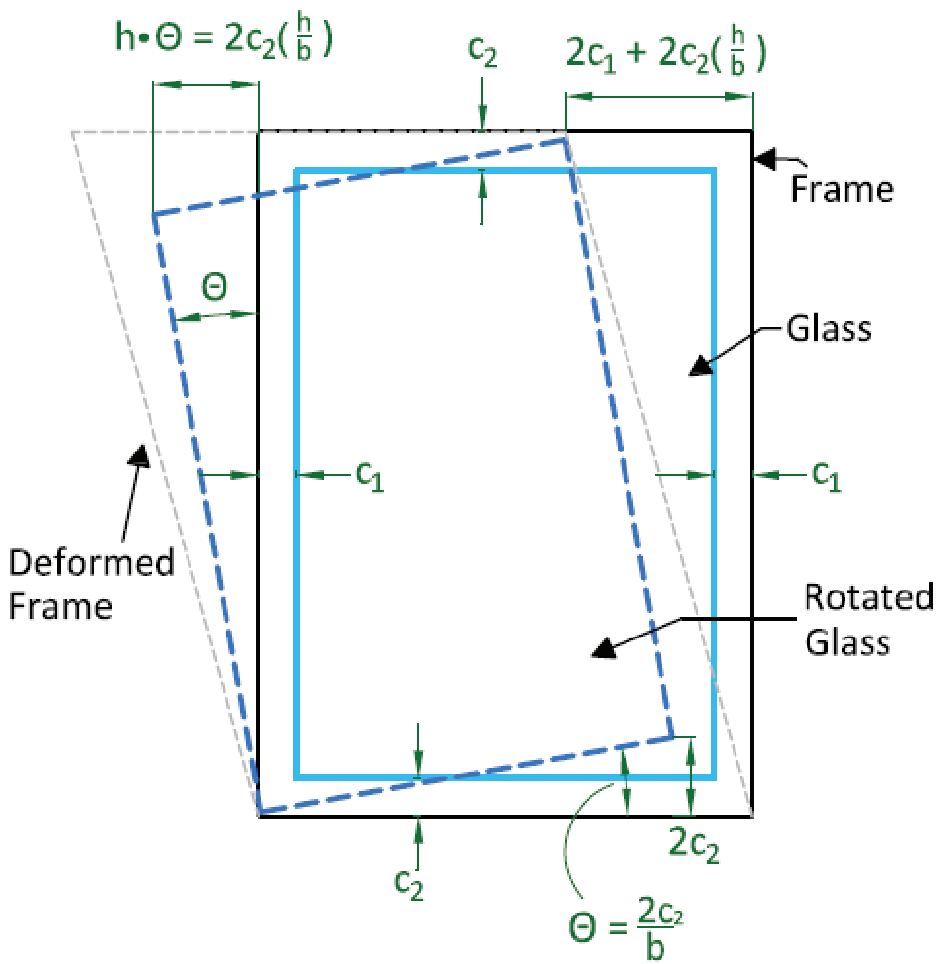


Figure 2: Definition of clearances and drift components for a glazing system. In this figure, h is the height and b the width of the glass panel.

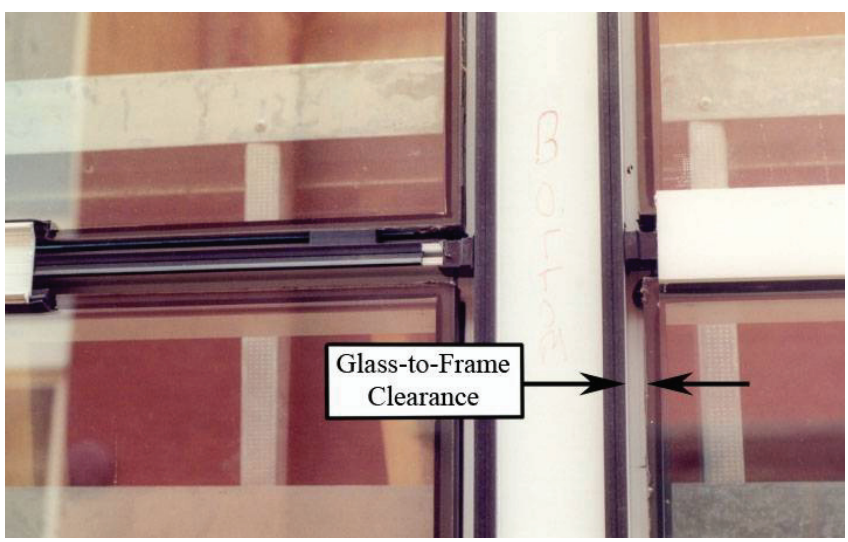


Figure 3: Example clearances in a dry-glazed curtain wall system under construction.

In essence, D_{clear} gives an estimate of the drift in a dry-glazed system beyond which glass distress can be expected. Equation (2) then requires the glass-to-frame clearances to be large enough to avoid glass-to-frame contact and potential subsequent damage. It should be noted that although Equation (1) is general and applies to all types of glazing systems such as stick-built or unitized systems, Equations (2) and (3) can be thought of to apply primarily to dry-glazed stick-built systems. For example, while Equation (1) can also apply to four-sided structural sealant glazing (SSG) systems in stick-built or unitized systems, because in such systems the glass edge is not captured (mechanically) in a glazing frame pocket, glass-to-frame issue is not relevant in four-sided SSG systems and therefore, Equation (3) is not applicable.

There have been some contributions in the past, and efforts are continuing to develop methods to predict glass damage in glazing systems using analytical approaches including finite element modeling. Research to develop analytical approaches for prediction of stresses in architectural glass has been primarily limited to modeling for prediction of glass panel surface stresses under out-of-plane wind-induced air pressure and/or windborne debris impact and thermal-induced stresses along glass panel edges. One analytical effort (Sucuoglu and Vallabhan 1997) attempted to develop a glass failure prediction model based on glass in-plane plate buckling for dry-glazed architectural glass under seismic-induced, in-plane diagonal force. Their failure prediction modeling approach is based on the assumption that glass strength is a function of combined tensile stresses and stress raising flaws on the surface of the glass. This failure modeling approach has been validated and used to develop glass thickness charts under wind loading conditions, windborne debris impacts, prediction equations for glass damage due to thermal edge stresses (Beason and Morgan 1984, Beason et al. 1998). For very large and thin glass plates, buckling under in-plane loading could govern the response. However, for glass sizes normally used in curtain walls on commercial buildings, repeated observations during in-plane racking tests (e.g., Behr 1998; Memari et al. 2003, 2004, 2006a) have shown that glass damage initiates as a result of glass-to-frame contacts that occur along glass panel edges in corner regions as shown in Figure 4. Moreover, the flaw distribution at glass edges differs from that on the face of glass panels, and flaws along glass edges are more severe, which shifts failure origins from the faces of a glass panel under in-plane forces to the glass panel edges. These differences must be accounted for in glass failure prediction models for seismic forces acting on glass panels. Limited work has been done to either experimentally measure or model the failure of glass due to edge stresses (Beason and Lingnell 2002, Carre and Dauderville 1999, Pantelides et al. 1994), but none of these studies have considered seismic loading along edges.

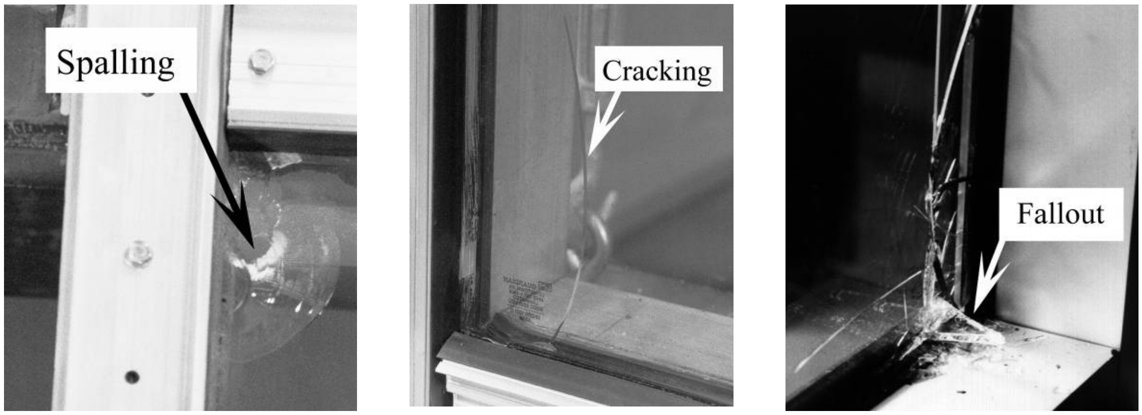


Figure 4: Typical glass damage progression at the corners of insulating glass units constructed with annealed monolithic glass panes with picture (a) showing spalling; (b) cracking; and (c) fallout.

Of course, glass strength along the edges is also a function of how the edge is finished (Memari et al. 2006a). For example, glass panels with cut, ground, seamed, or a polished finish will differ in their crack initiation drift capacity because flaws characteristics of each finish type will differ in their severity and distribution. Consideration of these factors in finite element modeling is a challenge because crack initiation at glass edges is a function of glass-to-frame contact stresses and glass edge finish conditions. However, experimental test results can be used to guide the development of appropriate failure models. A recent pilot study (Memari et al. 2007) has indicated that finite element modeling can be used to approximate the critical stresses created in a dry-glazed glass CW under pushover in-plane testing.

In general, because of the lack of a well-defined approach for seismic design of glazing systems, under current design practices selection of appropriate architectural glazing for seismic resistance can be a challenging and rather open-ended exercise. With respect to design under the performance-based design methodology, it is even more important for nonstructural systems including glazing systems to be properly evaluated and the appropriate selections made as part of an array of options available to decision makers. For this reason, it is necessary to evaluate the projected behavior of a glazing design choice with respect to potential damage and cost of repair. To develop the necessary database for this form of evaluation, experimental data available can be processed and compiled into a form consistent with the ATC 58 program based on fragilities. A series of lab studies carried out over the past two decades have generated a substantial database of information that is available and accessible on the expected seismic performance of various CW and SF systems (e.g., Behr et al. 1995a, Behr 1998, Memari et al. 2003). This existing database along with more recent tests on four-sided SSG unitized and storefront systems were used to develop the fragilities that will be discussed subsequently in this report.

3. Experimental Plan, Test Facility and Procedure

3.1 Description of Specimens

Racking test results on CW and SF wall systems consisting of dry-glazed stick-built systems or unitized four-sided SSG systems are presented. The mock-ups including a variety of annealed (AN), heat strengthened (HS), and fully tempered (FT) glass. The tests included monolithic, insulating glass units (IGU), asymmetric IGUs with an interior monolithic pane and an exterior laminated pane, and single thickness laminated glass units. Furthermore, the configurations varied by glass size, glass-to-frame clearance, framing type, and glass thickness. All of the glass configurations included in this report had square corner geometry. The number of specimens tested for each glass configuration type ranged from one to twenty-four.

Table 1 is a summary of the forty-four different CW and SF configurations used for fragility development for this report. Listings of these glass configurations with more specific glazing details can be found in Appendix A, and a discussion of how these specific glass configurations were chosen is presented later in the report. Table 2 illustrates an example of the CW configuration detail descriptions presented in Appendix A. Configurations 32 through 44 that include unitized and storefront systems followed a unique test setup as they were real construction systems prefabricated by curtain wall design firms. These systems were tested recently and are discussed in more detail compared to other systems.

Table 1: Summary of Glass Configurations.

ID	System	Glazing Type	Glass-to-Frame Clearance	Aspect Ratio	Sealant
1	MR	1/4 in. (6 mm) AN monolithic	0.43 in. (11 mm)	6:5	Dry
2	MR	1 in. (25 mm) AN insulating glass unit (IGU) [1/4 in. (6 mm) inner and outer panes]	0.43 in. (11 mm)	6:5	Dry
3	MR	1/4 in. (6 mm) inner AN / 1/4 in. (6 mm) outer AN LAM (0.030 PVB) IGU	0.43 in. (11 mm)	6:5	Dry
4	MR	1/4 in. (6 mm) inner AN / 1/4 in. (6 mm) outer AN LAM (0.060 PVB) IGU	0.43 in. (11 mm)	6:5	Dry
5	MR	1/4 in. (6 mm) inner AN / 1/2 in. (13 mm) outer AN LAM (0.030 PVB) IGU	0.43 in. (11 mm)	6:5	Dry
6	MR	1/4 in. (6 mm) AN LAM (0.030 PVB)	0.43 in. (11 mm)	6:5	Dry
7	SF	1/4 in. (6 mm) AN monolithic	0.41 in. (10 mm)	6:5	Dry
8	SF	1 in. (25 mm) AN IGU	0.59 in. (15 mm)	6:5	Dry
9	SF	1/4 in. (6 mm) AN LAM (0.030 PVB)	0.41 in. (10 mm)	6:5	Dry
10	MR	1/4 in. (6 mm) AN monolithic	0 in. (0 mm)	6:5	Dry
11	MR	1/4 in. (6 mm) AN monolithic	0.13 in. (3 mm)	6:5	Dry
12	MR	1/4 in. (6 mm) AN monolithic	0.25 in. (6 mm)	6:5	Dry

13	MR	1 in. (25 mm) AN IGU [1/4 in. (6 mm) inner and outer panes]	0.25 in. (6 mm)	6:5	Dry
14	MR	1/4 in. (6 mm) AN monolithic	0.43 in. (11 mm)	2:1	Dry
15	MR	1/4 in. (6 mm) AN monolithic	0.43 in. (11 mm)	1:2	Dry
16	MR	1/4 in. (6 mm) AN monolithic, 2-sided SSG, Center Panel	0.43 in. (11 mm)	6:5	Wet
17	MR	1/4 in. (6 mm) AN monolithic, 2-sided SSG, Outside Panel	0.43 in. (11 mm)	6:5	Wet
18	MR	1/4 in. (6 mm) FT monolithic, 2-sided SSG, Center Panel	0.43 in. (11 mm)	6:5	Wet
19	MR	1/4 in. (6 mm) FT monolithic, 2-sided SSG, Outside Panel	0.43 in. (11 mm)	6:5	Wet
20	MR	1/4 in. (6 mm) AN laminated, 2-sided SSG, Center Panel	0.43 in. (11 mm)	6:5	Wet
21	MR	1/4 in. (6 mm) AN laminated, 2-sided SSG, Outside Panel	0.43 in. (11 mm)	6:5	Wet
22	MR	1 in. (25 mm) AN IGU [1/4 in. (6 mm) inner and outer panes], 2-sided SSG, Center Panel	0.43 in. (11 mm)	6:5	Wet
23	MR	1 in. (25 mm) AN IGU [1/4 in. (6 mm) inner and outer panes], 2-sided SSG, Outside Panel	0.43 in. (11 mm)	6:5	Wet
24	MR	1/4 in. (6 mm) HS monolithic	0.43 in. (11 mm)	6:5	Dry
25	MR	1/4 in. (6 mm) FT monolithic, Seamed Edge	0.43 in. (11 mm)	6:5	Dry
26	MR	1/4 in. (6 mm) FT monolithic, Polished Edge	0.43 in. (11 mm)	6:5	Dry
27	MR	1/4 in. (6 mm) AN monolithic	0.43 in. (11 mm)	6:5	Dry
28	MR	1/4 in. (6 mm) AN monolithic	0.43 in. (11 mm)	2:1	Dry
29	MR	1/4 in. (6 mm) AN monolithic	0.43 in. (11 mm)	1:2	Dry
30	MR	1 in. (25 mm) HS IGU [1/4 in. (6 mm) inner and outer panes]	0.43 in. (11 mm)	6:5	Dry
31	MR	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes]	0.43 in. (11 mm)	6:5	Dry
32	US	1-1/4 in. (32 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], 4-sided SSG, VHB™ SGT™	0.43 in. (11 mm)	Varies	Wet*
33	SF	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Planar Specimen	0.43 in. (11 mm)	1.89:1	Dry
34	SF	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, in-plane	0.43 in. (11 mm)	1.89:1	Dry
35	SF	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, combined	0.43 in. (11 mm)	1.89:1	Dry
36	SF	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, Short side	0.43 in. (11 mm)	2.83:1	Dry
37	SF	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Planar Specimen	0.43 in. (11 mm)	1.88:1	Dry
38	SF	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, in-plane	0.43 in. (11 mm)	1.88:1	Dry
39	SF	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, combined	0.43 in. (11 mm)	1.88:1	Dry

40	SF	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, Short side	0.43 in. (11 mm)	2.82:1	Dry
41	SF	3/8 in. (10 mm) FT monolithic, Planar Specimen	0.5 in. (13 mm)	1.93:1	Wet
42	SF	3/8 in. (10 mm) FT monolithic, Corner Cond. Specimen, in-plane	0.5 in. (13 mm)	1.93:1	Wet
43	SF	3/8 in. (10 mm) FT monolithic, Corner Cond. Specimen, combined	0.5 in. (13 mm)	1.93:1	Wet
44	SF	3/8 in. (10 mm) FT monolithic, Corner Cond. Specimen, Short side	0.5 in. (13 mm)	2.72:1	Wet

SF = Storefront System AN = Annealed LAM = Laminated FT= Fully Tempered Wet = Silicone Glazing
MR = Mid-Rise Curtain Wall System Dry = Rubber gaskets US = Unitized Curtain Wall system HS= Heat Strengthened
* System uses a structural silicone tape that replaces traditional wet glazing

Table 2: Glazing details provided in Appendix A for the first glass configuration.

Serviceability Limit States

ATC-58 Project ID	PACT Software ID	Component Description:	Describe Specimens:
1	B2022.001	Curtain wall, monolithic, annealed glass, aluminum framing, square corners, cut corner finish, cut edge finish	5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing

Describe Excitation:	Demand Parameter:	Damage Evidence:	Damage Measure:
Displacement controlled cyclic racking loading	Cracking Transient Interstory Drift Ratio	glass-to-frame contact, corner crushing, fallout, gasket/sealant damage, cracking	Serviceability type failure

Ultimate Limit States

ATC-58 Project ID	PACT Software ID	Component Description:	Describe Specimens:
1	B2022.001	Curtain wall, monolithic, annealed glass, aluminum framing, square corners, cut corner finish, cut edge finish	5 ft W x 6 ft H 1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing

Describe Excitation:	Demand Parameter:	Damage Evidence:	Damage Measure:
Displacement controlled cyclic racking loading	Fallout Transient Interstory Drift Ratio	glass-to-frame contact, corner crushing, fallout, gasket/sealant damage, cracking	Ultimate type failure

Configurations 1-6 and 10-31 were stick-built as in mid-rise construction, while Configurations 7-9 and 33-44 were storefront. The only configuration that was unitized was Configuration 32. Configurations 1-15 and 24-31 were dry-glazed, i.e., rubber gaskets were used between the glass and the aluminum CW frame along the entire glass panel perimeter. The rubber gaskets act as both a weatherseal and a means of distributing the clamping force used to keep the glass panel in the framing system. Mid-rise curtain wall glass panels were mocked up in a Kawneer 1600™ aluminum mid-rise framing system. Configurations 16-23 were constructed based on two-sided SSG approach. SF glass panels in configurations 7-9 were mocked up in a Kawneer TriFab II® 450 or 451 aluminum framing system. SF systems 33-44 were prefabricated Oldcastle BuildingEnvelope™ systems known formerly as Vistawall systems. The unitized systems were designed and constructed by En-Wall curtain wall designers. While SF Configurations 7-9 were dry-glazed systems, SF Configurations 33-44 were constructed based on four-sided SSG method using Dow Corning structural silicone to adhere glass panes to aluminum framing. Similarly, the unitized systems Configuration 32 were constructed based on four-sided SSG; however, instead of silicone, 3M VHB™ Structural Glazing Tape SGT™ was used to attaché glass to the glazing frames.

For the mid-rise dry-glazed CW system, pressure plates were installed using self-drilling screws located 9 in. (229 mm) on center and a torque limiting drill attachment to torque the screws to 95 -100 in. • lbs (10.7 - 11.3 N • m) as recommended in the Kawneer 1600™ system installation instructions (1998). Figure 5 shows general details of the mid-rise dry-glazed CW components used for the monolithic, laminated, and IGU specimens. Essentially, rubber setting blocks and side spacers provide cushion support for the glass panel along its bottom and sides while perimeter gaskets hold the glass panel within the aluminum frame through the friction developed between the glass and the rubber gaskets. The nominal glass-to-frame clearance for each MR specimen (except configurations 10-13 in Table 1 was 0.43 in. (11 mm), which is the recommended clearance for practical applications. For most of the MR tests, contact sensors were attached in each corner of the specimen (see Figure 6), and a contact-sensor display was used to determine when contact between the glass edges and the CW frame occurred.

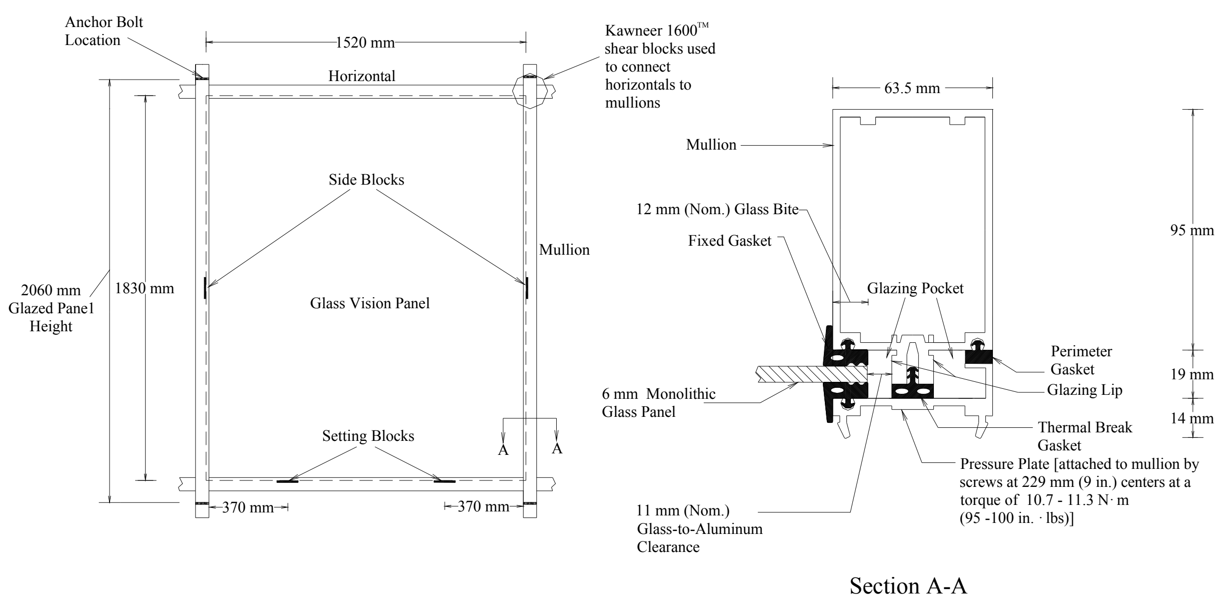


Figure 5: General glazing details for the mid-rise aluminum curtain wall framing system.

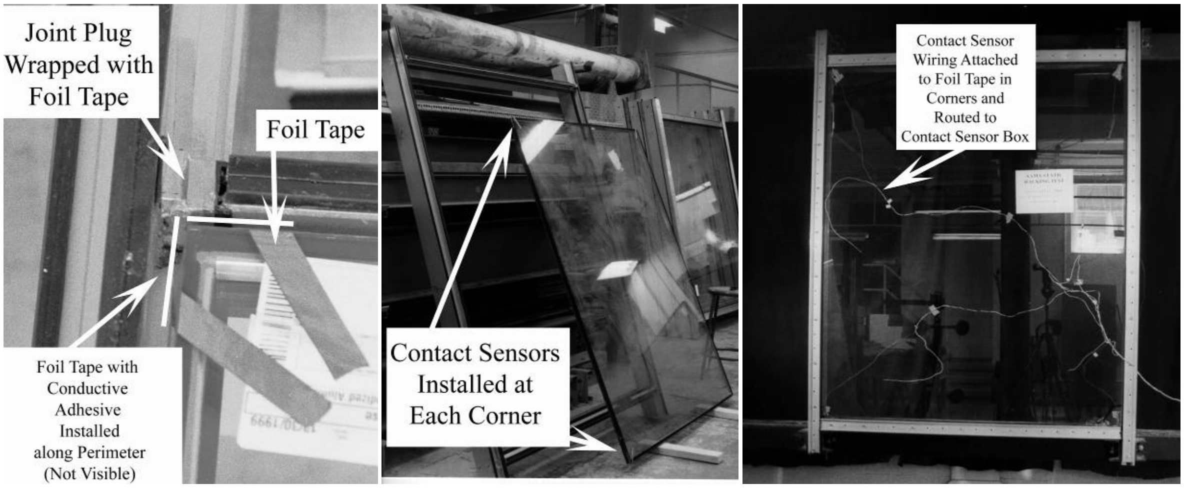


Figure 6: Contact sensor installation and setup with pictures showing (a) taping; (b) overall placement; and (c) wiring when glass is glazed.

The SF configurations 7-9 used comparable installation methods to that of the CW MR systems. Typical details of the glazing components for the SF configurations are shown in Figure 7. The nominal glass-to-frame clearance for the 1/4 in. (6 mm) glass thickness types was 0.41 in. (10 mm) while for the 1 in. (25 mm) glass thickness types the nominal clearance was 0.59 in. (15 mm). Because the results of the testing carried out on SF configurations 33-44 and unitized CW Configuration 32 are not currently available in open literature, and there is increasing interest in the seismic response of four-sided SSG CW and SF systems, detailed descriptions of these tests are presented in separate sections subsequently. In particular, because most of the discussions in this report are related to the conventional stick-built dry-glazed systems, it is appropriate to have a separate discussion on unitized CW and SF four-sided SSG systems.

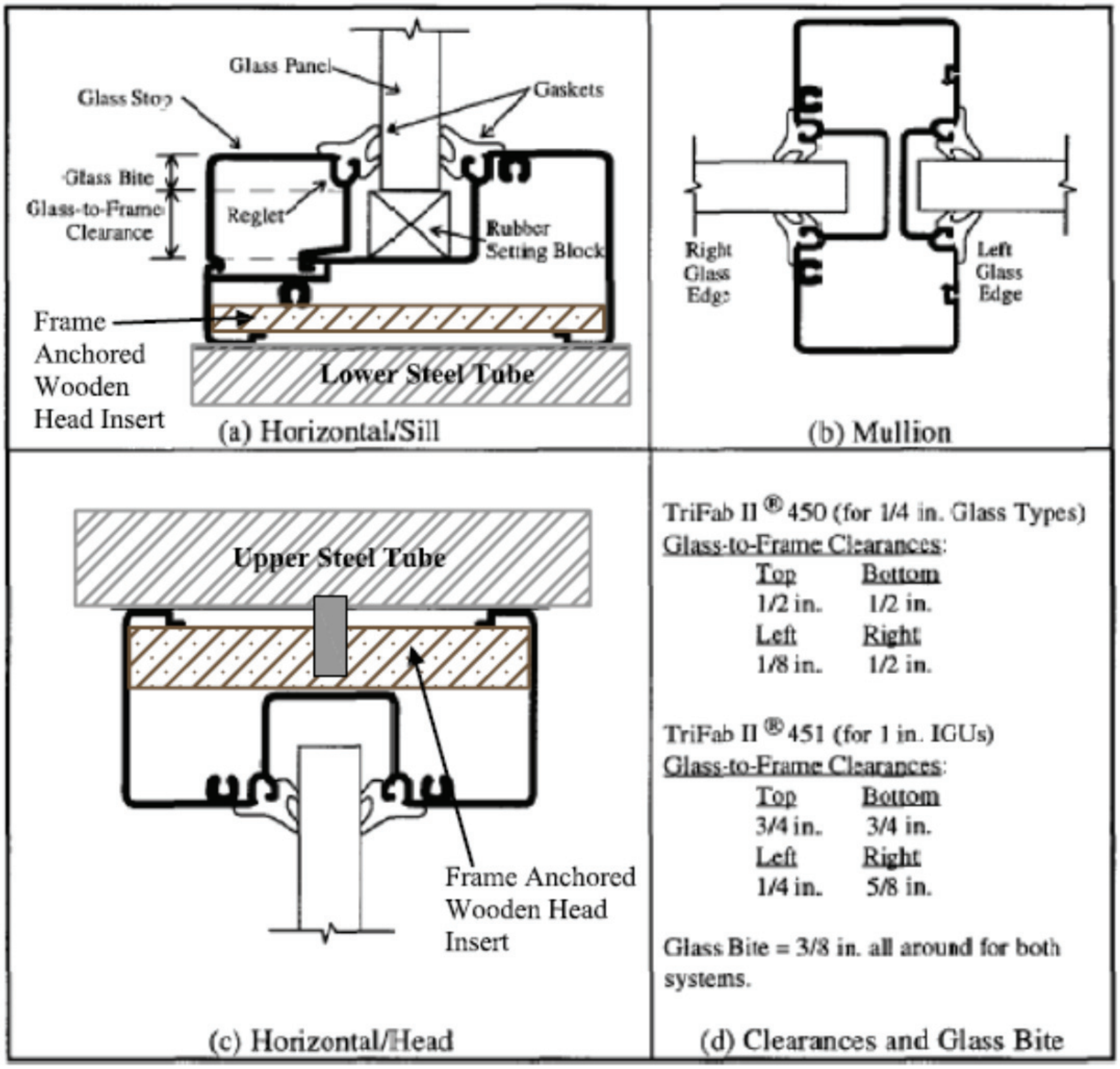


Figure 7: Glazing details for the Storefront aluminum framing system (Behr and Belarbi 1996).

3.2 Description of Test Facility

In-plane cyclic racking tests were performed using the racking test facility shown in Figure 8. Specimens 1-6 and 10-15 were tested one at a time on the facility, while SF configurations 7-9 were tested three panels at a time as shown in Figure 9. Each specimen was connected to the facility by attachment to both an upper and a lower sliding steel tube that are interconnected with a fulcrum arm used to transmit in-plane racking displacements to the specimen as further described in section 3.1.3.

Mid-rise CW specimen vertical mullions were attached at all four corners to the facility's sliding steel tubes using the pi-shaped steel anchor connections detailed in Figure 10. Two 1/2 in. (12 mm) diameter, 13 threads per inch, grade 8 steel bolts were used to attach the anchors to the test facility through 9/16 in. (14 mm) holes in the 6 in. (152 mm) sliding steel tubes. Also, reinforcement plates were welded around the anchor edges to avoid damage to the anchors during testing. The bolts used in conjunction with the bearing plate inserted between the reinforcement plate and the glazing frame horizontals as noted in Figure 10 were hand tightened only. This detail served to restrict excessive horizontal rotations, which would not typically be expected in an earthquake event because of adjacent glass panels above and below the glass panel or head and sill restrictions that would be present in a large expanse of CW framing on a building. To attach the aluminum glazing frame to the anchors, 3/8 in. (10 mm), grade 8 bolts were typically routed through the center of the anchors. Furthermore, the frame was shimmed with wood to fill the typical 1/8 to 1/4 in. (3 to 6 mm) gaps between the anchor and the frame. This anchor detail created a relatively fixed connection detail as compared to a real CW installation. This point is further discussed later in the report.

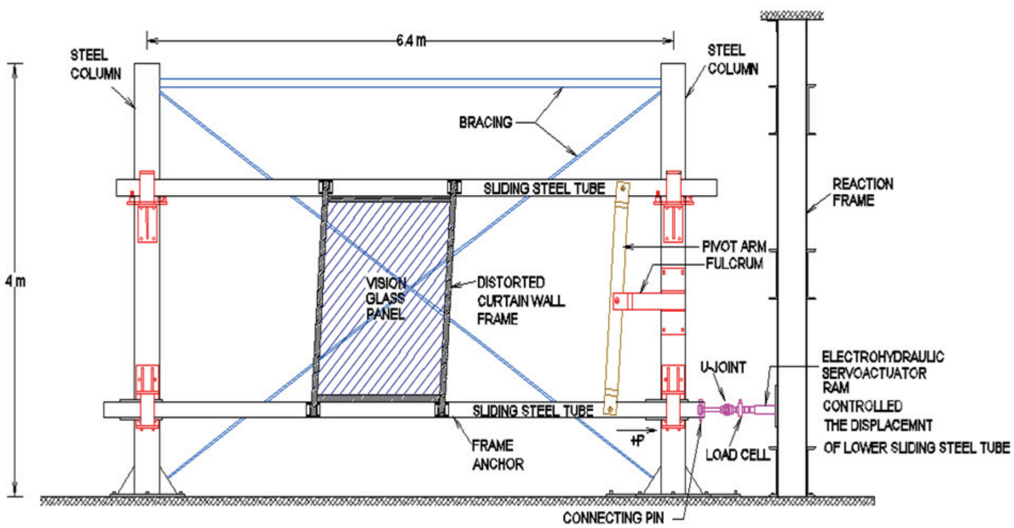


Figure 8: Dynamic racking test facility schematic for CW mock-ups.

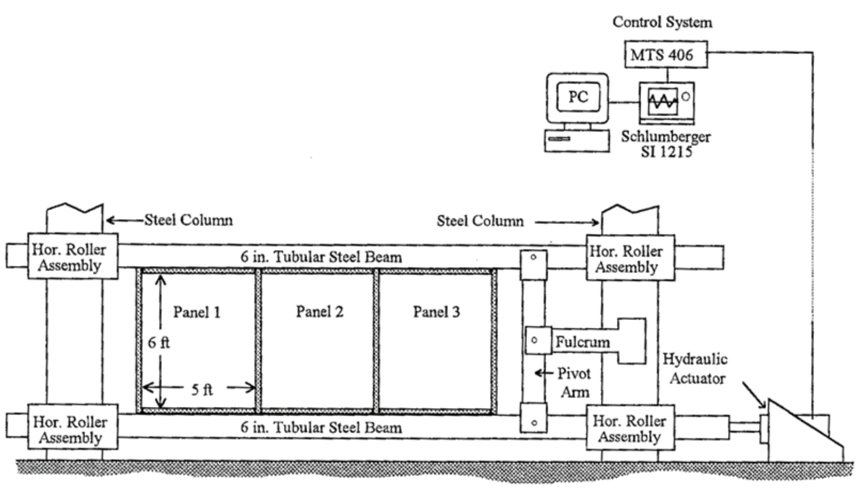
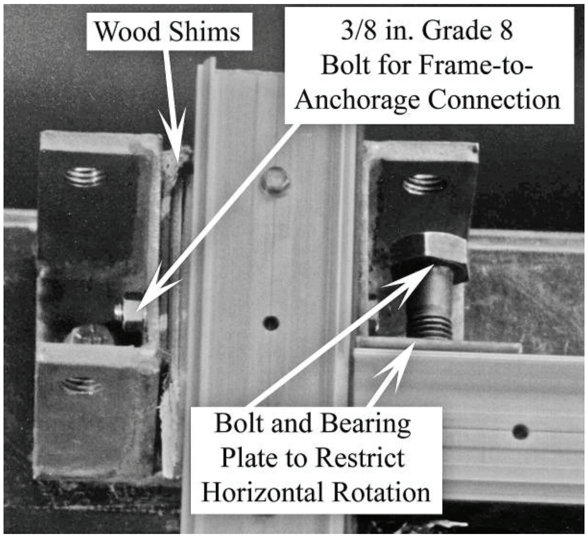


Figure 9: Test setup for storefront configurations.



(a)

(b)

Figure 10: (a) View of connection detail for MR CW mock-up specimen corners to the racking test facility sliding steel tubes; (b) Isometric view of connection detail without frame installed.

The SF system configurations 7-9 were anchored to the racking facility through the use of anchored wooden head inserts. These wooden members were located within the aluminum framing as shown in Figure 7 and were connected to the framing with screws. Unlike the CW configurations, the SF glazing frame was therefore attached directly under the top horizontal sliding steel tube and directly above the bottom sliding steel tube of the racking facility.

3.3 Flexibilities in Connections

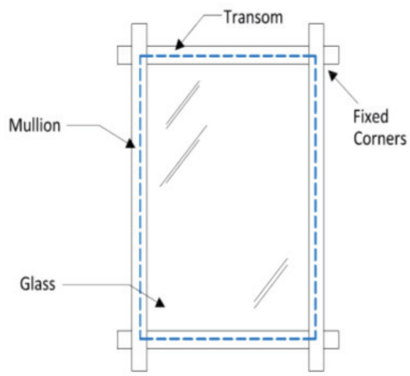
The details of the connection of mullions in different glazing frame types to the building structural system are varied. As a result, the expected flexibility of the framing system during seismic loading will also vary for a given CW or SF wall system. The flexibility of the connection detail can affect the amount of drift that is transferred from the structural system of the building to the exterior CW during a seismic event. Examples of CW field connections are shown in Figures 11 and 12. In general, these connections are not rigid and have some flexibility depending on the connection type used. Therefore, as the building structural frame deforms, the continuous mullions at a given floor connection point would be expected to exhibit some rotation and even relative translation during seismic loading depending on the connection detail used. In most cases, the connection will translate the same distance as the structural frame and will not displace relative to the structure. As a result, the rotational capabilities of certain connections will be the dominant factor if flexibilities are present.

These rotations and translations, however, are generally small enough such that in cases where the connections are considered flexible, the CW will experience only a slightly smaller displacement than the drift displacement that the structural frame experiences. However, depending on the particular connection, a much higher effect is possible. The connections used for the CW mock-up tests discussed herein allow transference of nearly 100% of the drift experienced by the facility, which represents a building frame, to the CW frame mock-up. Although most CW installations would be expected to yield less than 100% drift transfer, for purposes of fragility development it is assumed that the drift transfer from building structure to the CW frame during a seismic event is a straight 1:1 ratio. This approach creates a small amount of conservatism in the fragilities, but also ensures that none of the fragilities will overestimate the failure capacity of curtain walls on buildings where the connections are rigid.

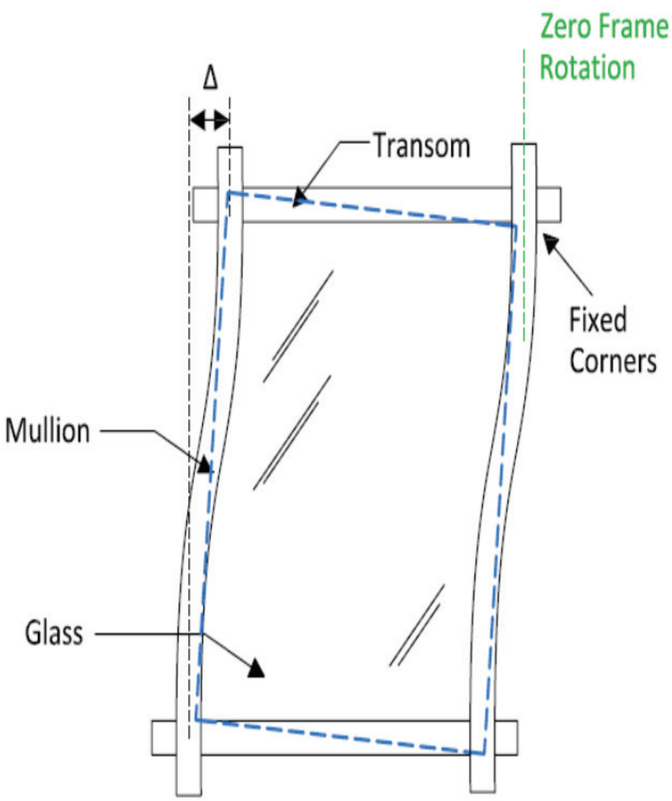
Figure 11: Curtain wall under construction in San Francisco with connection elements between CW frame and structural building frame highlighted.

Figure 12: Curtain wall system under construction in State College (Pennsylvania) with connection elements between CW frame and structural frame highlighted.

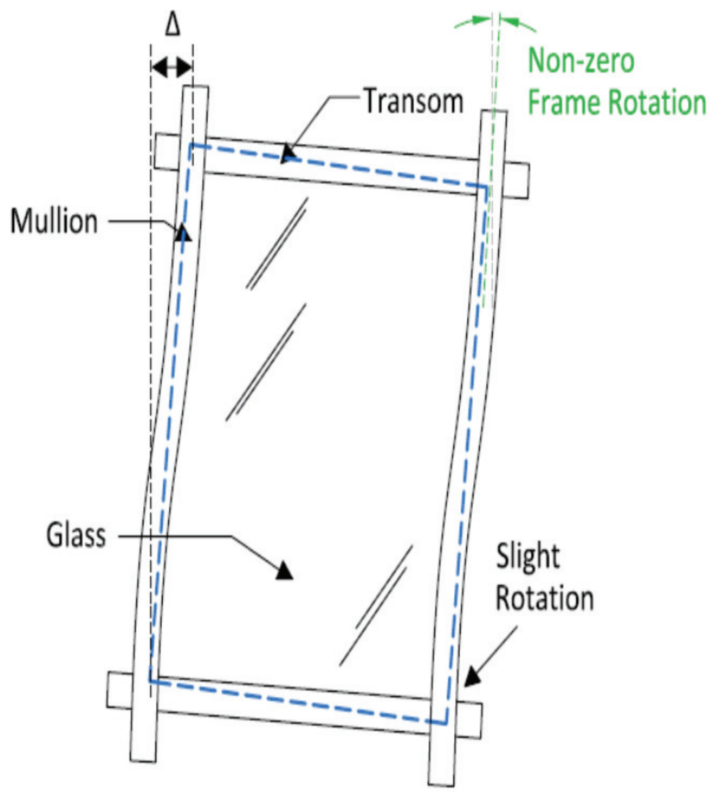
Rotational flexibility on the testing facility was not present due to the rigid counterparts (e.g., the connection detail used for the mid-rise curtain wall racking tests presented herein). As demonstrated schematically in Figure 13, a more flexible connection detail can lead to higher drift capacities for the wall system. Figure 13 illustrates three conditions: (1) a glass panel in a framing system with no lateral displacement (Figure 13a) ; (2) assumed rigid body movement of a glass panel while its frame is deforming due to a lateral displacement with rigid mullion-to-structure connection points exhibiting minimal corner rotation; and (3) assumed rigid body movement of a glass panel while its frame is deforming due to a lateral displacement with mullion-to-structure connection points that exhibit rotational capability through various means (e.g., reduced anchor stiffness, slotted holes, etc.). When rigid connections are present, the glass will contact the frame earlier than the glass panes in curtain walls with connections that exhibit more rotation. Thus, the results presented with rigid connection are inherently conservative (i.e., they do not tend to overestimate drift capacities of various glazing configurations), but the degree of conservatism is not known with sufficient accuracy to allow the development of a modification factor for the fragilities developed for the configurations presented herein.



(a) First Condition: Glass panel and framing system at rest



(b) Second Condition: Glass panel rigid body movement and frame deformation with fixed corners



(c) Third Condition: Glass panel rigid body movement and frame deformation with corners slightly rotating

Figure 13: Illustrated differences labeled as (a), (b), and (c) in structural deformations due to lateral forces between CW configurations with fixed corners versus corners with slight rotations

It should be noted that three different connection configurations were tested to quantitatively determine rotational stiffnesses including the connection used for mid-rise curtain wall racking tests. The connection used for curtain wall testing proved to be much stiffer than other "real-world" connections, leading to more conservative results during the mid-rise curtain wall racking tests. The degree of the dependency of glass performance on connection types is not known, but it is believed that using a stiffer connection for racking tests yields more conservative results.

3.4 Racking Test Protocol

As noted in section 3.1, the two racking facility sliding steel tubes slide on roller assemblies in opposite directions by means of a fulcrum and pivot arm mechanism. The bottom sliding tube is displaced by a computer-controlled electrohydraulic servoactuator having a dynamic stroke capacity of ±3.0 in. (±76 mm). The fulcrum and pivot arm mechanism attached to the top and bottom sliding steel tubes then yields relative displacement (between top and bottom steel tubes) that is twice the stroke capacity, that is an "inter-story" drift of 6.0 in. (152 mm). Drift reported in the laboratory studies is based on the displacement transducer embedded in the actuator, but as described in depth in section 3.3, this displacement is not the actual displacement that the specimen under test is subjected to because of the flexibilities within the racking facility.

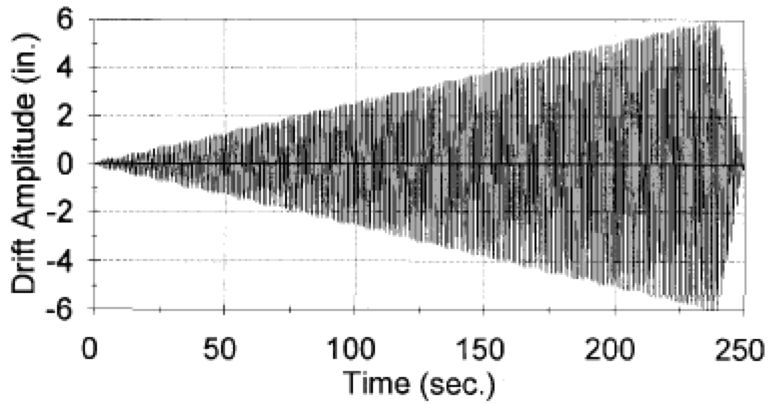
The same racking facility has been used for all of the laboratory studies, but a number of revisions have been made over time to the electrohydraulic servoactuator apparatus and servoactuator control electronics. In its current form, dynamic displacement load histories are applied to the wall specimen under test by means of a MTS 244.22 electrohydraulic servoactuator. An MTS 458.20 controller system is used to enable stroke (i.e., displacement) control of the electrohydraulic servoactuator. Drift loading histories are downloaded to a 458.91 Microprofiler function generator on the MTS controller across a RS232C serial interface from a personal computer running a LabVIEW program written for this purpose. Swept sine waveforms of varying amplitude, frequency, and number of cycles are generated in this manner and are applied to the servoactuator via a tuned, closed-loop control loop. Load and displacement signals generated during the tests were monitored and acquired using LabVIEW. In-plane racking loads are measured with a load cell placed between the servoactuator ram and the sliding steel tube, while racking displacements are measured with the LVDT embedded in the servoactuator. As noted in section 3.3, additional sensors are often used to further evaluate various displacements and rotations in the racking facility and at various locations for the specimen under test.

Racking tests on all of the specimens of Configurations 7, 8 and 9 in Table 1 were conducted using the fixed frequency (0.8 Hz), "crescendo test method" originally introduced by Behr and Belarbi (1996) as seen in Figure 14. Most of the specimens of Configurations 2 and 6 used the slightly "modified stepwise" crescendo test method (1Hz for amplitudes from 0 (0 mm) to 4.5 in. (114 mm), 0.8 Hz for amplitudes from 4.5 to 5.5

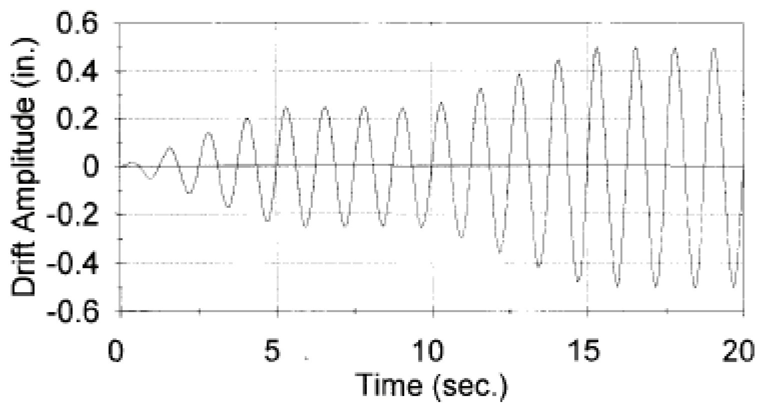
in. (114-140 mm), and 0.5 Hz for amplitudes from 5.5 to 6 in. (140-152 mm)) drift time history presented by Behr (1998) as shown in Figure 15. All other specimens of Configurations 2 and 6, and the other Configurations in Table 1 were tested using a stepwise version of the crescendo test method (0.8 Hz for amplitudes between 0 (0 mm) to 3 in. (76 mm), and 0.4 Hz for amplitudes from 3 in. (76 mm) to 6 in. (152 mm))) promulgated in AAMA 501.6 (AAMA 2001b) described below to evaluate the seismic performance of architectural glass and glazing systems, including $\Delta_{fallout}$. The original crescendo test method used by Behr (1998) and the AAMA 501.6-prescribed test method are nearly identical, with the exception of some slight frequency differences needed after 3 in. (76 mm) of racking amplitude. This deviation was devised by the AAMA standard committee to accommodate hydraulic power supply and servoactuator volumetric flow limitations and controller variations in the servoactuator systems which may be present in the typical hydraulic test system using the test standard. The results from tests on Configurations 2 and 6 and other configurations not reported herein have verified that the same results can be produced using any of the methods.

All three versions of the crescendo test method used are characterized by monotonically increasing-amplitude sinusoidal drift cycles to determine serviceability drift limits and ultimate drift limits for architectural glass components subjected to cyclic, in-plane racking displacements. Moreover, despite their frequency differences, the methods consist of a series of alternating “ramp up” and “constant amplitude” intervals, each comprised of four sinusoidal cycles. The “stepwise” crescendo test methods applied the crescendo displacement time history in a stepwise manner (1/4 in. [6 mm] increments) to provide a way of accurately recording of glass and glazing system serviceability performance parameters. However, after glass cracking was observed, the crescendo test typically was conducted in a continuous manner. Thus, for example, if cracking was observed at 1.5 in. (38 mm) the remainder of the crescendo test was performed continuously between ± 1.75 in. (± 44 mm), the next step in the crescendo test, and the ± 6 in. (± 152 mm) racking displacement limit of the test facility. Synchronized video recording of each dynamic racking test was used to determine additional serviceability data and ultimate drift limits for each architectural glass specimen after the onset of initial glass cracking.

Figure 16 presents the displacement time history for the AAMA 501.6 dynamic crescendo test when run continuously. Figure 17 is one of the as many as 24, 1/4 in. (6 mm) increments used for those configurations employing this test method. When concatenated with other steps, the result is the continuous drift time history shown in Figure 18.



(a) Entire Crescendo Test



(b) First 20 Seconds of Crescendo Test

Figure 14: Drift time history for (a) entire crescendo test and (b) first 20 seconds of crescendo test proposed in Behr and Belarbi (1996).

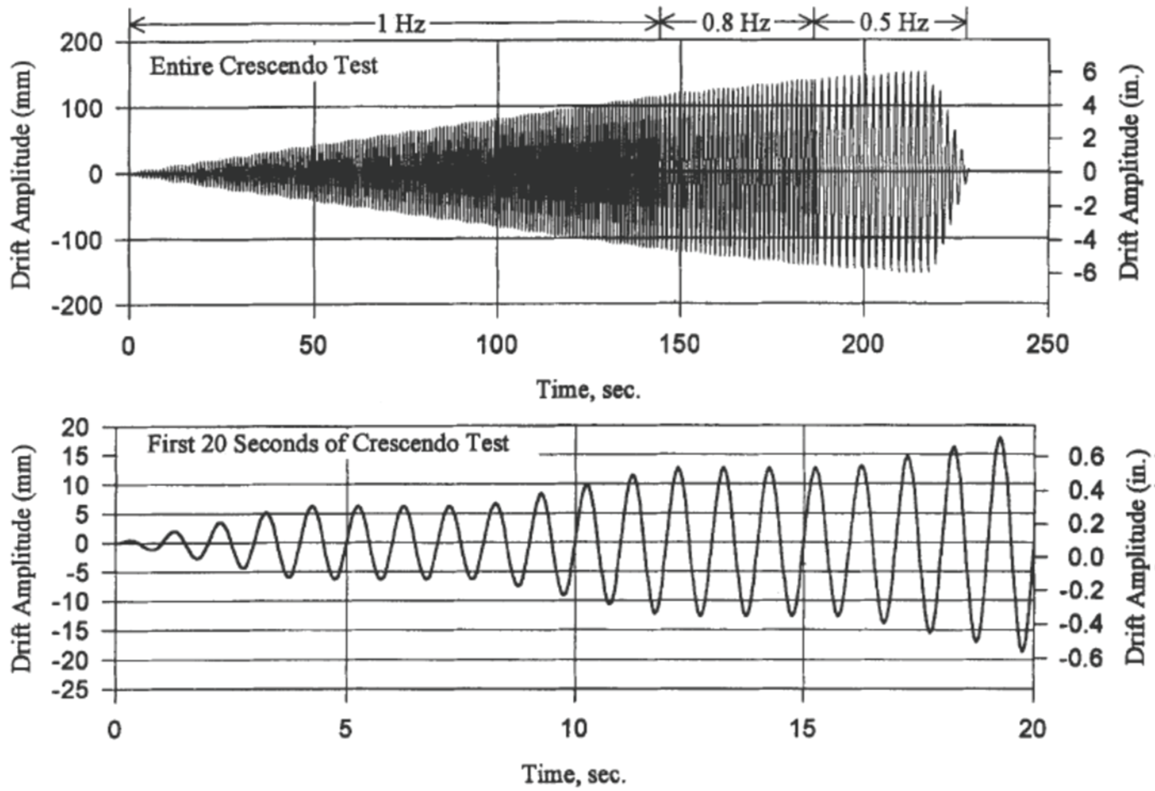


Figure 15: Drift time history profile for (a) entire crescendo test and (b) first 20 seconds of crescendo test used in the mid-rise curtain wall testing (Behr 1998).

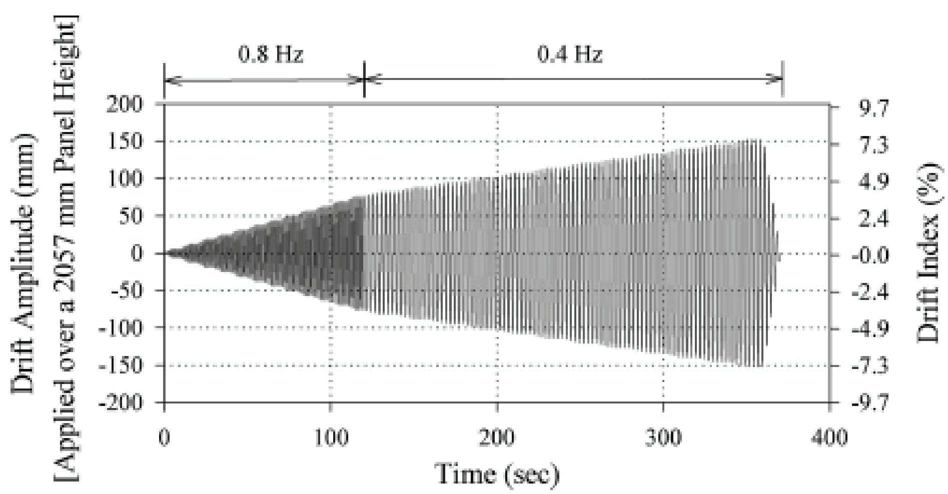


Figure 16: Displacement time history for dynamic crescendo tests adhering to the AAMA 501.6 test standard.

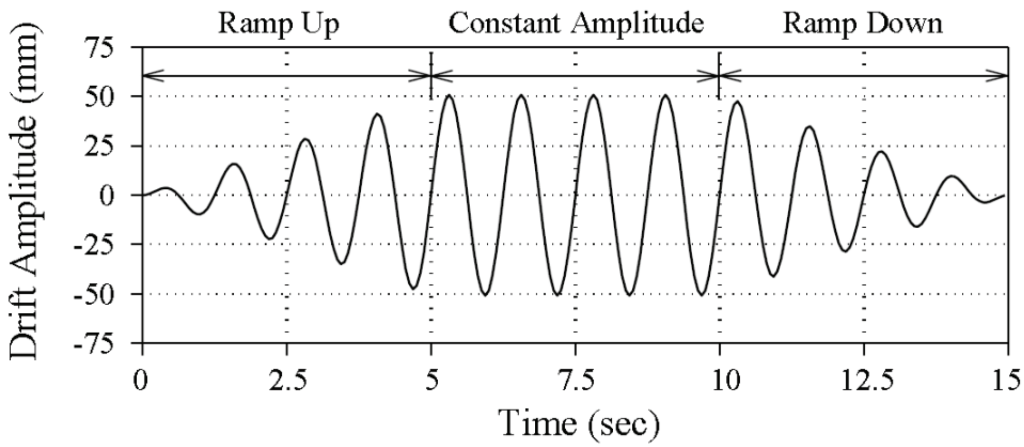


Figure 17: Typical racking Step (Step 8; 0.8 Hz; 2.5% drift% Drift Index.) for AAMA 501.6 stepwise dynamic crescendo tests.

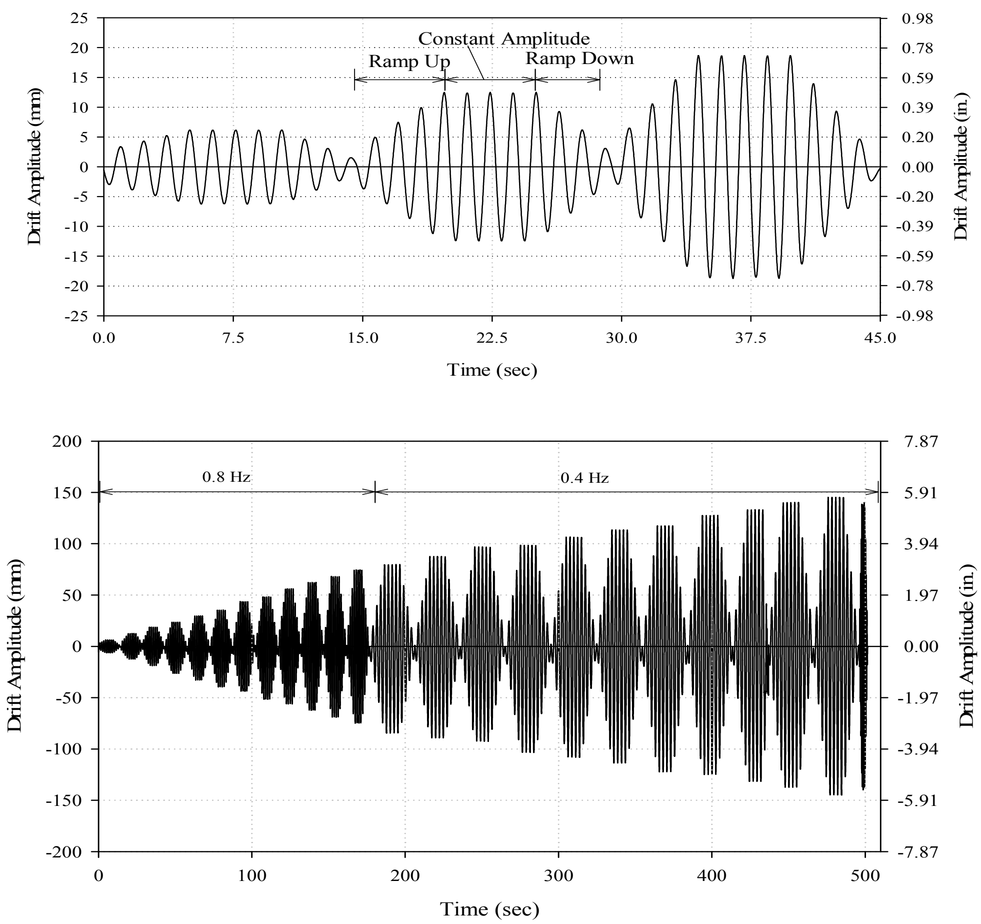


Figure 18: Time–history showing concatenated steps: Top: first three steps, Bottom: complete history.

3.5 Flexibilities in Racking Test Facility

In order to generate appropriately conservative fragility values, the effect of flexibility in the racking facility was evaluated. In an effort to ensure the accuracy of the testing results obtained, various sensor racking tests were run on the racking facility. Table 3 lists the various glass configurations on which sensor tests were performed. The variety of glass configurations allowed for comparisons among different configuration details. Sensors were attached to various points on the racking facility and glass panel. To measure the horizontal displacement of the lower and upper steel tubes of the testing facility, two linear potentiometers backed by a spring-controlled vertical slide to allow free movement up and down were installed. Also, a DC LVDT was attached to the actuator to measure the deflection of the actuator plate. Furthermore, a DC RVDT rotation sensor measured the angle of rotation of the fulcrum arm through the use of an x-y slide table. Lastly, three sensors were used to measure the rotational and translational movement of the glass pane relative to the framing. This was executed by connecting a DC RVDT rotation sensor to the center of the glass panel and having a horizontal and a vertical string potentiometers measure the linear translation from the center point of the glass panel. A summary of the additional sensors used for the racking tests can be found in Table 4.

Table 3: Summary of curtain wall configurations tested with sensors.

Curtain Wall Specimens Tested with Sensors	
1	AN Mono – Standard Clearance
2	AN Mono – 1/4 in. (6 mm) Clearance
3	AN Mono – 0 in. (0 mm) Clearance
4	AN IGU – Standard Clearance
5	AN IGU – 1/4 in. (6 mm) Clearance

Table 4: Summary of additional sensors used in sensor experimental testing.

Item Measured	Sensor Description
Actuator Plate Displacement	DC LVDT – spring loaded
Fulcrum Arm Rotation	DC RVDT – mounted on x-y plane
Lower Tube Displacement	Linear potentiometer – mounted on spring controlled slide
Upper Tube Displacement	Linear potentiometer – mounted on spring controlled slide
Glass Panel Rotation	DC RVDT – mounted on x-y plane
Glass Panel Horizontal Translation	String potentiometer – mounted on rotation sensor x-y plane with assembly that allows vertical slide
Glass Panel Vertical Translation	String potentiometer – mounted on rotation sensor x-y plane with assembly that allows horizontal slide

The resulting sensor data from the five configurations were then analyzed to determine if flexibilities were present in the racking facility. The analysis consisted of first determining the displacement measured by the lower and upper tube sensors. In a given racking step, the lower and upper tubes will experience eight peak displacements during the constant interval portion of a loading step. For the analysis, the average of the absolute value of these eight peaks was calculated to determine a horizontal displacement for a tube. Then the lower tube and upper tube displacements were added for an actual displacement experienced by the glass specimen for any given racking step.

Comparisons of the actual displacements with the expected displacements showed that some flexibilities existed in the racking facility. The first place that a flexibility was found was between the actuator and the lower tube. In this case, a flexibility arises between the point where the actuator applies a controlled load to the lower steel tube and the displacement the lower tube actually translates. However, this flexibility, or "slop", is relatively minor. A second flexibility was located when a variation was detected between the displacements of the lower and upper tubes. Ideally, the lower and upper steel tubes should displace the same amount of distance due to the behavior of the fulcrum and pivot arm mechanism. However, it appears that the upper tube displaces a degree less than the lower tube.

Overall, the effect of both flexibilities was consistent. Linear regressions based on actual displacement values versus expected (step) displacement values were created for each configuration, and high R-squared values for each regression indicated that the relationships between actual displacement values and those of the step values were nearly perfectly linear. Due to the linear nature of this relationship, the failure limit values from the previous experimental tests, which reflect the expected displacement, can be adjusted based on the properties of the linear regressions. Since the regressions for the four 1/4 in. (6 mm) and standard clearance configurations were very similar, the data was combined to create one regression that would serve as a standard data adjustment guide for all 1/4 in. (6 mm) and normal clearance configurations (AN monolithic and IGU) in the report. The 0 in. (0 mm) clearance AN monolithic configuration would be adjusted based off only the linear regression specific to that configuration, while the 1/8 in. (3 mm) clearance configuration would be adjusted based off of an interpolation between the AN monolithic 1/4 in. (6 mm) linear regression and the AN monolithic 0 in. (0 mm) linear regression. Figure 19 depicts the two separate linear regressions along with the actual displacement versus expected displacement data values.

The regressions and subsequent data adjustment apply to all serviceability limit state values for all of the configurations except SF specimens. Also, these regressions ideally apply to the ultimate limit state values of AN monolithic and AN monolithic panes within IGU configurations because the sensor data measurements end after the 2.75 in. (70 mm) racking step. However, the data adjustment was applied to all of the ultimate limit state values of CW configurations in order to be conservative, despite the fact that the adjustment will have minimal effect on the laminated glass unit fallout values since such failure drift is much higher than that of AN monolithic.

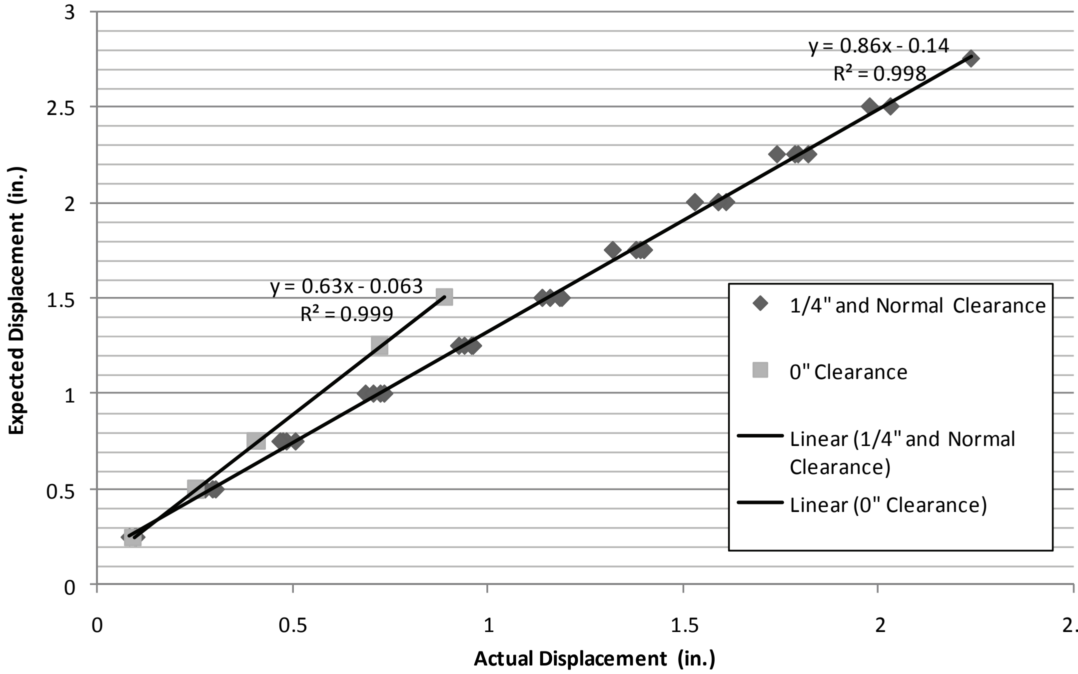


Figure 19: Linear regression properties based off of actual displacement versus expected displacement values.

4. Typical Test Results and General Observations from Experiments on Stick-built Systems

Most of the results of the experimental tests reported herein have been presented in previous publications as plots of drift amplitude and drift ratio (index) versus the wall system configuration type with separate data points plotted for various damage states. An example of a plot previously developed for Configurations 2-6 is shown in Figure 20. This plot presents data for the drift amplitude associated with: initial contact of the edge of the glass pane with the frame, first cracking in any pane, glass fallout for monolithic panes, pullout of the glass unit from the glazing pocket and for fallout (if any) of the entire glass panel. Each symbol plotted in Figure 20 is the mean value for specimens of a given configuration. In cases where the glass panel did not experience glass unit pullout from the glazing pocket and/or fallout of the entire unit by the end of the racking test, the test facility limit of ± 6 in. (± 152 mm) was used to calculate the average of these quantities for plotting purposes in the figure. It is certain that the drift capacity associated with unit pullout and entire unit fallout for those specimens that did not experience such failures would be greater than the ± 6 in. (± 152 mm) assigned.

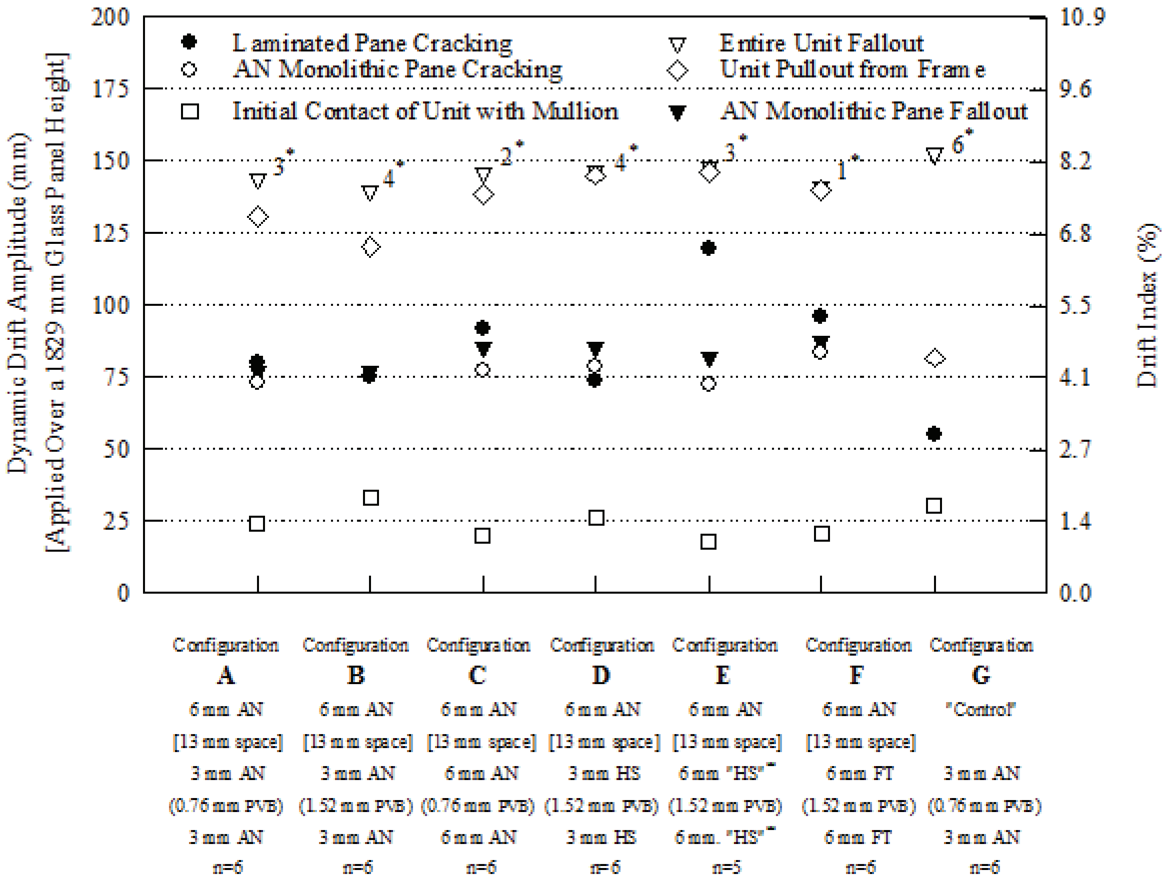


Figure 20: An example of presenting dynamic racking crescendo test results for a set of IGU glass configurations.

For all specimens tested with exception of the unitized system, initiation of glass damage during the racking test was traced to CW frame distortion (i.e., deformation of the initially rectangular frame into a parallelogram shape). Frame distortion led to glass panel rotation and translation within the CW frame because of frictional forces transmitted through the dry-glazed rubber gasket installed between the CW frame and the glass panel perimeter. As the racking drift amplitude increased, the relative movement between the glass and the CW frame also increased. Localized glass crushing followed by cracks propagating radially outward from the corner regions of the AN monolithic glass pane (Figure 21) were observed as a result of the significant load transfer to the glass unit that occurred when opposing diagonal corners of the glass were forced into contact with the glazing pockets of the aluminum frame members. Configurations that used fully tempered glass reached cracking failure and ultimate failure

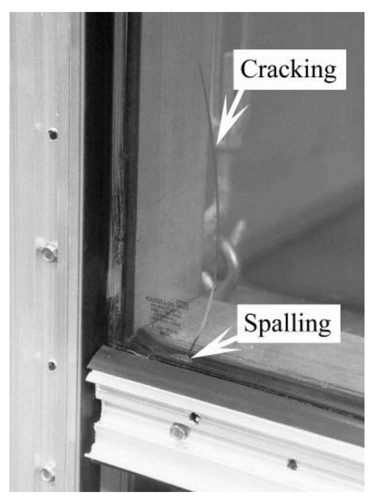


Figure 21: Glass cracking caused by localized corner crushing.

simultaneously as is the nature of FT glass.

The unitized system (US) configuration (discussed in detail subsequently) did not show any signs of glass damage. The framing was allowed to slide freely at the horizontal stack joint past each other without significant transfer of load. In other words, the specimens did not rack, rather, the panels above the stack joint attached to the top sliding tube translated with respect to the panels below the stack joint attached to the lower sliding tube. Failure did occur after a boundary element was in place that restricted the specimen's ability to freely slide. This did cause some racking motion, although non-destructive. The failure state reached was the dislodging of framing members. The frame was merely "snapped" together rather than being mechanically attached with screws as in the stick-built systems tested. Once the framing "unsnapped", failure was reached. It should be noted that the panels in unitized systems are individually supported at one floor level (usually the top floor) through bearing supports, and such dislodging is not expected to lead to entire panel fallout.

In the glass curtain wall studies, several parameters have been varied to determine their effects on drift capacity. Among the parameters varied in these tests, one can see glass type (AN, HS, FT), glass thickness, corner and edge finish, glass-to-frame clearance, PVB interlayer thickness in laminated glass panes, and glazing frame type (CW versus SF versus US). The fragility development has included monolithic, laminated glass units, or insulating glass unit types with varying types of glass type (AN, HS, and FT).

Despite the similarity of drift limits (e.g., observed crack or fallout drift limits) for some specimens of a given configuration type, the forms of damage and the observed damage mechanisms were sometimes different. In general, initiation of glass damage in these specimens can be traced to in-plane glazing frame deformation (i.e., racking of the initially rectangular frame into a parallelogram shape). Frame distortion and the frictional forces transmitted through the rubber dry-glazing gasket installed between the glazing frame and the glass panel perimeter caused the glass panel rotations and translations. As the racking drift amplitudes increased, the relative movement between the glass and the glazing frame also increased. The damage states were consistently in the following order with increasing drift: glass-to-frame contact, cracking, and then glass fallout. Figure 22 compares the average initial glass-to-frame contact drift ratios with the average cracking drift ratios for Configurations 2-5 (initial contact data was only available for these configurations). From this chart, it can be determined that initial glass contact preceded the glass cracking damage state for all four CW configurations shown.

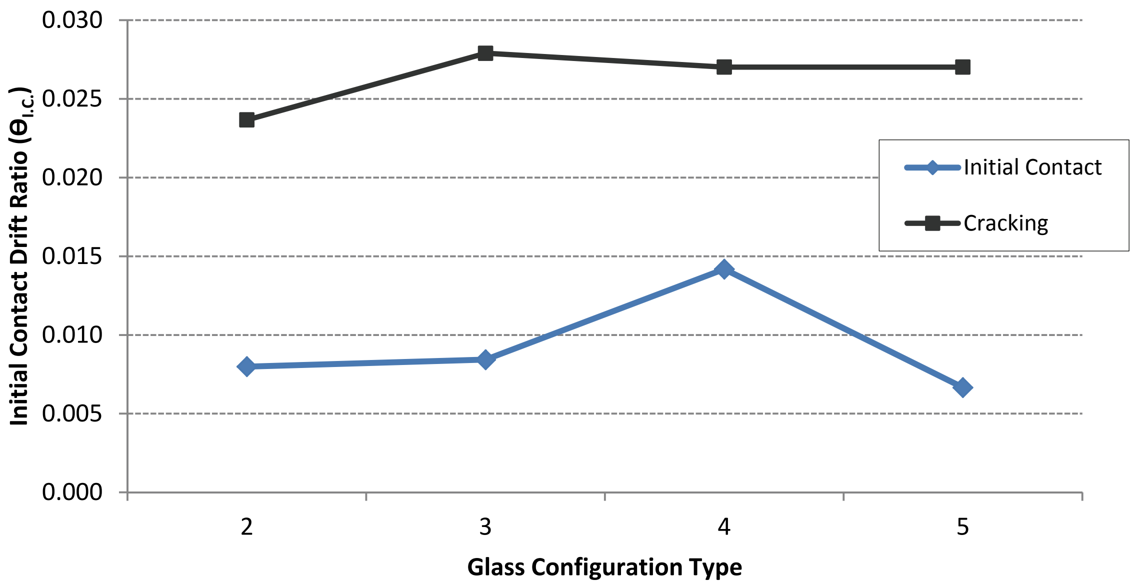


Figure 22: Comparison of average initial contact and cracking damage state drift ratios for glass configurations 2 through 5 (AN laminated monolithic glass unit and asymmetric IGU).

Besides such damage states, other damage was also observed that may not normally be considered as a damage state since sometimes it is hidden in the glazing pockets and was not visible from the exterior or interior of the wall system panel. Such damage included localized glass corner crushing and glass spalling that occurred as a result of the significant load transfer to the glass panel when opposing diagonal corners of the glass were forced into contact with the glazing pockets of the aluminum CW frame during subsequent racking steps. In some tests, viewing slots were milled into the vertical and horizontal pressure plates so that this damage could be observed, as depicted in Figure 23. Glass crushing and spalling were generally followed by cracks propagating radially outward from the corner regions in AN panes.

Figure 23: A test on an AN mono pane where viewing slots were created along the pressure plates at the corners so that localized glass corner crushing and spalling could be observed.

There are also some observations that are not reflected in the drift data, but could be of interest to some design professionals. One result was that for the IGU configurations with AN inner pane and laminated outer pane, glass cracking first occurred in the AN monolithic inner pane in about 80% of the tests. In the remaining 20% of the tests where initial glass cracking occurred simultaneously in both the inner and outer pane or first in the outer pane, such cracking was more relevant in specimens with thinner, 1/8 in. (3 mm) laminated glass plies and a 0.06 in. (1.52 mm) PVB interlayer. In addition, laminated ply cracking almost always occurred initially in the inner glass ply of the laminated ply, followed by cracking in the outer glass ply. This occurrence of first cracking in the inner glass ply can be inferred from the relative location of each ply along the frame glazing lip. As the lip deforms during glass-to-frame contact, the outer glass ply contacts that portion of the lip that experiences the greatest deformation.

Still another observation was that the use of laminated glass as the outer glass pane in the IGU configuration increased the cracking drift capacity by an average of about 60% as compared to configuration with a single laminated glass unit. However, the same result is not obtained with respect to the fallout drift. That is, the fallout drift is not substantially changed.

In general, considering factors that led to entire unit fallout of IGU's with thicker outer pane, it can be suggested that for applications using a comparable framing system to the systems tested, entire unit fallout could be prevented or delayed by (1) using closer spacing of pressure plate screws, (2) using larger screws to connect pressure plates to the bottom horizontals and to connect shear blocks to the vertical mullions, and (3) using a higher pressure plate clamping force.

5. Prefabricated Storefront System Tests and Results

Racking tests were performed on the Oldcastle BuildingEnvelope™ FG-3000, Series 3000 Thermal MultiPlane (3000-TMP), and FG-2000 storefront systems. These storefront systems are stick-built systems, meaning that framing members must be assembled, and the glass installed on-site. FG-3000 and 3000-TMP storefronts employ a 2 in. H x 4-1/2 in. W mullion designed for 1 in. infills with a 7/16 in. glass bite, whereas the FG-2000 storefronts use a 1-3/4 in. H x 4-1/2 in. W mullion designed for 3/16 in. – 3/8 in. infills with a 5/16 in. glass bite. FG-2000 and FG-3000 mockups utilized the non-thermal screw spline frame assembly detail, while 3000-TMP storefronts had a thermal break integrated in the screw spline frame assembly detail. All mockups were glazed with Oldcastle BuildingEnvelope™-specified, lubricated EPDM rubber gaskets to hold the glass edges within the frame glazing pockets with the exception of the butt-glazed, inter-panel joints in the FG-2000 mockups that were formed with DOW Corning 983 structural sealant. These three systems also vary somewhat in their head and sill detailing.

Racking tests were conducted on at least two mockups each of the planar and reentrant corner configurations of each storefront wall system. An elevation view for the FG-3000 reentrant corner mockup is shown in Figure 24, and is representative generally of the various wall system mockups. Planar mockups had nominal overall dimensions of 8 ft H x 12 ft W, and were constructed with three, 1 in. nominal thickness FT IGUs (FG-3000 and 3000-TMP mockups) or 3/8 in. nominal thickness FT monolithic glass panels (FG-2000 mockups). Planar glass panel nominal outside dimensions were 8 ft H x 4 ft W.

Reentrant corner detail mockups had a fourth panel glazed perpendicular to the planar panels with nominal dimensions of 8 ft H x 3 ft W. Rubber setting blocks were placed at the quarter points for all glass panels.

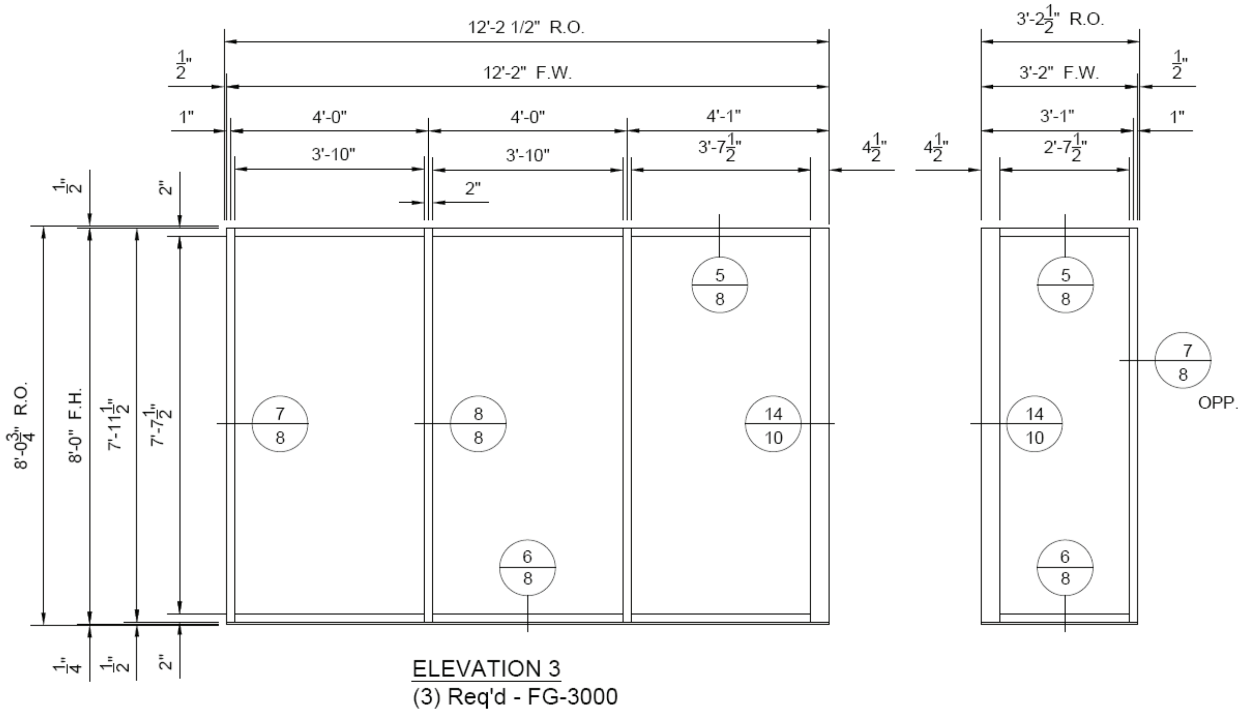


Figure 24: Elevation view for FG-3000 reentrant corner mockups.

The objective of the tests was to investigate potential damage/failure modes as a function of racking displacement under different imposed boundary conditions. The onset and extent of a number of damage modes were tracked during the racking tests—gasket damage, butt-glazed sealant damage, loss of seal, frame damage, glass damage, and glass fallout. As expected, the results showed that glass panel translation and rotation with respect to the framing is the cause of most observed damage modes.

5.1 Testing Program

To accommodate the reentrant corner mockup tests, two HSS steel extensions were fitted out-of-plane to the facility that was discussed in Section 3.2. One extension was attached to the top sliding tube and the other to the bottom sliding tube, to form the 90º facility corner projection to which the reentrant corner details of the mockups were attached. The elevation view of the modified facility fitted with a planar mockup and side elevation views for planar and reentrant corner mockups are shown in Figure 25.

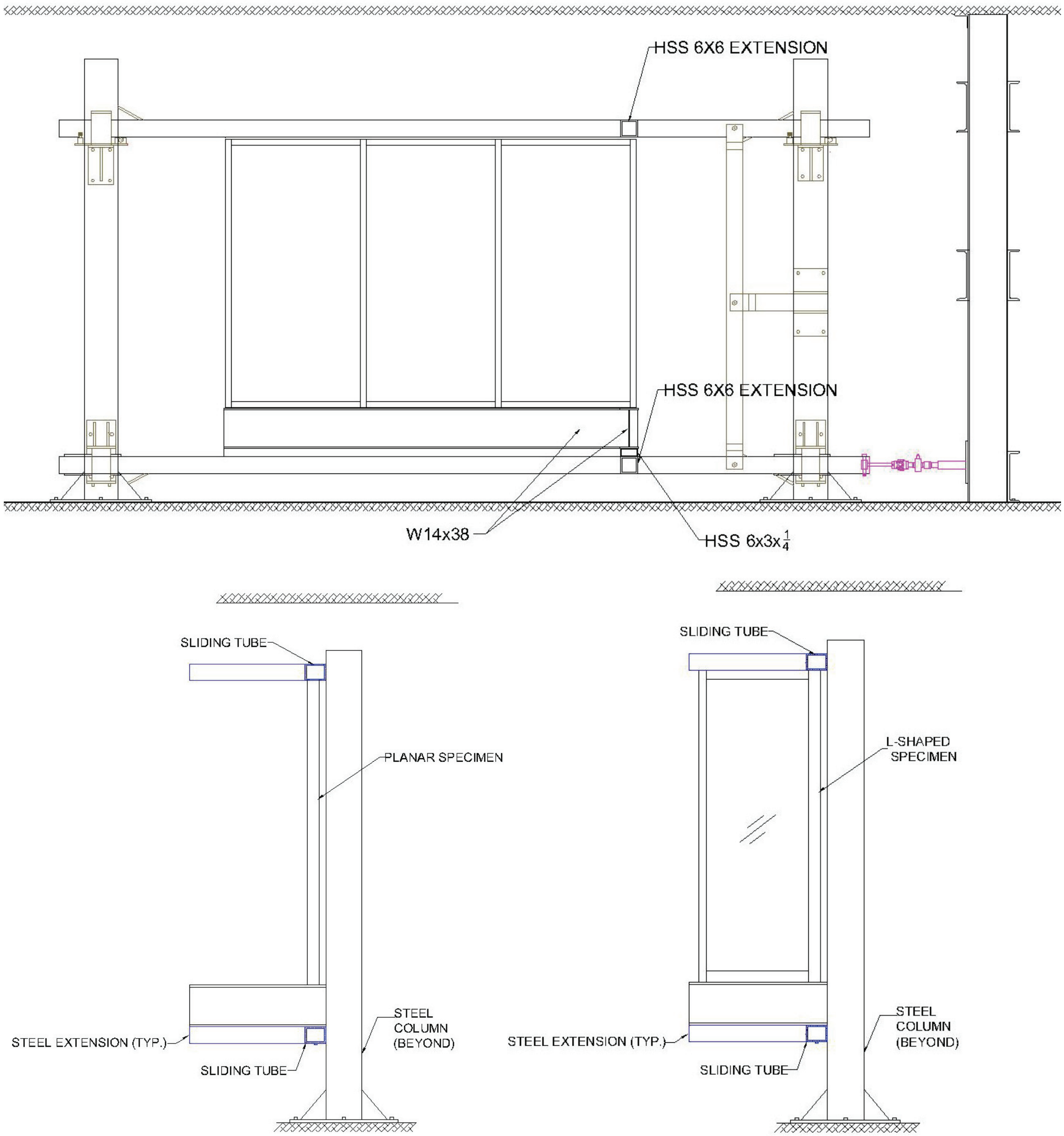


Figure 25: Facility with mounted planar storefront mockup (top), side view of mounted planar mockup (bot. left) and a reentrant corner mockup (bot. right).

To create realistic end restraints, four steel end stops were installed for each of the planar mockups in recognition of the fact that actual planar storefront installations are integrated into the structure that surrounds the glazing system. End restraints simulate hard boundaries along the outside vertical edges of a storefront wall such as those formed when abutted with an adjoining masonry wall. Without the end restraints installed, significant in-plane resistance would not result during racking unless the framing system moved far enough with respect to the head and sill anchors such that the vertical mullions bear against the head anchors. Head and sill anchor details for the FG-3000 system shown in Figure 26 do not restrict movement in the plane of racking unless the aforementioned relative movement of the framing with respect to the anchors occurs. An example of an end stop used in these tests is shown in Figure 27.

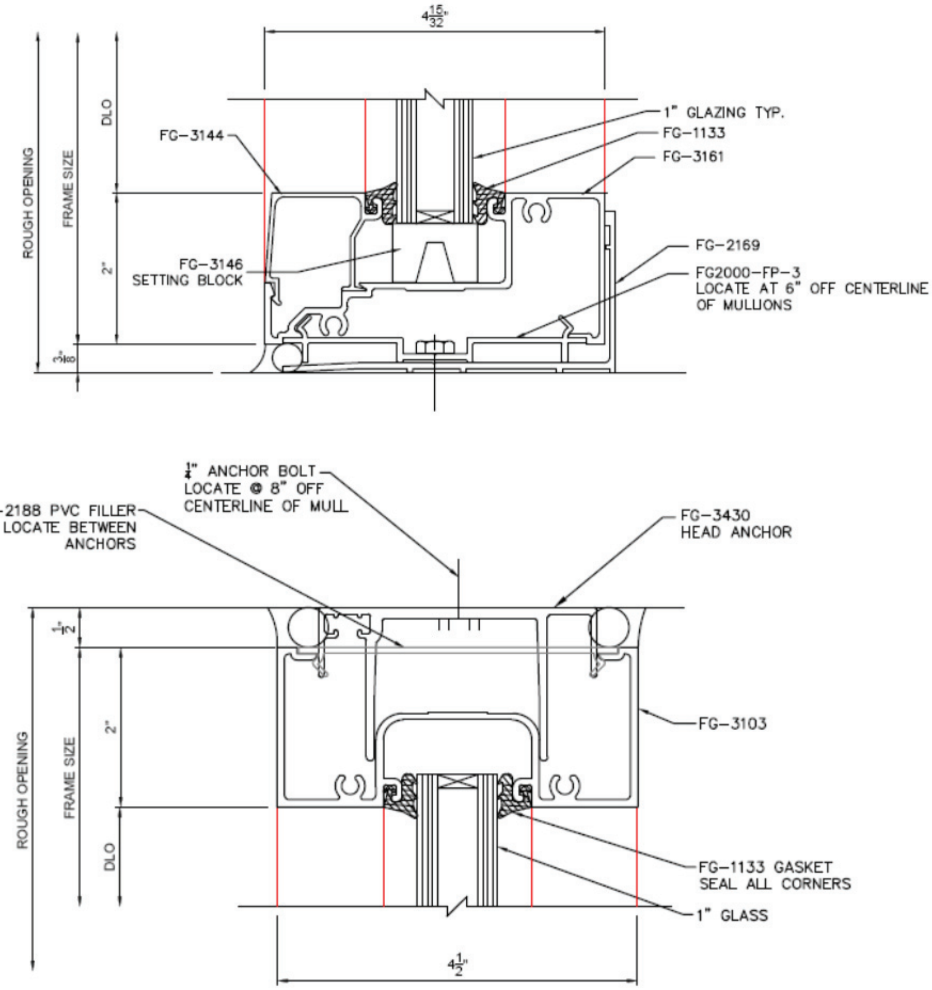


Figure 26: Sections detailing: head (top) and sill (bottom) anchors for the FG-3000 system.

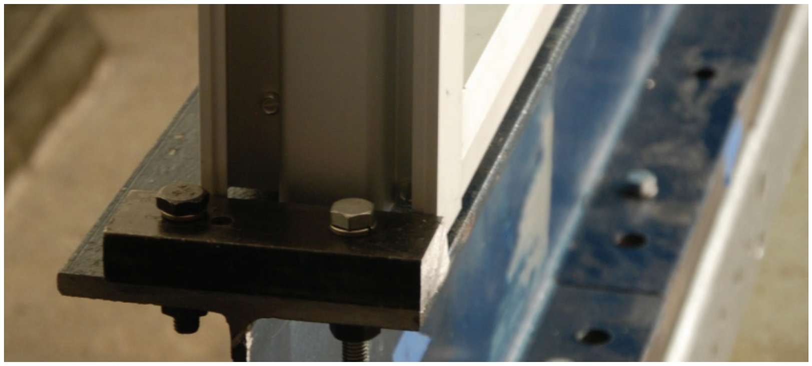


Figure 27: Example of an end restraint.

To ensure the accuracy of testing, and also to acquire measured data in addition to visually monitored data, sensors were used. Sensors were attached to both the in-plane glass panels and to the racking facility itself. The upper and lower steel tubes had string potentiometers that were free to move in the vertical direction and thus measure pure horizontal motion. A direct current linear variable differential transformer (DC LVDT) was placed on the actuator to measure any displacement on the actuator plate. Also, the fulcrum arm had a direct current rotary variable differential transformer (DC RVDT) sensor that was mounted on a vertical and horizontal slide table to allow for free movement laterally. There were also two translation sensors and a rotational sensor mounted on all in-plane glass panels. These sensors supplied data that measured the exact movement of glass and the relative movement of the respective glass panel with respect to the other panels and sensors.

5.2 Racking Tests of the Storefront Specimens

As racking steps increased in amplitude, it was noted that glass panels tended to "walk" in their respective glazing pockets, thereby increasing or decreasing the clearance between the vertical edges of the glass lite and the framing (or adjacent panels as in the case of the butt-glazed FG-2000 mockups). In the FG-3000 and the 3000-TMP mockups, glass lites tended to walk to the right, which would eventually lead to an opening or loss of seal along the left edge of the glass. Glass-to-frame clearances limited this net movement to about 0.5 in. As shown in Figure 28, vertical glazing pockets along the left edge of the center and rightmost panels within these two systems have different clearances. The shallow clearance along the left edges of these panels made some contribution to the net translation of these glass lites to one side during racking. The FG-2000 system only has vertical mullions at the system jamb conditions as shown in Figure 28 and uses silicone sealant butt-glazing between adjacent glass lites leaving only two glazing pockets at the end vertical edges of a planar mockup. In addition to net translation of glass panels causing loss of glass seal, bypass of glass panels along the butt-glazed joints was also observed in the FG-2000 system after glass-to-frame clearances were overcome by glass panel translation and rotation. Onset damage and cumulative damage to the butt-glazed sealant joints in the FG-2000 mockups as a result of glass panel translation/rotation/bypass was tracked during testing. Only cohesive failures were observed. Cohesive failure in the butt-glazed seals represents another form of glass panel seal loss. Loss of seal caused by net translation/rotation of glass panels is a serviceability failure because it allows air and water to freely move through the glazing system. Moreover, it would require resetting of glass panels. Butt-glazed sealant damage would require damaged joint removal and application of new sealant.

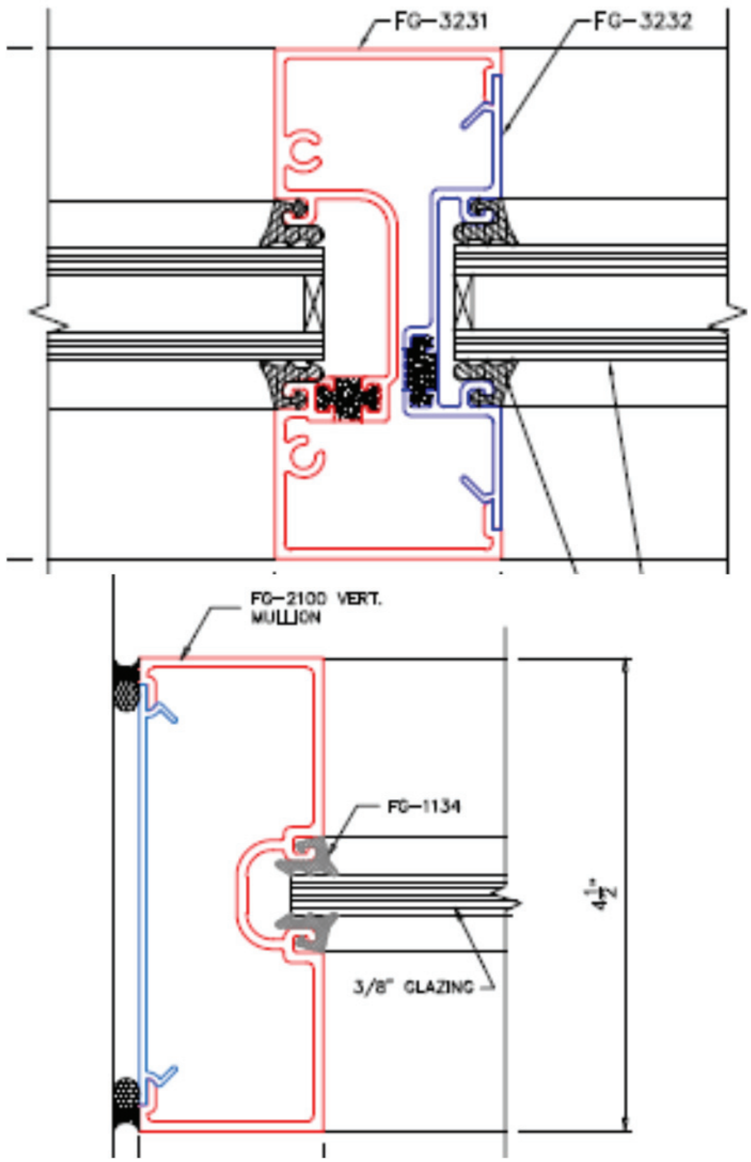


Figure 28: Glass edge–to-vertical glazing pocket clearances in FG-3000 and 3000-TMP mockups (top) and FG-2000 mockups (bottom).

Another observed glazing system failure mode is permanent gasket movement caused by the frictional forces and slippage caused by resistance of glass panels to the varying deflected shapes of the framing induced by the racking facility. Three primary types of permanent gasket damage were observed: (1) gasket shrinkage (2) gasket rolling, and (3) gasket pullout. Gasket shrinkage typically occurred as early as ½ to 1 in. of racking displacement and is indicative of compression in the gasket caused by glass and frame movement. As the glass panels began to rotate more significantly, glass panel edges in the corner regions would pull out of the glazing pocket and cause rolling of the gasket under the glass panel edges as the panel reentered the glazing pocket during racking in the opposite direction. These movements of the glass panel within the glazing pocket would in time begin to dislodge or pull out portions of the gasket from the glazing pocket entirely as racking progressed. The use of sealant to seal the intersection of the horizontal and vertical gasket runs in each corner is a recommended practice. The use of the sealant was found to delay the onset of these types of gasket damage somewhat. Gasket rolling and gasket pullout began to occur by about 2.5 in. in all of the mockups tested. An example of gasket rolling and gasket pullout are given in Figure 29. Permanent gasket movement is also a serviceability failure because it causes loss of seal and would require resetting of gaskets.

Figure 29: Gasket rolling (top), and gasket pullout (bot.).

Frame damage was also an observed failure mode. The 1.0 inch thick fully tempered IGUs used in the FG-3000 and 3000-TMP mockups, and the 3/8 in. thick monolithic fully tempered glass panels used in the FG-2000 mockups have high edge strength. As a result, glass-to-frame contacts cause substantial zones of plastic deformation in the relatively light duty storefront aluminum framing. Horizontal framing members exhibited the most damage as a result of these contacts. Typical cross-sectional damage to horizontal mullions is shown in Figure 30, which shows the deformation at one end, i.e., at a glass corner region along a horizontal mullion. The center part of the cross-section bent in a curved shape due to the force from the glass during racking. Because the glass loaded the center of the cross-section, the entire cross-section tended to "cave in" around the glazing pockets at the ends of the horizontals. This bowing action is responsible for causing the glass stops that hold the bottom edge of glass panels in place to dislodge and fall from the system (see Figure 31).

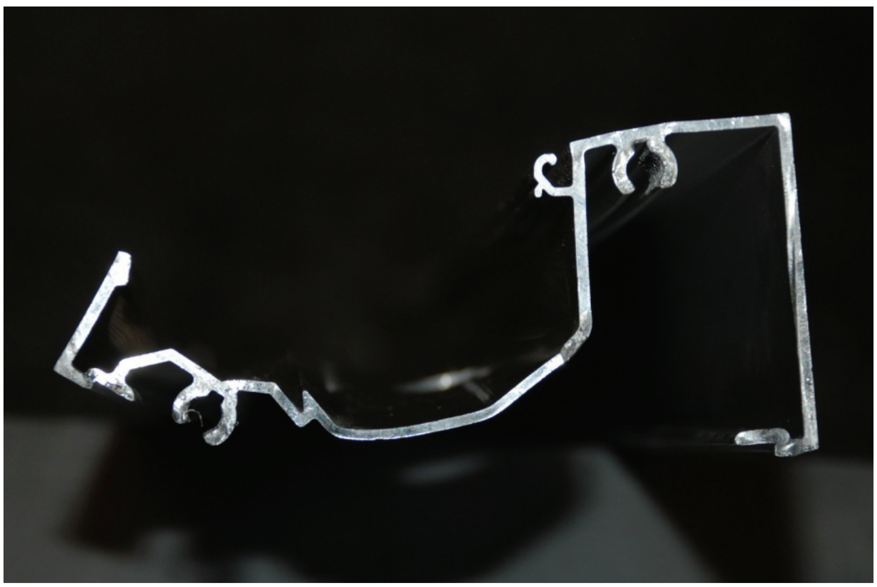


Figure 30: Typical damage to horizontal mullions.

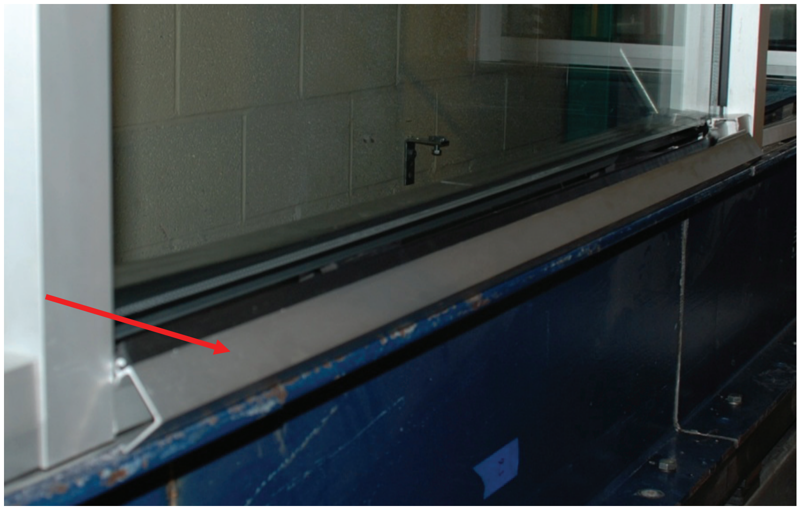


Figure 31: Glass stop dislodging.

Insofar as possible, discrete frame damage events were recorded during the racking tests. Cumulative damage to all framing components was recorded at the completion of the racking tests. Onset of frame damage is more difficult to determine because damage to the frame cross-section is not often clearly seen unless the frame is dismantled.

Although they did not occur extensively, glass cracking and glass fallout failure modes were also observed. Generally in fully tempered glass panels, glass cracking and glass fallout occur simultaneously. However, edge stresses generated by glass-to-frame and adjacent glass panel interactions during racking tests on FT IGUs and FT monolithic glass panels thicker than ¼ in. often lead to spalling and on rare occasions break off of through-thickness corner fragments without the complete failure of the glass lite. A number of instances of spalling and chipping were observed during these tests, and were recorded and plotted as glass damage. A typical cause of spalling was glass panel bypass in the FG-2000 mockup tests. Only one instance of glass fallout was observed in the planar mock-ups, which occurred during the 5-1/2 in. racking step for one of the FG-3000 mockups. The interior lite of the leftmost glass panel cracked and fell out. During the 6.00 in. racking step, the intact outer pane fell out of the frame and shattered upon contact with the floor. According to the ASCE 7-10 (2010), the maximum allowable drift ratio is 2.5%, while the drift ratio for glass fallout reported here is over 5%. Thus, glass failure is highly unlikely to occur in these wall systems in real building installations under the structural system design loads and displacements.

For reentrant corner mockup testing, end restraints were placed along the leftmost vertical edge of the planar section of the reentrant mockups in the same manner as planar mockups; however, end restraints were varied at the reentrant corner. A reentrant mockup is shown Figure 32. In most reentrant corner installations, the only end restraint along the corner would probably be that caused by the interconnections of the planar and reentrant portions of the framing and the head and sill anchors along the reentrant portion of the framing. Thus, at least one mockup of each wall system was tested with no end restraints at either the top or bottom of the reentrant corner framing. In addition, some reentrant corner mockups were tested with end restraints at the reentrant corner.

Figure 32: A Reentrant mockup.

All of the damage modes described for the planar mockups were also observed and tracked for the reentrant mockups. Not surprisingly, the glass panel and the gaskets in the reentrant portion of the glass framing generally did not experience any distress for the FG-3000 and 3000–TMP mockups, but did in a number of the FG-2000 mockups. For this study, it was of interest to determine the effect of the out-of-plane reentrant panel on the in-plane panels. The glazing pockets along the reentrant panel's top and bottom edges and corner framing detailing allowed the glass panel to rotate out-of-plane without significant resistance so very little force acted on this glass panel. When the reentrant panel was unrestrained, the head anchor and also the upper horizontal mullion of the reentrant panel accumulated damage. During application of large racking displacement amplitudes to the FG-3000 and 3000-TMP reentrant corner mockups, head anchor deformation allowed out-of-plane translation of the upper horizontal mullion. Head anchors are expected to prevent this from happening. A deformed head anchor can be seen in Figure 33.

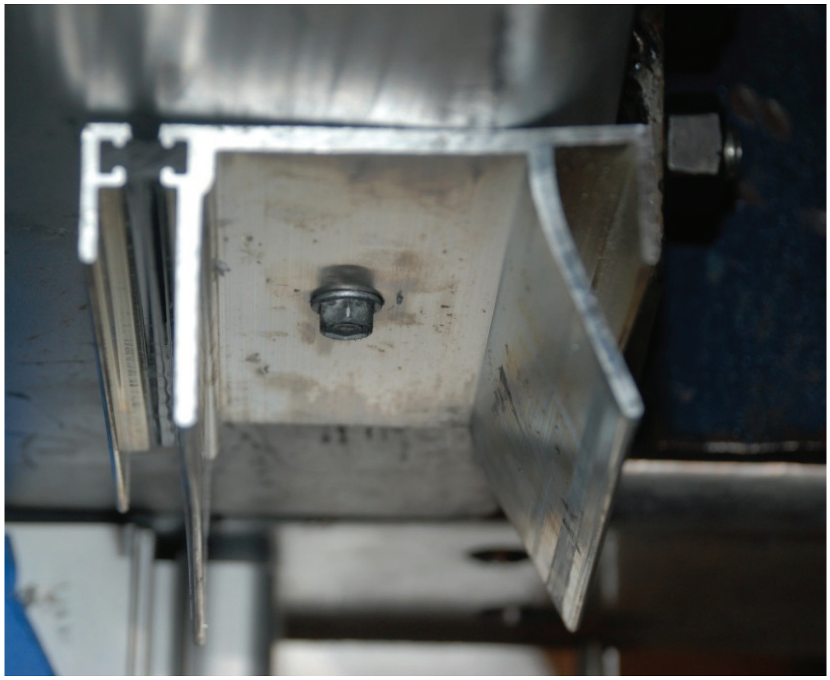
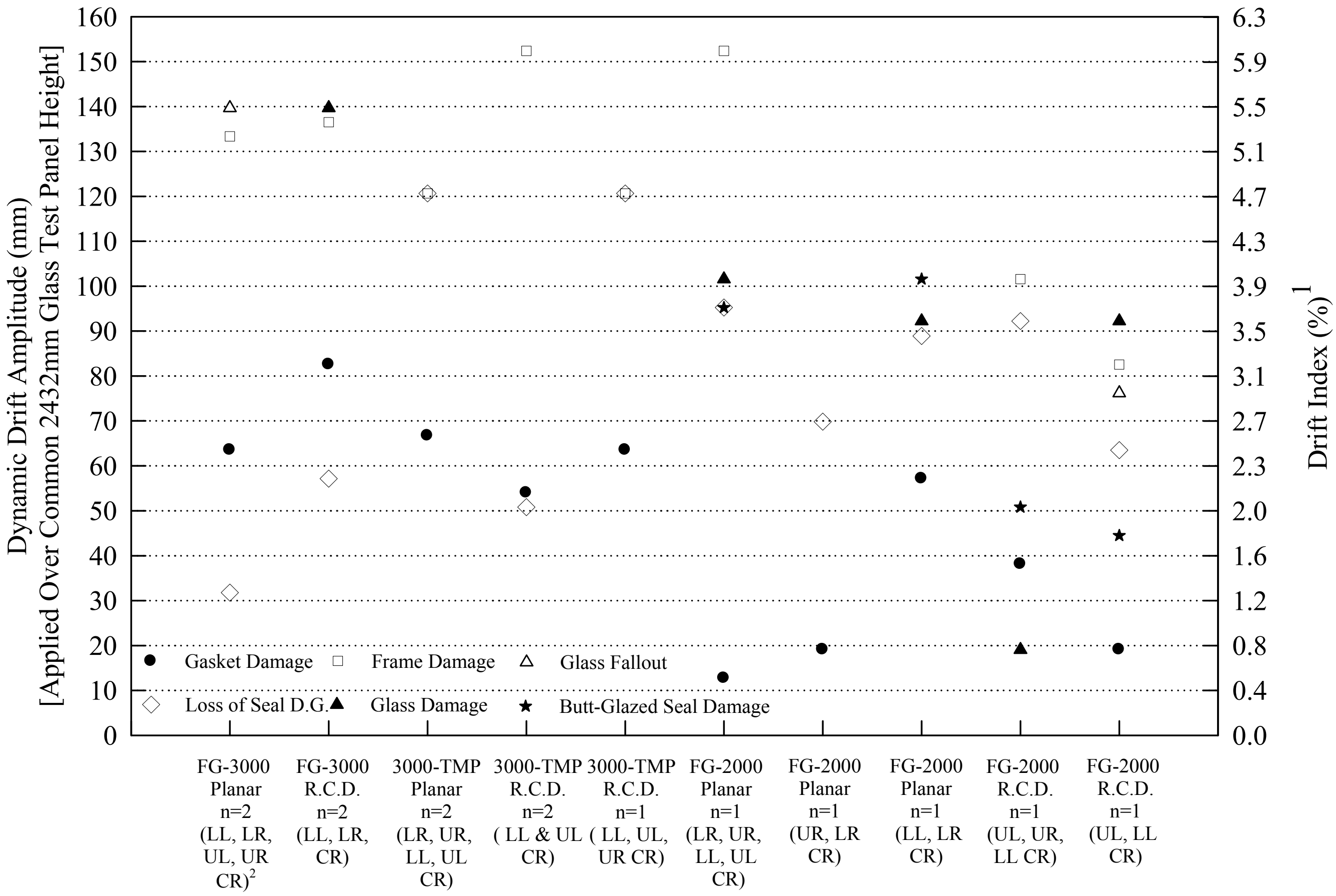


Figure 33: End of test condition of a reentrant corner head anchor.

Test data for each damage mode described herein are presented in Figure 34 and for each wall system planar and reentrant corner mockup variation tested. Data plotted in Figure 34 represent the average across all glass panels for the onset of each failure mode. First instance of each damage mode in the mockup would plot somewhat lower, but is not presented herein. Effects of end restraint variations and mockup plan (planar or reentrant corner) on damage modes are readily seen in Figure 34. In general, more restrained boundaries force glass panels to translate and rotate more than an equivalent mockup with less restraint. This additional motion of glass panels relative to the frame leads to an earlier incidence of most damage modes. Tables 5 and 6 show specimen descriptions and a summary of test data, respectively. The system details related to the I.D. numbers used in Table 3 are outlined in Table 5.



[1] Drift index is calculated here by dividing drift limit by the glass panel height and multiplying by 100

[2] Abbreviations: LL-Lower Left; LR- Lower Right; UL-Upper Left; UR-Upper Right; CR-Corner Restraint; R.C.D.-Reentrant Corner Detail; D.G.- Dry Glazed

Figure 34: Summary of test data for all mockups tested.

Table 5- Specimen I.D. Descriptions.

I.D.	Component Description	Specimen Description
33	Storefront, IGU, fully tempered glass, aluminum framing, square corners, planar configuration	4 ft. 7/8 in. W x 7 ft. 8 in. H (1.2 m x 2.3 m) size, 1.89:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, Oldcastle FG-3000 framing
34	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, in-plane panel	4 ft. 7/8 in. W x 7 ft. 8 in. H (1.2 m x 2.3 m) size, 1.89:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, planar panels, Oldcastle FG-3000 framing
35	Storefront, IGU, fully tempered glass, aluminum framing, square corners, combined in-plane panels from in-plane and L-shaped tests	4 ft. 7/8 in. W x 7 ft. 8 in. H (1.2 m x 2.3 m) size, 1.89:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, planar panels, Oldcastle FG-3000 framing
36	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, out of plane panel	2 ft. 8-3/8 in. W x 7 ft. 8 in. H (.8 m x 2.3 m) size, 2.83:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, corner panel, Oldcastle FG-3000 framing
37	Storefront, IGU, fully tempered glass, aluminum framing, square corners, planar configuration	4 ft. 7/8 in. W x 7 ft. 7-5/8 in. H (1.2 m x 2.3 m) size, 1.88:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, Oldcastle 3000 MultiPlane Center Set framing system
38	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, in-plane panel	4 ft. 7/8 in. W x 7 ft. 7-5/8 in. H (1.2 m x 2.3 m) size, 1.88:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, planar panels, Oldcastle 3000 MultiPlane Center Set framing system
39	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, combined in-plane panels from in-plane and L-shaped tests	4 ft. 7/8 in. W x 7 ft. 7-5/8 in. H (1.2 m x 2.3 m) size, 1.88:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, planar panels, Oldcastle 3000 MultiPlane Center Set framing system
40	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, out of plane panel	2 ft. 8-3/8 in. W x 7 ft. 7-5/8 in. H (.8 m x 2.3 m) size, 2.82:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, corner panel, Oldcastle 3000 MultiPlane Center Set framing system
41	Storefront, fully tempered glass, aluminum framing, square corners, wet glazed, planar configuration	4 ft. W x 7 ft. 8-5/8" in. H (1.2m x 2.35m) size, 1.93:1 aspect ratio, 3/8 in. (10 mm) thick, Oldcastle FG-2000 framing system
42	Storefront, fully tempered glass, aluminum framing, square corners, wet glazed, L-shaped configuration, in-plane panel	4 ft. W x 7 ft. 8-5/8" in. H (1.2m x 2.35m) size, 1.93:1 aspect ratio, 3/8 in. (10 mm) thick, planar panels, Oldcastle FG-2000 framing system
43	Storefront, fully tempered glass, aluminum framing, square corners, wet glazed, L-shaped configuration, combined in-plane panels from in-plane and L-shaped tests	4 ft. W x 7 ft. 8-5/8" in. H (1.2m x 2.35m) size, 1.93:1 aspect ratio, 3/8 in. (10 mm) thick, planar panels, Oldcastle FG-2000 framing system
44	Storefront, fully tempered glass, aluminum framing, square corners, wet glazed, L-shaped configuration, out of plane panel	2 ft. 9-15/16 in. W x 7 ft. 8-5/8" in. H (0.9 m x 2.35m) size, 2.72:1 aspect ratio, 3/8 in. (10 mm) thick, corner panel, Oldcastle FG-2000 framing system

Table 6- Summary of Failure Drifts*.

Specimen ID	Loss of Seal			Gasket Degradation			Frame Damage			Glass Cracking/Fallout		
	in.	mm	D.I.	in.	mm	D.I.	in.	mm	D.I.	in.	mm	D.I.
33.1	[a]	[a]	[a]	-	-	-	5.285	134.226	0.055	5.2845	134.226	0.055
33.2	[a]	[a]	[a]	-	-	-	5.767	146.469	0.060	[a]	[a]	[a]
33.3	[a]	[a]	[a]	-	-	-	4.803	121.984	0.050	[a]	[a]	[a]
33.4	[a]	[a]	[a]	2.634	66.891	0.027	5.767	146.469	0.060	[a]	[a]	[a]
33.5	1.188	30.163	0.012	1.911	48.527	0.020	4.080	103.619	0.042	[a]	[a]	[a]
33.6	1.188	30.163	0.012	2.634	66.891	0.027	4.321	109.741	0.045	[a]	[a]	[a]
34.1	1.188	30.163	0.012	3.598	91.377	0.037	5.767	146.469	0.060	[a]	[a]	[a]
34.2	1.911	48.527	0.020	2.875	73.012	0.030	4.321	109.741	0.045	[a]	[a]	[a]
34.3.	1.188	30.163	0.012	2.875	73.012	0.030	4.562	115.862	0.047	5.2845	134.226	0.055
34.4	2.875	73.012	0.030	5.767	146.469	0.060	5.767	146.469	0.060	[a]	[a]	[a]
34.5	2.634	66.891	0.027	1.670	42.405	0.017	5.767	146.469	0.060	[a]	[a]	[a]
34.6	2.875	73.012	0.030	[a]	[a]	[a]	5.044	128.105	0.052	[a]	[a]	[a]
35.1	[a]	[a]	[a]	-	-	-	5.285	134.226	0.055	5.2845	134.226	0.055
35.2	[a]	[a]	[a]	-	-	-	5.767	146.469	0.060	[a]	[a]	[a]
35.3	[a]	[a]	[a]	-	-	-	4.803	121.984	0.050	[a]	[a]	[a]
35.4	[a]	[a]	[a]	2.634	66.891	0.027	5.767	146.469	0.060	[a]	[a]	[a]
35.5	1.188	30.163	0.012	1.911	48.527	0.020	4.080	103.619	0.042	[a]	[a]	[a]
35.6	1.188	30.163	0.012	2.634	66.891	0.027	4.321	109.741	0.045	[a]	[a]	[a]
35.7	1.188	30.163	0.012	3.598	91.377	0.037	5.767	146.469	0.060	[a]	[a]	[a]
35.8	1.911	48.527	0.020	2.875	73.012	0.030	4.321	109.741	0.045	[a]	[a]	[a]
35.9	1.188	30.163	0.012	2.875	73.012	0.030	4.562	115.862	0.047	5.2845	134.226	0.055
35.10	2.875	73.012	0.030	5.767	146.469	0.060	5.767	146.469	0.060	[a]	[a]	[a]
35.11	2.634	66.891	0.027	1.670	42.405	0.017	5.767	146.469	0.060	[a]	[a]	[a]
35.12	2.875	73.012	0.030	[a]	[a]	[a]	5.044	128.105	0.052	[a]	[a]	[a]
36.1	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
36.2	[a]	[a]	[a]	[a]	[a]	[a]	5.044	128.105	0.052	[a]	[a]	[a]

[a]Limit state was not reached by conclusion of test

*Note that the drift values have been adjusted for racking facility flexibility.

Table 6 (cont.) – Summary of Failure Drifts*.

Specimen ID	Loss of Seal			Gasket Degradation			Frame Damage			Glass Cracking/Fallout		
	in.	mm	D.I.	in.	mm	D.I.	in.	mm	D.I.	in.	mm	D.I.
37.1	a	a	a	3.12	79.25	0.033	5.77	146.56	0.060	a	a	a
37.2	a	a	a	2.39	60.71	0.025	5.77	146.56	0.060	a	a	a
37.3	4.56	115.82	0.048	2.39	60.71	0.025	5.77	146.56	0.060	a	a	a
37.4	a	a	a	2.39	60.71	0.025	5.77	146.56	0.060	a	a	a
37.5	a	a	a	2.39	60.71	0.025	4.80	121.92	0.050	a	a	a
37.6	a	a	a	2.39	60.71	0.025	4.08	103.63	0.043	a	a	a
38.1	a	a	a	2.39	60.71	0.025	5.77	146.56	0.060	a	a	a
38.2	a	a	a	1.19	30.23	0.012	5.28	134.11	0.055	a	a	a
38.3.	1.19	30.23	0.012	1.19	30.23	0.012	5.77	146.56	0.060	a	a	a
38.4	a	a	a	3.36	85.34	0.035	5.77	146.56	0.060	a	a	a
38.5	a	a	a	2.87	72.90	0.030	5.77	146.56	0.060	a	a	a
38.6	2.63	66.80	0.027	2.15	54.61	0.022	5.77	146.56	0.060	a	a	a
38.7	4.56	115.82	0.048	2.63	66.80	0.027	3.12	79.25	0.033	a	a	a
38.8	a	a	a	0.95	24.13	0.010	5.04	128.02	0.053	a	a	a
38.9	a	a	a	1.43	36.32	0.015	5.77	146.56	0.060	a	a	a
39.1	a	a	a	3.12	79.25	0.033	5.77	146.56	0.060	a	a	a
39.2	a	a	a	2.39	60.71	0.025	5.77	146.56	0.060	a	a	a
39.3	4.56	115.82	0.048	2.39	60.71	0.025	5.77	146.56	0.060	a	a	a
39.4	a	a	a	2.39	60.71	0.025	5.77	146.56	0.060	a	a	a
39.5	a	a	a	2.39	60.71	0.025	4.80	121.92	0.050	a	a	a
39.6	a	a	a	2.39	60.71	0.025	4.08	103.63	0.043	a	a	a
39.7	a	a	a	2.39	60.71	0.025	5.77	146.56	0.060	a	a	a
39.8	a	a	a	1.19	30.23	0.012	5.28	134.11	0.055	a	a	a
39.9	1.19	30.23	0.012	1.19	30.23	0.012	5.77	146.56	0.060	a	a	a
39.10	a	a	a	3.36	85.34	0.035	5.77	146.56	0.060	a	a	a
39.11	a	a	a	2.87	72.90	0.030	5.77	146.56	0.060	a	a	a
39.12	2.63	66.80	0.027	2.15	54.61	0.022	5.77	146.56	0.060	a	a	a
39.13	4.56	115.82	0.048	2.63	66.80	0.027	3.12	79.25	0.033	a	a	a
39.14	a	a	a	0.95	24.13	0.010	5.04	128.02	0.053	a	a	a
39.15	a	a	a	1.43	36.32	0.015	5.77	146.56	0.060	a	a	a
40.1	a	a	a	a	a	a	a	a	a	a	a	a
40.2	a	a	a	a	a	a	a	a	a	a	a	a
40.3	a	a	a	4.08	103.63	0.043	5.04	128.02	0.053	a	a	a

[a]Limit state was not reached by conclusion of test
*Note that the drift values have been adjusted for racking facility flexibility.

Table 6 (cont.) – Summary of Failure Drifts*.

Specimen ID	Loss of Seal			Gasket Degradation			Frame Damage			Sealant Damage			Glass Cracking/Fallout		
	in.	mm	D.I.	in.	mm	D.I.	in.	mm	D.I.	in.	mm	D.I.	in.	mm	D.I.
41.1				[a]	[a]	[a]				3.12	79.25	0.033	3.84	97.54	0.040
41.2	[a]	[a]	[a]	0.46	11.68	0.005	5.77	146.56	0.060	3.84	97.54	0.040	3.84	97.54	0.040
41.3				0.46	11.68	0.005				-	-	-	3.84	97.54	0.040
41.4				0.71	18.03	0.007				[a]	[a]	[a]	[a]	[a]	[a]
41.5	5.77	146.56	0.060	[a]	[a]	[a]	5.77	146.56	0.060	[a]	[a]	[a]	[a]	[a]	[a]
41.6				0.46	11.68	0.005				-	-	-	[a]	[a]	[a]
41.7				2.15	54.61	0.018				2.87	72.90	0.030	3.60	91.44	0.038
41.8	[a]	[a]	[a]	[a]	[a]	[a]	5.77	146.56	0.060	4.80	121.92	0.050	4.80	121.92	0.050
41.9				1.91	48.51	0.016				-	-	-	4.80	121.92	0.050
42.1				0.71	18.03	0.007				2.39	60.71	0.025	2.87	72.90	0.030
42.2	3.60	91.44	0.038	2.15	54.61	0.022	5.77	146.56	0.060	[a]	[a]	[a]	[a]	[a]	[a]
42.3.				0.71	18.03	0.007				-	-	-	[a]	[a]	[a]
42.4				0.46	11.68	0.005				[a]	[a]	[a]	3.84	97.54	0.040
42.5	3.12	79.25	0.033	[a,3]	[a,3]	[a,3]	2.87	72.90	0.030	[a]	[a]	[a]	3.60	91.44	0.038
42.6				0.95	24.13	0.010				-	-	-	[a]	[a]	[a]
43.1				[a,3]	[a,3]	[a,3]				3.12	79.25	0.033	3.84	97.54	0.040
43.2	[a]	[a]	[a]	0.46	11.68	0.005	5.77	146.56	0.060	3.84	97.54	0.040	3.84	97.54	0.040
43.3				0.46	11.68	0.005				-	-	-	3.84	97.54	0.040
43.4				0.71	18.03	0.007				[a]	[a]	[a]	[a]	[a]	[a]
43.5	5.77	146.56	0.060	[a,3]	[a,3]	[a,3]	5.77	146.56	0.060	[a]	[a]	[a]	[a]	[a]	[a]
43.6				0.46	11.68	0.005				-	-	-	[a]	[a]	[a]
43.7				2.15	54.61	0.018				2.87	72.90	0.030	3.60	91.44	0.038
43.8	[a]	[a]	[a]	[a,3]	[a,3]	[a,3]	5.77	146.56	0.060	4.80	121.92	0.050	4.80	121.92	0.050
43.9				1.91	48.51	0.016				-	-	-	4.80	121.92	0.050
43.10				0.71	18.03	0.007				2.39	60.71	0.025	2.87	72.90	0.030
43.11	3.60	91.44	0.038	2.15	54.61	0.022	5.77	146.56	0.060	[a]	[a]	[a]	[a]	[a]	[a]
43.12				0.71	18.03	0.007				-	-	-	[a]	[a]	[a]
43.13				0.46	11.68	0.005				[a]	[a]	[a]	3.84	97.54	0.040
43.14	3.12	79.25	0.033	[a,3]	[a,3]	[a,3]	2.87	72.90	0.030	[a]	[a]	[a]	3.60	91.44	0.038
43.15				0.95	24.13	0.010				-	-	-	[a]	[a]	[a]
44.1	[a]	[a]	[a]	2.39	60.71	0.025	2.15	54.61	0.022	1.43	36.32	0.015	[a]	[a]	[a]
44.2	1.91	48.51	0.020	0.95	24.13	0.010	5.77	146.56	0.060	1.67	42.42	0.017	3.60	91.44	0.038

5.3 Conclusions Regarding Storefront Tests

Primary failure modes observed during racking tests of these storefront wall system mockups are seal loss via gasket movement or sealant damage and frame damage. Glass damage did occur on occasion but was not extensive. Serviceability failures that led to loss of seal would be repairable in an actual installation. The extent of seal loss would depend on the severity of glass/frame movements experienced during an earthquake. Repair of frame damage could be much more costly because in most instances glass panels would need to be removed and the damaged framing components replaced. This would disrupt the use of the building and result in indirect economic losses beyond direct economic losses attributed to repair of the wall system. Although frame damage is not always discernable upon direct visual inspection, storefront and entrance wall system framing in buildings that experience high interstory drift ratios should be examined after an earthquake event. These tests showed that the design of the storefront systems tested is adequate for seismic regions because damage to glass was minimal and could occur only at large drift ratios well beyond the code maximum value of 2.5%.

6. Prefabricated Unitized System Tests and Results

The unitized system specimen shown in Figure 35 was comprised of six EN-WALL 7250 Curtain Wall Units (U1-U6) containing nine glass lites positioned three panes high and three panes wide. The configuration simulated a story height in a typical commercial building with two spandrel areas and a section for vision glass. 3M Industrial and Adhesives and Tape Division has developed 3M™ VHB™ Structural Glazing Tape G23F, which is a two-sided pressure sensitive acrylic foam tape, as an alternative to wet and dry glazing. Rather than applying a thick liquid silicone sealant bead to the perimeter of the glass, 3M™ VHB™ Structural Glazing Tape G23F performs like a peel and stick adhesive sealant (3M 2008). This tape bonds on contact with no curing or drying time. For the study presented here, EN-WALL provided curtain wall specimens with outside dimensions of 180 in. wide by 156 in. high comprised of nine glass panels. Each specimen was made up of the EN-WALL 7250 Curtain Wall System that had 1-1/4 in. thick fully tempered insulating glass units consisting of fully tempered monolithic 1/4 in. thick inner and outer lites with a 3/4 in. air space. These glass panels varied in height and width according to the dimensions provided in Figure 35. 3M™ VHB™ Structural Glazing Tape G23F was used to form the structural bond between glass lites and aluminum extrusion surfaces.

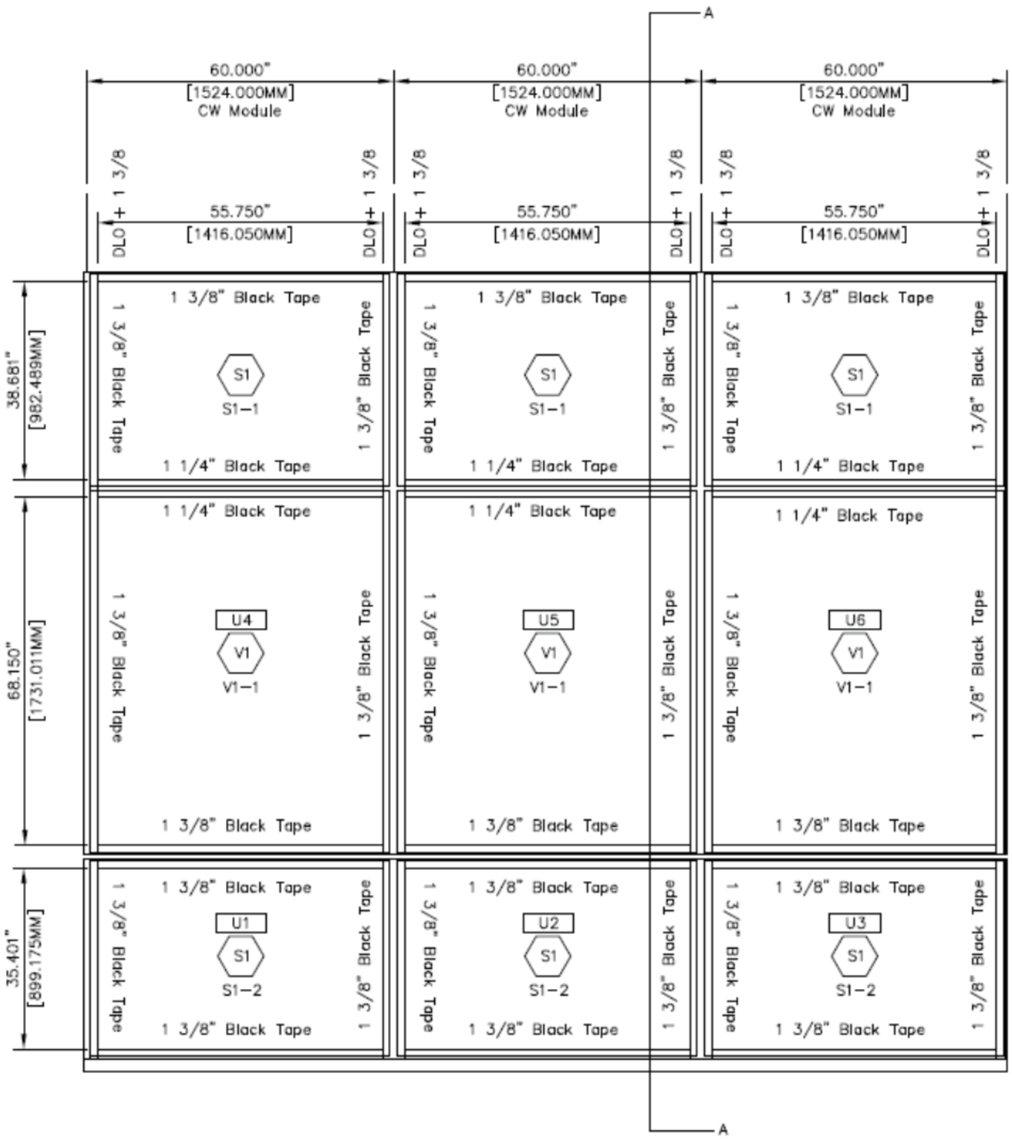


Figure 35: Unitized System Designed by EN-WALL.

6.1 Testing Program for Unitized Systems

The facility used for racking tests of the unitized systems shown in Figure 36 is the same facility described in Section 3.2 with slight modifications. The unitized specimens were mounted directly to the steel sliding tubes spaced at ten feet to simulate a typical floor height as shown in Figures 37 and 38. Frame-to-structure connections designed by EN-WALL for an actual installation of the unitized wall system on a building were used as shown in Figure 39. The connection used extruded aluminum anchor knuckles (clips) bolted on either side of vertical mullions to engage custom-formed steel angles attached to the racking facility (representing the building structure). Anti-walking clips were also mounted on the support angles on the outside of the knuckles. The facility was also modified with three 3/4 in. plates and a 16 ft long 8x6x1/2 angle that were mounted to the bottom sliding tube as shown in Figure 40. The bottom of the unitized system was then anchored to this angle.

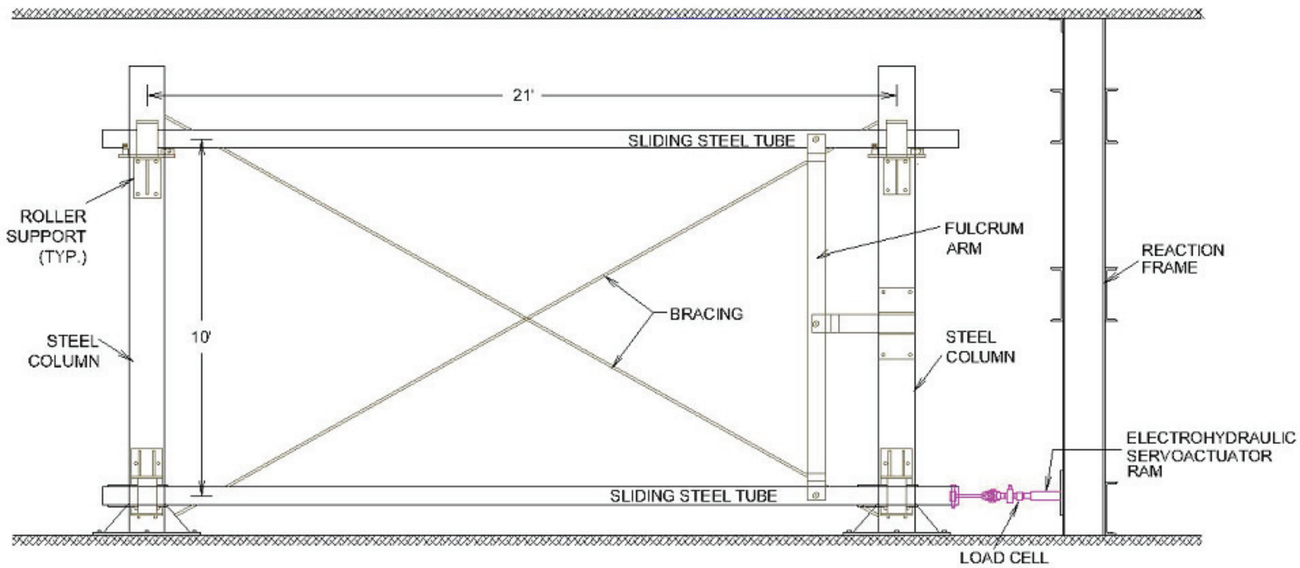


Figure 36: Racking Facility.

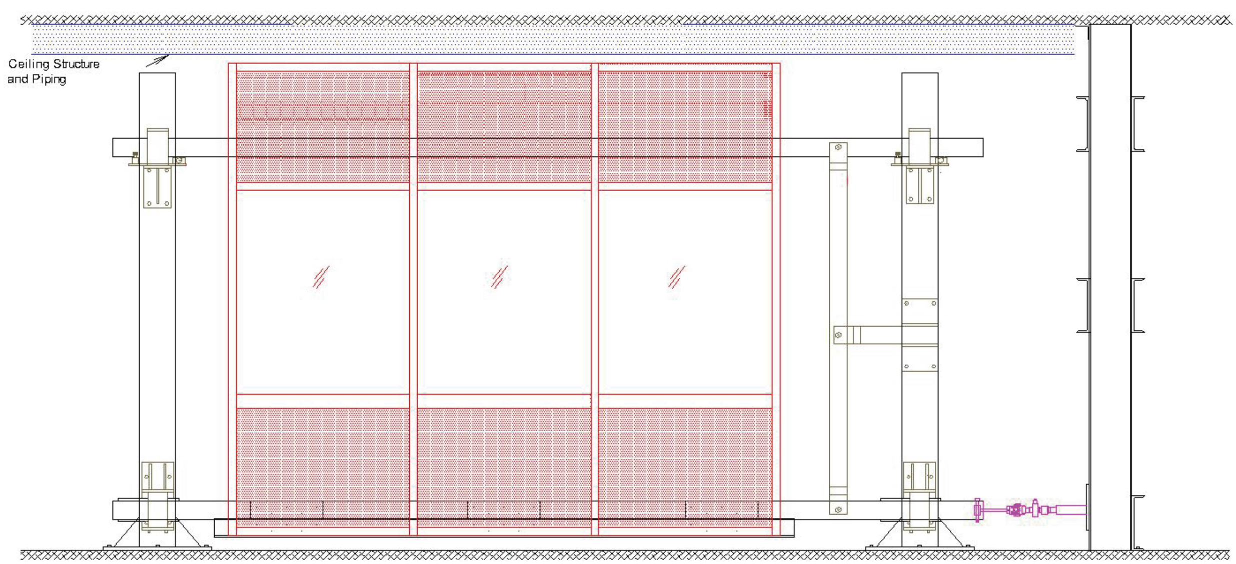


Figure 37: Unitized System Mounted to Facility.

Figure 38: Photo of the Actual Specimen on the Facility.

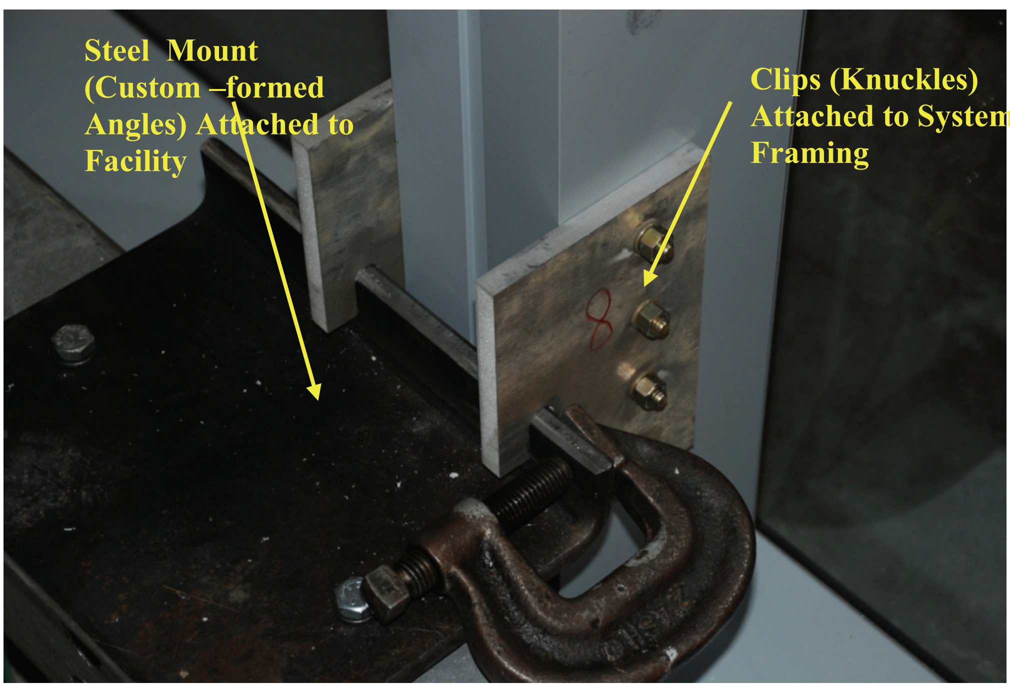


Figure 39: Additional Steel for Frame-to-Structure Connection.

Figure 40: Attachment of the Bottom of the Specimen to the Facility.

6.2 Test Setup and Specimen Assembly

The EN-WALL 7250 Curtain Wall units were fabricated and glazed by EN-WALL in a shop environment. The completed units were then shipped to the Building Envelope Research Laboratory at Penn State University. The panels were assembled in the laboratory to construct the specimen on the racking facility. The unitized system was composed of 6 panels, 3 of which are considered larger panels with two lites of glass and the other 3 are considered smaller panels that are each composed of one glass lite. Like panels were clipped together at their vertical joints to form a wall system. The panels were simply pushed together so that the male mullion (left side) of one curtain wall unit engages the female mullion (right side) of the adjoining curtain wall unit. The male mullion unit contained two EPDM air gaskets. Two hooks on the left side of the panel connected to two more hooks on the right side forming a mechanical connection that holds the system together. The left and right sides (relative to an exterior view of the system) can be seen in Figures 41 and 42, respectively.

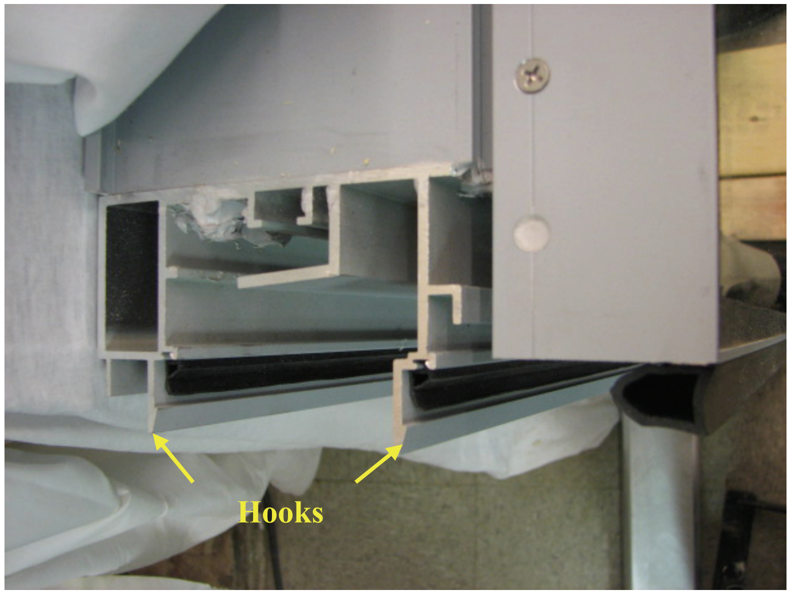


Figure 41: Left Side of Unitized System Panel (male Mullion).

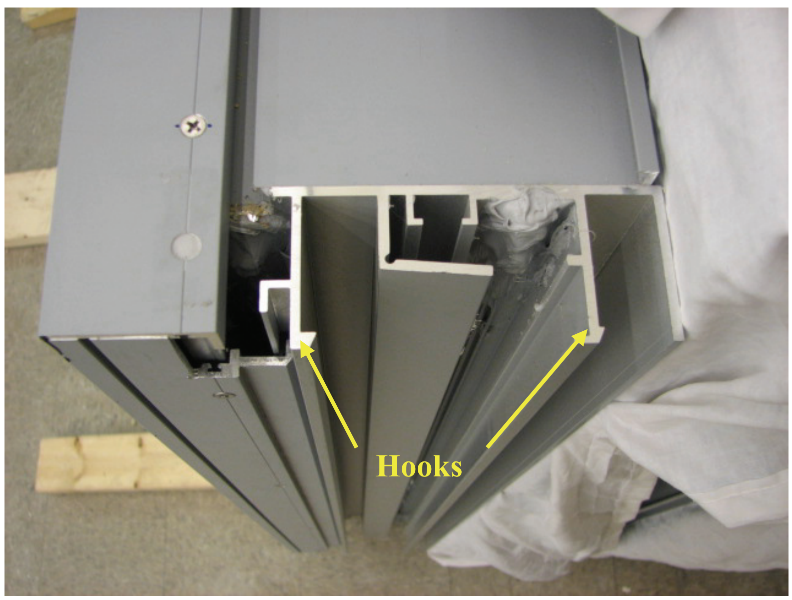


Figure 42: Right Side of Unitized System Panel (Female Mullion).

The taller panels were attached on top of the shorter panels through a continuous length horizontal stack joint that spanned all three panels where this joint connected to the top of the shorter panels and to the bottom of the taller panels. This stack joint was continuous across the width of all three panels. The stack joint attached to the lower panels can be seen in Figure 43 and the stack joint with the addition of the upper panels can be seen in Figure 44.

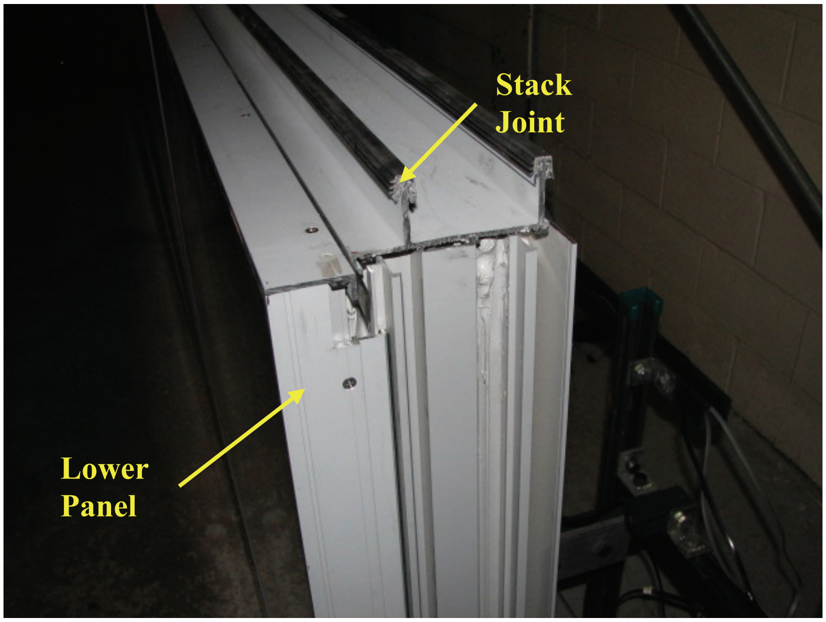


Figure 43: Horizontal Stack Joint Attached to Lower Panels.

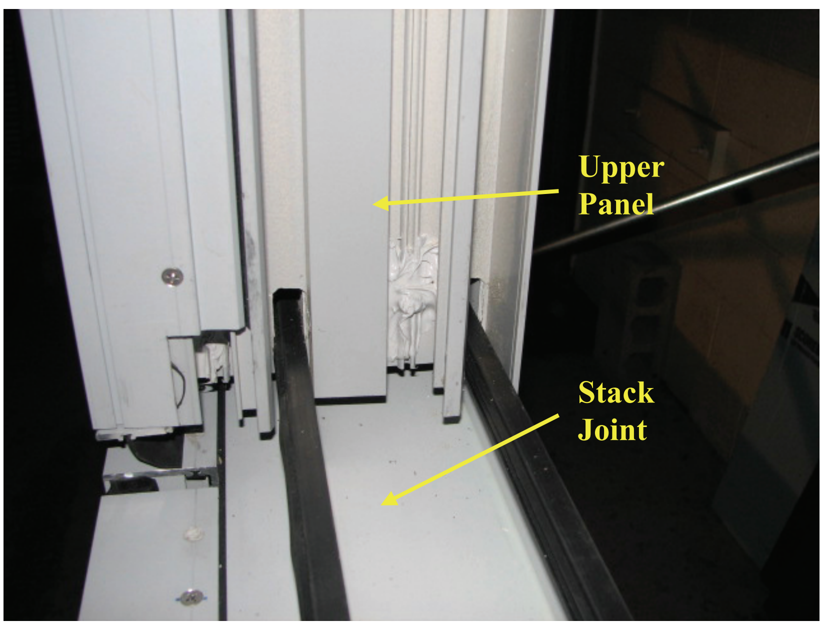


Figure 44: Horizontal Stack Joint Attached to both Lower and Upper Panels.

The system was mounted to the racking facility through twelve dead load anchors or knuckles. Six of these anchors were attached to the framing (mullions) connecting the top three panels and six were attached to the bottom three panels. The anchors were attached to the unitized system using four bolts so that the anchors were butted against the inside face of the vertical mullions. These anchors then "sat" on custom-formed angles (steel plates) that were curved at 90° on one end. The plates were then bolted to the sliding tubes of the facility. The anchor setup can be seen in Figure 45.

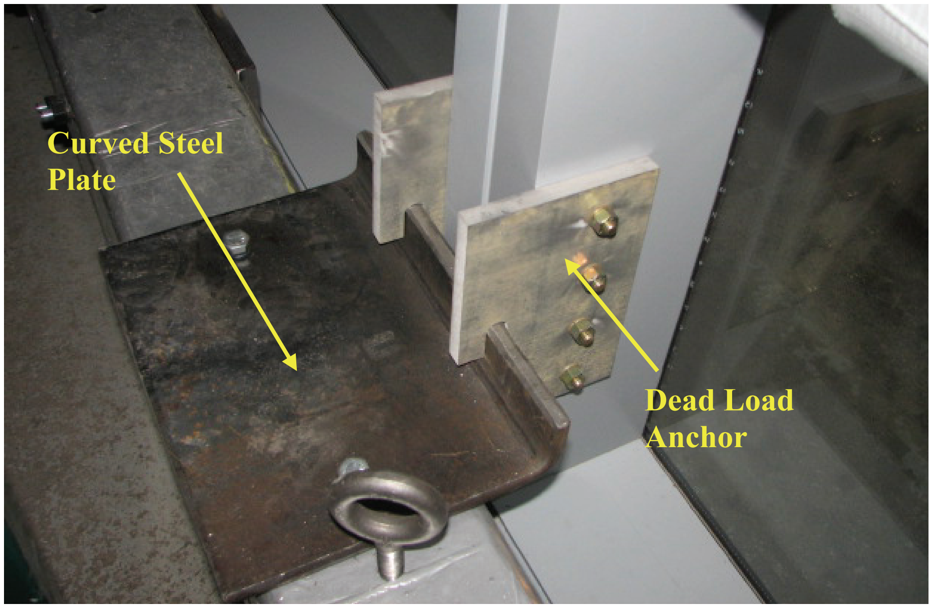


Figure 45: Dead Load Anchor Attachment.

To ensure the accuracy of testing, and also to acquire measured data in addition to visually monitored data, sensors were used on a number of glass panels. Sensors were attached to both the glass panels and to the racking facility itself. The upper and lower steel tubes had string potentiometers that were free to move in the vertical direction and thus measure pure horizontal motion. A direct current linear variable differential transformer (DC LVDT) was placed on the actuator to measure any displacement on the actuator plate. Also, the fulcrum arm had a direct current rotary variable differential transformer (DC RVDT) sensor that was mounted on a vertical and horizontal slide table to allow for free movement laterally. There were also two translation sensors mounted on the center panel (U5), the middle right panel (U6), and the lower right panel (U3). A fully built specimen before testing is shown in Figure 46.

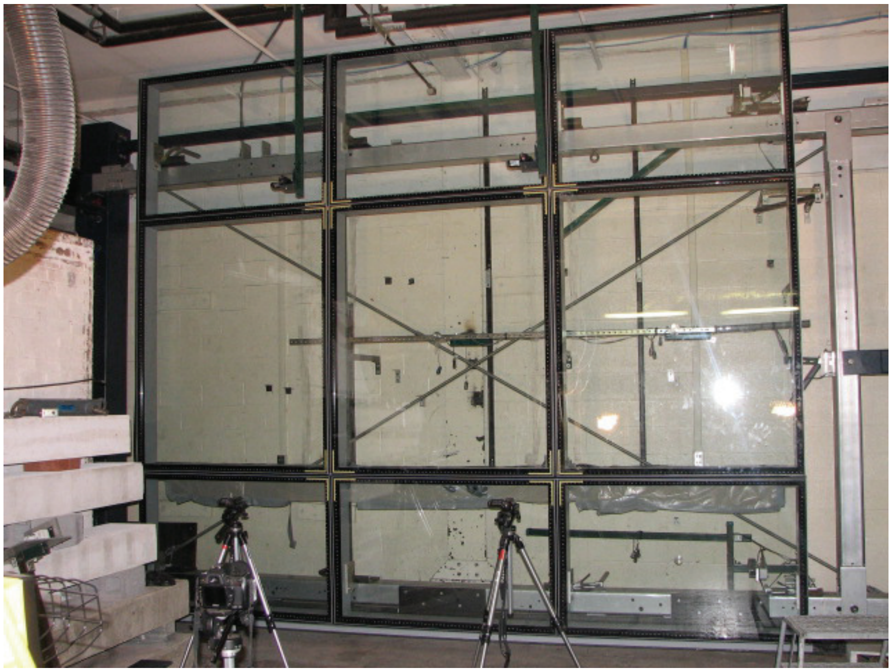


Figure 46: Fully Built Unitized System Test Specimen.

6.3 Racking Tests of the Two Specimen

The main objective of the testing program was to evaluate the performance of the unitized system specimens with and without special end boundary conditions. In real-life construction, adjacent curtain wall panels are either planar (are along the same plane) or they intersect at corners (either interior or exterior corner). Furthermore, an end panel can be attached to a wall or column. In order to evaluate the performance of these planar specimens for corner or end wall/column boundary conditions, some artificial boundary conditions were created. The tests then included planar specimen test without and with some boundary restraint conditions. This section qualitatively reviews the results of the two unitized system specimens. The first specimen (Specimen 1) was tested twice, once without restraint at the stack joint and dead load anchors (Test 1), and once with restraints (Test 2). The second specimen (Specimen 2) had dead load anchor restraints and was tested three times, once without restraint at the stack joint (Test 1), and twice with two different types of restraints (Test 2, Test 3).

6.3.1 Specimen 1, Test 1

Racking tests were performed on the described unitized system. Because of the nature of inter-panel connections (at stack joint) it was expected that the system would be able to handle large drifts before the onset of any damage to the specimen. As expected, the first racking test on the first specimen indicated that the horizontal stack joint was free to slide relative to the lower panels. This in turn translated very little force to the glass panels themselves. The rubber gaskets that connect to the upper panels were able to hold the upper panels in place, but the horizontal stack joint's connection to the lower panels provided little resistance against free translation. This movement can be seen in Figures 47 and 48.

Figure 47: First Specimen before Racking Step.

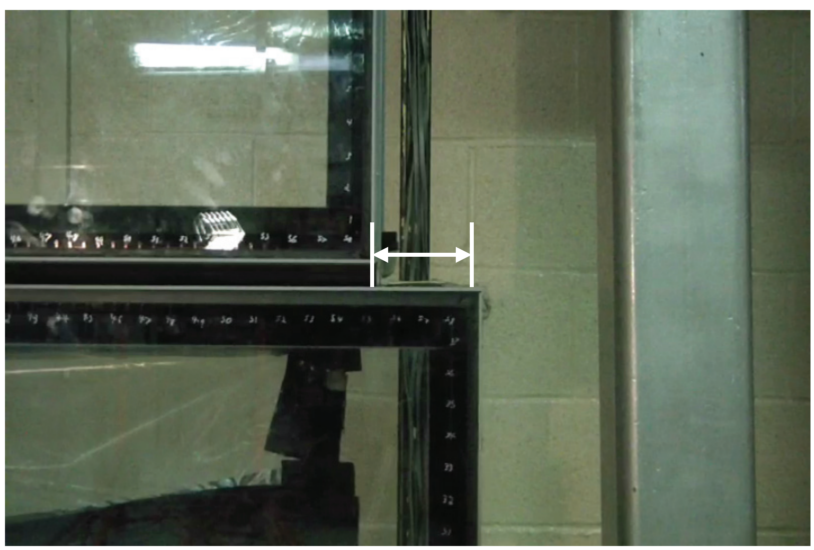


Figure 48: First Specimen during Racking Step.

The system also experienced permanent displacements similar to that shown in Figure 48. After the racking step of 1-3/4 in., the upper panels displaced 5/8 in. to the left relative to the lower panels. This displacement continued to grow. After a racking step of 2 in., this displacement grew to 1-7/16 in. Throughout the entire test, the three upper panels stayed connected to each other and the three lower panels stayed connected to each other. Glass panels did not rack and experienced very little load as a result of the sliding horizontal stack joint. However, upper panels exhibited permanent displacement, which increased as racking displacement increased, with respect to the upper sliding beams and therefore the lower panels because no anti-walking clips or clamps were installed. Stack wiper gasket and friction fit wedge spacer gasket pullout (Figure 49) was also observed during the racking test. Although these documented forms of gasket damage do not present a life-safety concern, they would lead to system maintenance to reset the panels and reinstall the dislodged gaskets. The wiper gasket is a rainscreen gasket, and the wedge gasket maintains spacing between framing components. Pullout didn't damage the gaskets, so they could be reused. Moreover, pullout of these gaskets does not represent a loss of primary seal within the system that could lead to unintended air leakage and moisture penetration through the system. However, potential seal loss related to permanent movement of the glass panels was not evaluated with this specimen.

The only "failure" that was observed was the sliding out of a wedge gasket that helped hold the horizontal stack joint to the lower panels and can be seen in Figure 49. Because of the relative movement between the horizontal stack joint and the lower panels the wedge gasket slowly worked its way out of the system. Because of the lack of damage to this specimen, a maximum displacement of 6 in. was applied to the specimen multiple times, and after three racking steps at 6 in. the wedge gasket fully left the system. The test was considered completed after the first racking step of 6 in. without any damage to glass or 3M™ VHB™ SGT.

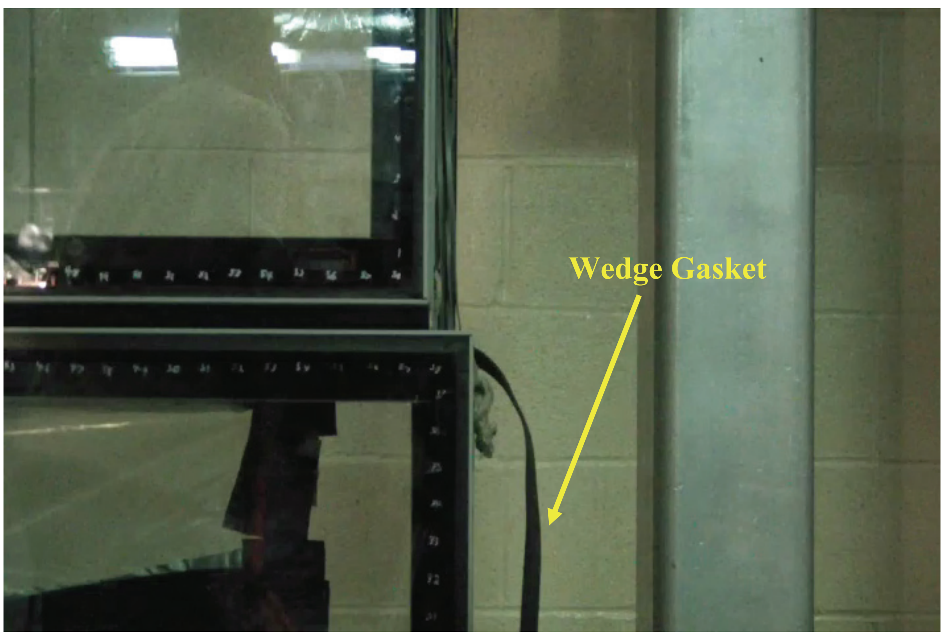


Figure 49: Wedge Gasket Leaving the System.

The three primary damage states considered when testing glass systems consists of glass cracking, glass fallout, and gasket or seal degradation. While the wedge gasket shown in Figure 49 did leave the system after many racking cycles, the test resulted in no damaging stresses in the glass panels or any sealant damage, whether 3M™ VHB™ Structural Glazing Tape G23F or silicone sealant weatherseal. The glass was left undamaged even after reaching the displacement limits of the testing facility (6 in. actuator displacement); hence, the cracking and fallout states were not reached. In other words, no such damage occurred under a maximum facility drift of 6 in. Gasket degradation usually refers to gaskets that surround the glass panel and not an internal gasket for the framing system. Observed stack joint and wedge gasket pullout may be avoided if the end condition was not open as was the case in testing. In a typical building installation, the right and left vertical sides that were exposed on the specimen would not be exposed. Instead, detailing such as an inside or outside corner connection or adaptation into another building wall system would most probably be present at the far boundaries of the wall system. The gasket may still pull out to some degree, but it would depend on restrictions presented by the boundary detailing. It is clear from this first test that the stack joint and anchor combination can minimize wall system component damage at large drifts because it does not restrict the panels from moving. During the initial test, the horizontal stack joint was allowed unlimited movement, while in an actual installation, detailing at the far boundaries would be expected to affect movement capacity and perhaps damage modes in a manner not evaluated in this initial test.

6.3.2 Specimen 1, Test 2

Test 2 of Specimen 1 was run using an end boundary condition to join the upper and lower panels. Because in practical applications of unitized systems on buildings some degree of restraint at the horizontal stack joint exists such as at corners of two perpendicular panels, it was desired to determine the behavior of the specimen if some form of restraint was used at the vertical edge. For this purpose, it was decided to first attach an aluminum bar to the vertical edge of the specimen to imitate the end detail shown in Figure 50 that shows the edge of the EN-Wall system anchored to the structure.

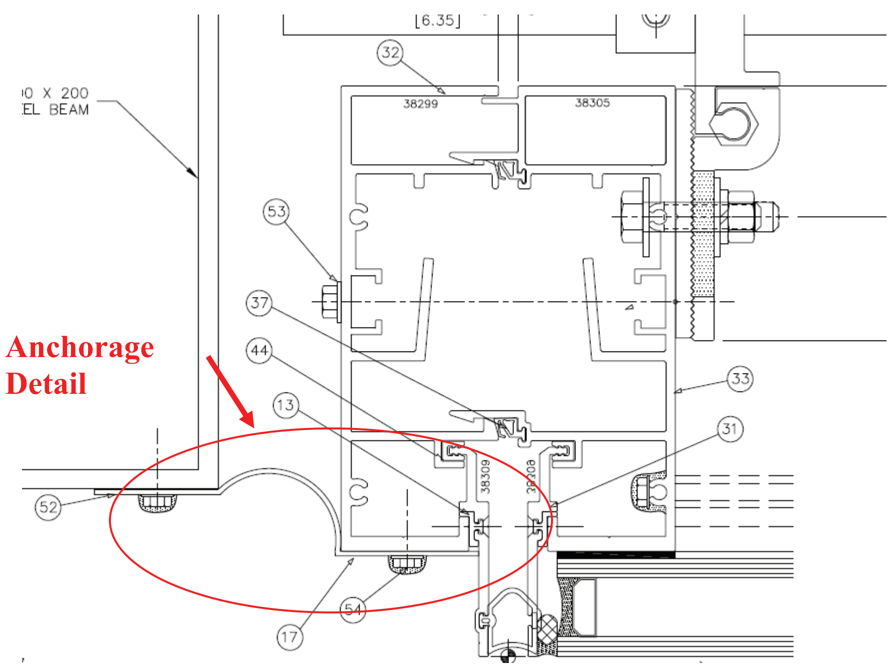


Figure 50: Side Anchorage Detail.

The additional piece added was intended to help to tie the upper and lower panels (at the stack joint) together without over stiffening the mounted area. The added piece was only anchored to the top and bottom panels and not anchored to any part of the racking facility. It was shown through preliminary testing that the system did not see any damage if the top and bottom panels were tied together. In practical applications, the sliding movement (sway) at the horizontal stack joint would be restricted, and the added piece represented a more realistic condition compared to completely unrestrained situation. For this condition, a Kawneer 1600 pressure plate was used. This plate was chosen because of its stiffness properties as it was not overly stiff and was not expected to greatly restrict the systems inherent movement capacity if properly fastened to the edge. It was however stiff enough to appropriately limit movement in the system.

In addition, a combination of anti-walk clips and clamps shown in Figure 51 were mounted on both sides of the dead load anchors to restrict permanent displacements in both directions, and also to ensure that the dead load anchor knuckles did not slide off the curved steel plates completely. For ease of installation, multiple bar clamps were used and attached to the curved steel plate (custom-formed angle) so they were butted against the dead load anchors. Eight anchors were used; two at each corner panel, to restrict permanent movement of the system and also to ensure that the dead load anchors did not slide off the curved steel plates. An example of these bar clamps' orientation can be seen in Figure 52.

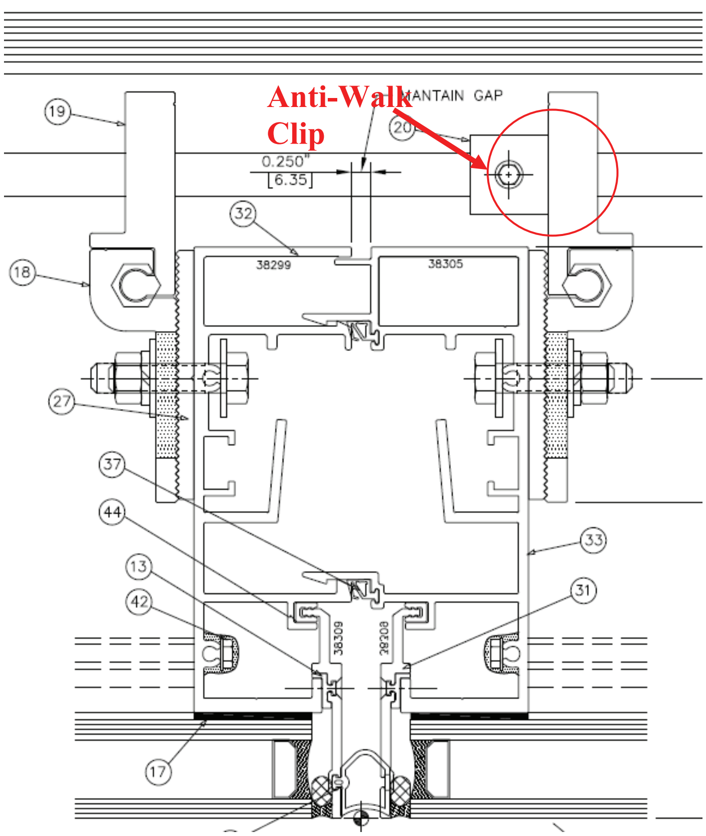


Figure 51: Anti-Walk Clips.

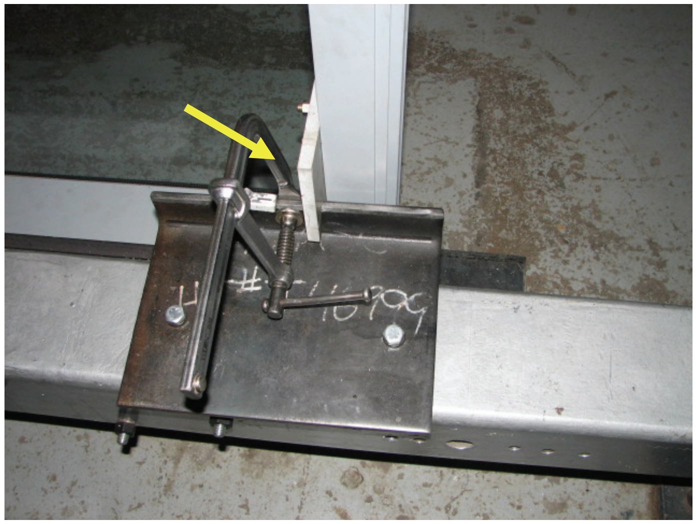


Figure 52: Bar Clamp Restraint.

After the first racking test, the permanent drift observed was recorded by carefully realigning the lower and upper panels. The pressure plate was then attached to the right side of the unitized system using self-drilling (TEK) screws. Seven screws were spaced at 3 in. starting approximately 1 ft from the horizontal stack joint on both the upper and lower panels for a total of 14 TEK screws. It was predicted that screws that were placed close to the horizontal stack joint would easily pry out and thus the screws attached the plate at about 1 ft from the horizontal stack joint to allow deformation of the plate in this region. Figure 53 shows the pressure plate attached to the facility.

Figure 53: Pressure Plate Attached to First Specimen as an End Boundary Condition.

After the installation of both the pressure plate end boundary and anti-walking clips and bar clamps around the anchor knuckles, the first specimen underwent a second round of AAMA 501.6 racking test. The bar clamps worked as desired leaving the system with no permanent displacement after a given racking step. Prying action developed in the pressure plate during racking movement caused initiation of screw pull out at the 2-1/4 in. racking step. Under smaller displacements, the screws remained engaged and the pressure plate bent and flexed with the racking movement. Once the displacement became large enough, the screws closest to the horizontal stack joint lost full engagement and began to pull out as shown in Figure 54. The screws that were placed farther away from the horizontal stack joint did not show signs of prying and stayed tightly fastened throughout the duration of the test. During larger displacements the pressure plate was observed to act solely as a tension member. Many screws were not subject to prying and therefore did not experience a large force in the direction of racking. These screws did, however, allow the pressure plate to carry the tensile loads created during racking movements. As the lower panels and upper panels move in opposite directions, the pressure plate was bent to meet this displacement. As a result, the pressure plate pulled the lower right panel towards the upper right panel (as shown in Figure 55). This does not represent a real world situation; however, the addition of this boundary condition induced some derailment. During the 5-3/4 in. racking step, the horizontal stack joint dislodged from the lower right panel. It is important to note that the wedge gasket could not be replaced before the second round of testing on this specimen (Specimen 1) and may have contributed to this behavior. The dislodged horizontal stack joint can be seen in Figure 56.

This damage mode may not occur in an actual installation because it does not fully represent the far boundaries used. Moreover, it may have little relevance because under such a large drift of 5.75 in. or a drift ratio of approximately 4.8%, the building structural system is severely damaged. According to the building code (ICC 2006, ASCE 2006), the maximum drift ratio allowed is 2.5%, which corresponds to a drift of about 3.00 in. for the specimen. Nonetheless, the objective of this second racking test was to investigate potential failure modes for more restrictive boundary conditions.

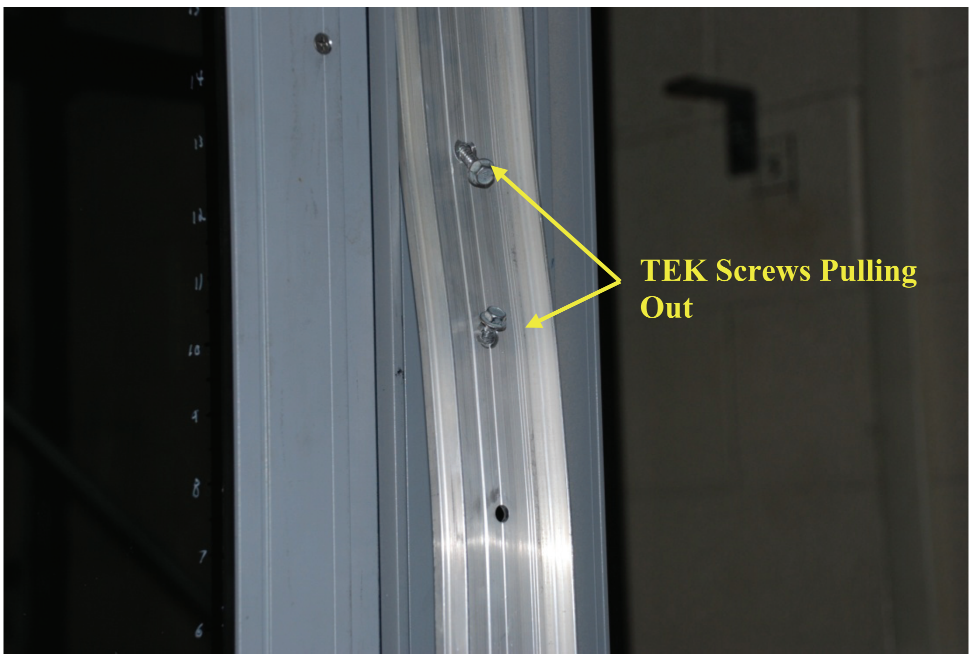


Figure 54: TEK Screws Pulling Out.

Figure 55: End Boundary Acting as a Tension Member.

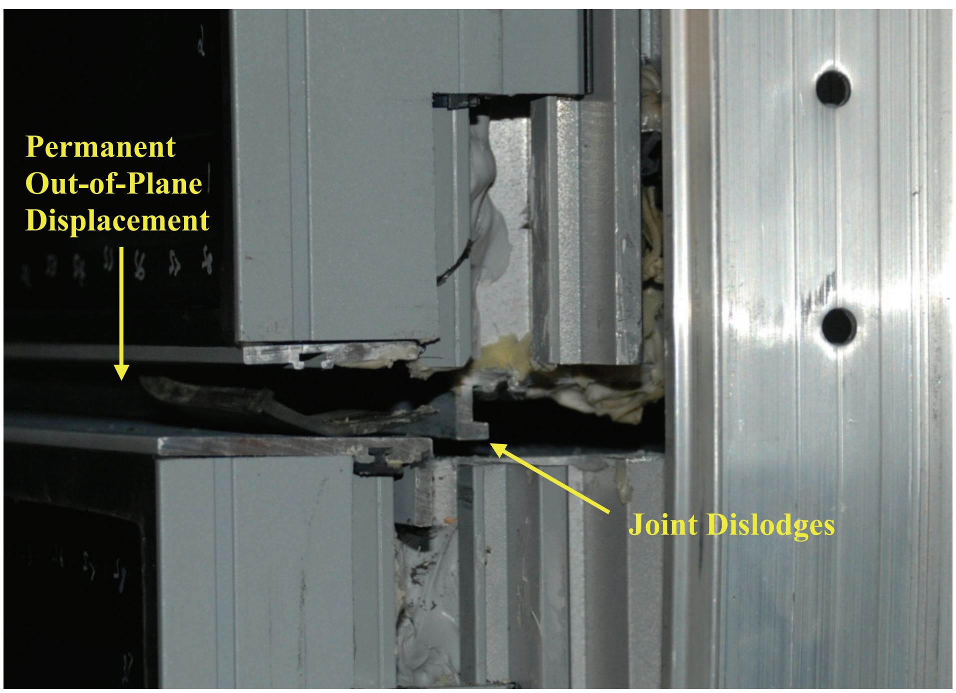


Figure 56: Dislodging of Horizontal Stack Joint and Lower Right Panel.

As a result of the horizontal stack joint dislodging, the right panels were free to move out of plane as shown in Figure 56. Under such a boundary condition, this can potentially create a situation where an entire unitized panel or part of it has a greater chance of derailment at the stack joint. During possible subsequent additional racking, a panel's dead load anchors may slide off the curved steel plates (refer to Figure 45) or the racking motion may cause the dead load anchors (knuckles) to jump over the curved steel plate (custom-formed angles). This failure mode was not observed during testing, but the experiment shows the importance of sufficient dead load anchor design and its restraint.

It should be emphasized that the objective of adding the boundary conditions was indeed to impose a condition on the specimen to identify potential mode of failure if such a boundary condition is created as a result of building movement during an earthquake. Therefore, what this experiment showed is that the worst case scenario would be a potential derailment at stack joint. However, since the upper panel is supported by the bearing supports (curved steel plates (Figure 45), fallout of the panel as a whole is highly unlikely as a result of such derailment for properly designed and erected bearing supports.

6.3.3 Specimen 2, Test 1

A second unitized system was constructed in the same manner as the first specimen. This specimen was also subjected to three full, AAMA 501.6 racking test. The specimen was unrestrained during the first test, and different end boundary conditions were employed for the second and third tests. Although the first test did not use any type of restraint along the stack joint boundary between the upper and lower panels, bar clamps were installed around the knuckle anchors as previously described from beginning of the test to prevent translation of panels within the system. This test did show some forms of damage. The vertical joints surrounding the upper center panel began to open up during the test. Inter-panel spacing between the center upper panel and the two neighboring upper panels were measured along the vertical joints at all four corners of the central upper panel throughout the test and are presented in Table 7. An example of racking-induced increases in the inter-panel spacing can be seen in Figure 57. Typical values for this joint dimension at the start of the test were about 0.6 in.

Table 7- Gap between Upper Center Panel and Neighboring Upper Panels (in inches).

	Lower Left Corner	**Lower Right Corner**	**Upper Left Corner**	**Upper Right Corner**
After 1-3/4" Drift	0.92	0.61	0.61	0.58
After 2-1/2" Drift	1.06	0.61	0.59	0.62
After 2-3/4" Drift	1.18	0.61	0.58	0.62
After 3-1/4" Drift	1.21	0.61	0.58	0.61

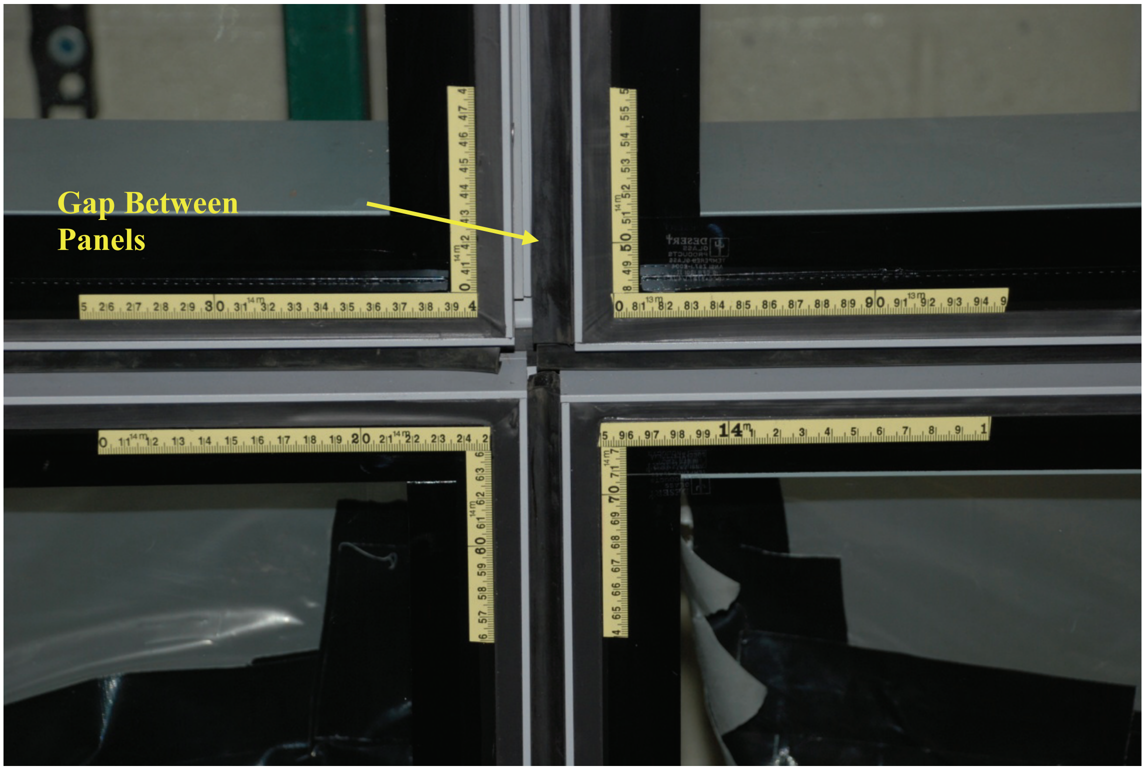


Figure 57: Gap between Center and Left Upper Panels.

As shown in Table 7, the opening at the lower left corner of the upper center panel (shown in Figure 57) nearly doubled in magnitude from the start of the test (0.62 in. to 1.21 in.). This joint began to open up at a drift of 1.75 in. and continued to open until a drift of 3.25 in., beyond which the opening remained fixed. All other openings remained relatively constant throughout the test. This implies that, as an example, the upper left panel rotated clockwise and also translated slightly to the left to maintain a constant upper left corner inter-panel spacing. This form of damage is considered a serviceability failure because water and air would have a clear pathway through the system.

Wedge gasket that maintains spacing along the horizontal stack joint attachment to the lower panels pulled out at the lower left corner of the central panel. While the gasket was loose before it began pulling out, after the 4-1/4 in. racking step (3.5% drift ratio), the gasket protruded past the exterior face of the system. Figure 58 shows this after the 5-1/2 in. racking step (4.6% drift ratio) and also at the conclusion of this test. As noted for the second test of the first specimen, the high drift index associated with the onset of this gasket failure mode represents extreme conditions that would also likely be coincident with severe structural failure. As mentioned before, the objective of these tests was to develop a better understanding of how such a unitized system could fail under excessively large drifts. This behavior represents the curtain wall response under much more severe condition than would be expected under building code design loading condition.

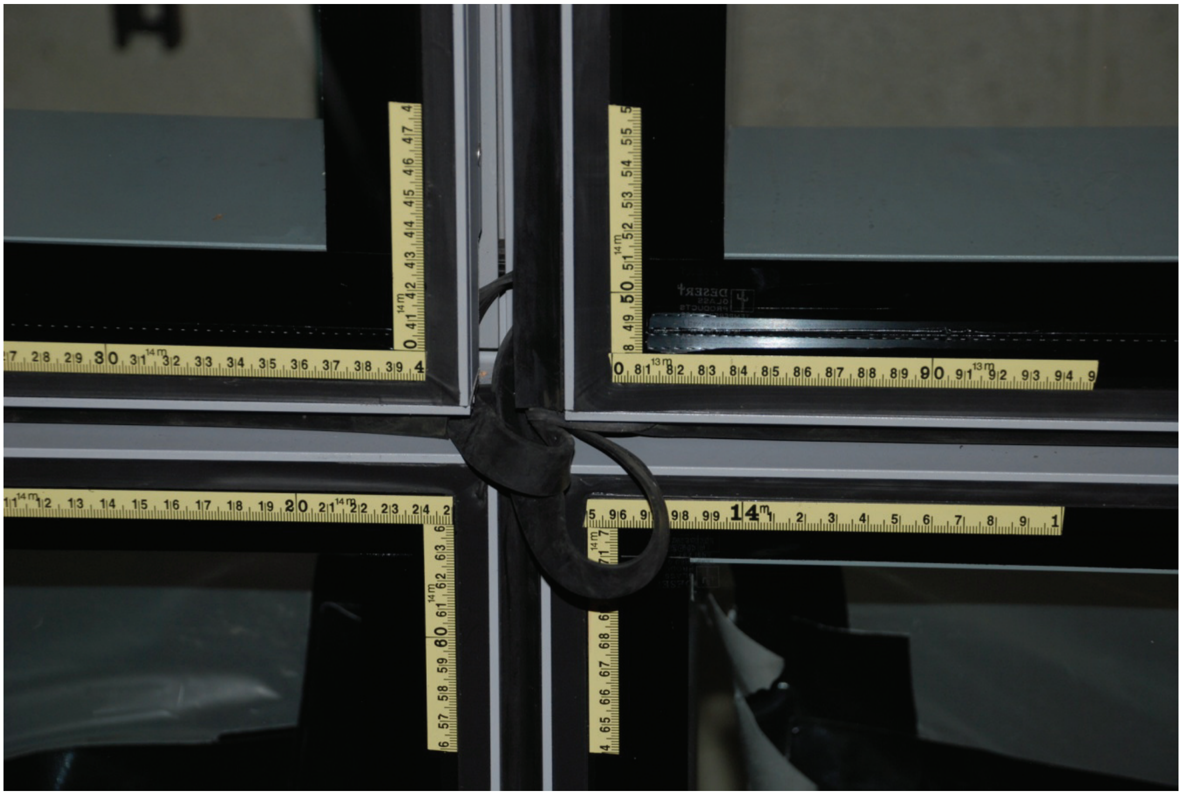


Figure 58: Wedge Gasket Pulling out at Gap between Panels.

6.3.4 Specimen 2, Test 2

Because no permanent damage to the system was encountered during the first racking test, the second unitized system specimen was realigned and prepared for a second racking test. For this test, a new boundary condition was used in an effort to mitigate the amount of fastener pullout observed in the second test of the first specimen and to prevent the end boundary from acting as a tension member. It was observed that the fasteners used for the pressure plate boundary condition used in the first specimen test experienced significant prying. Also, once the fasteners closest to the horizontal stack joint pulled out, the pressure plate served mainly as a tension member. In an initial effort to create a more accurate boundary condition, two readily available aluminum angles and a slotted-hole aluminum connection piece were used. The aluminum angles were attached to the back side of the specimen at both ends so that the screws used for fastening were pointed out-of-plane (perpendicular) with respect to the racking plane. This orientation eliminated the prying action that occurred with the first boundary condition test. Also, the aluminum connection piece was made by milling slotted holes in the thin piece of aluminum bar used to link the two aluminum angle pieces together as shown in Figure 59. This slotted-hole aluminum angle boundary condition prevented the boundary condition from acting as a tension member.

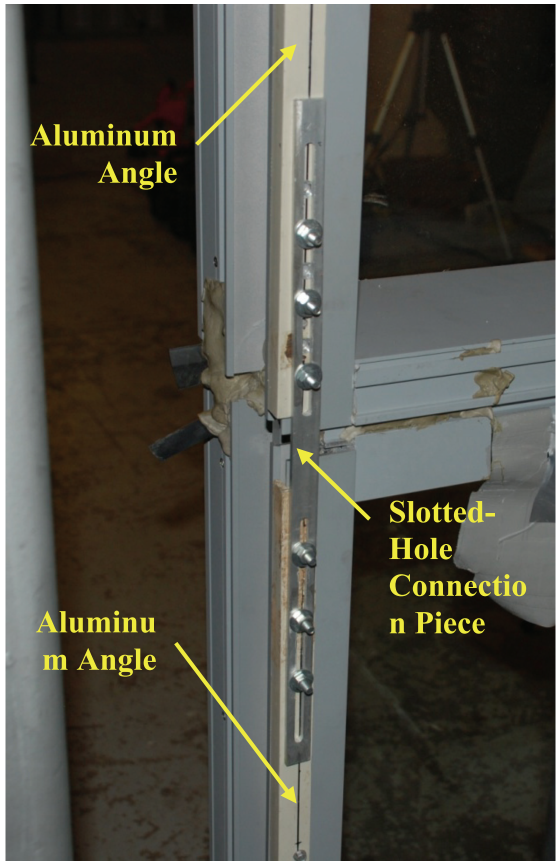


Figure 59: Slotted-Hole Aluminum Angle Boundary Condition.

The slotted holes allowed for movement along the length of the piece so that the end boundary could resist considerable tensile loads in the connection detail. Early on in the racking test, the slotted-hole detail was observed to perform as desired, and allowed the free movement of the connection piece along its length. Ultimately, the piece did not perform as desired in the direction of racking due to the small cross section of the slotted-hole piece. It was observed that after the 1-3/4 inch racking step that the slotted-holes widened due to the in-plane racking forces. This widening of the holes can be seen in Figure 60.

Figure 60: Widening of Slotted-Holes.

These holes continued to expand with racking, and at 2 ¼ in. drift the slotted holes effectively failed through widening and could not offer much restraint. Consequently beyond this point, the specimen behaved more like the first test of the second specimen with no boundary restraint. During the 2-1/4 in. racking step, the right boundary element failed and the slotted-hole connection piece was released from the system. The extent of the width of the slotted-holes can be seen in Figure 61. The test continued using only the left boundary element for two more racking steps and then the tests concluded when the right boundary element failed just as the left one did. Because of the lack of any effective boundary element, the system performed as an unrestrained system and of course no longer represented a realistic practical boundary condition. There was no failure in the unitized system during this test. It can be concluded that the boundary system used is not desirable for representing a corner condition found in typical unitized system construction. In this study, it was desired to select a boundary condition that created the worst case scenario while not unrealistically over stiffening the system. Also, part of the research was to investigate the effect of difference in the forms of boundary conditions on the response of the system.

Figure 61: Extent of Slotted-Hole Widening.

6.3.5 Specimen 2, Test 3

Again, because no major damage was inflicted to the unitized system, the specimen was prepared for a third racking tests. A new boundary condition was used for this test that combined desired characteristics of the previous two boundary conditions tested. Two pressure plates, identical to the one used in the restrained test for the first specimen were attached to span both the right and left stack joint ends of the specimen using fasteners spaced at 6 in. Fastener holes through the pressure plate were also slotted to limit the development of significant tensile stresses within the boundary element. After application of the 1/2 in. racking step, it was noticed that the upper left panel separated from the upper center panel, much like in the second test of the first specimen. This time, the inter-panel spacing was affected along the entire vertical joint and increased significantly more than during the first specimen throughout the test. Table 8 shows the gap between the center panel and its neighboring panels after specific racking steps.

Table 8- Gap between Upper Center Panel and Neighboring Upper Panels (in inches).

	Lower Left Corner	Lower Right Corner	Upper Left Corner	Upper Right Corner
Initial Gaps	0.66	0.58	0.56	0.61
After 1-3/4" Drift	1.08	0.62	0.56	0.61
After 3" Drift	1.38	0.62	0.85	0.62
After 4-3/4" Drift	1.46	0.63	1.16	0.62

The nature of these gaps differs slightly from those of the first specimen. The first specimen showed a gap only at the lower left corner, while the slotted-hole pressure plate end condition test showed a large gap at the top and bottom of the left vertical center panel edge. This slotted-hole pressure plate end boundary experienced a similar failure to that of the first restrained test (first and second specimens 1 test 2). During the 4-1/4 in. racking step, the horizontal stack joint dislodged from the lower left panel as shown in Figure 62. The lower left panel was pushed towards the exterior of the wall system relative to the upper left panel. Again, this represents a derailment potential noting that only the dead load anchors would be holding the upper left panel in place.

Figure 62: Horizontal Stack Joint Dislodges from Lower Left Panel (Magnitude is shown by arrow).

During the subsequent two racking steps, the slotted-hole pressure plates sheared with the left boundary element shearing during the 4-1/2 in. racking step and the right boundary condition failing during the 4-3/4 in. racking step. By the time the boundary elements failed, the unitized system itself was thought to have reached a failure state (both vertical and horizontal joint dislodging). A sheared boundary element can be seen in Figure 63.

Figure 63: Sheared Boundary Element.

6.4 Discussion of the Racking Test Results of the Unitized System

Racking tests showed that this unitized system can accommodate a large amount of movement. The system by nature will slide or sway and adjust as needed to accommodate racking movements. The unrestrained racking test for the first specimen did not inflict any significant damage on the system. The unrestrained test with anti-walking means installed on the second specimen did cause a serviceability failure (air/water penetration) when the upper left and upper center panels separated along their mutual vertical joint. The separation was caused by the anti-walking restriction on the dead load anchors. Typically, a unitized panel is surrounded by other unitized panels either along the same plane or at intersecting planes with interior or exterior corners in an actual building installation. This was not the case in testing this specimen and it was left free to translate. In an effort to simulate an actual installation, end boundaries were added to the unitized system specimens for subsequent racking tests. The first boundary element used (a pressure plate) was attached to only the right side of the system and did not incorporate slotted-holes for the fasteners. The pressure plate proved to be flexible enough to allow some movement, but also created an end condition that did not allow unlimited movement. During testing with this detail, the unitized system did experience some serviceability damage when the horizontal stack joint released from the lower panels. The second end boundary installed was a slotted-hole angle connection. It was noticed during latter racking steps using the pressure plate end boundary element that the pressure plate acted as a tension member, which led to the use of slotted-holes. This end boundary, while good in concept, did not perform as desired. The third boundary element combined the two previously used elements to more accurately portray a real installation. A pressure plate was used with slotted-holes for fasteners to allow for movement along the vertical axis. The unitized system specimen tested with the slotted-hole pressure plate boundary element experienced a similar but more extensive failure exhibited by opening of the entire vertical joint between the upper left and upper center panels. Based on racking tests, weak points in the unitized system have been determined. Depending on the boundary conditions in real life situation, the stack wiper seal and the wedge gasket seals could be vulnerable to pullout to some degree. The horizontal stack joint is susceptible to dislodging from the lower panels under certain boundary conditions and very large racking displacements. Vertical inter-panel joints are also vulnerable to some separation, leaving a pathway for air and water penetration. The damage behavior reported occurred at drifts much larger than the maximum code allowable drifts.

A summary of results can be seen in Table 9 to help quantitatively compare the data. It is important to note that the first specimen did not experience any vertical joint dislodging in both unrestrained and restrained tests, while the second specimen did experience this limit state in both the unrestrained test and also the test using the slotted-hole pressure plate. Accordingly, this failure mode is perhaps dependent on the method of construction and not as dependent on system properties. Furthermore, it is possible that during the installation of the unitized panels of the second specimen, the gaskets lining the horizontal stack were compressed and during racking tests were allowed to return to their original position. Of course, this issue was not investigated sufficiently during this study, but should be considered further in follow-up studies.

Table 9- Summary of Unitized System Failure Drifts*.

Description	**Vertical Joint Dislodging**			**Horizontal Stack Joint Dislodging**		
	in.	**mm**	**Drift Index**	**in.**	**mm**	**Drift Index**
First Specimen- Unrestrained	[a]	[a]	[a]	[a]	[a]	[a]
First Specimen- Pressure Plate End Boundary Condition	[a]	[a]	[a]	5.72	145.3	0.047
Second Specimen- Unrestrained	1.67	42.4	0.014	[a]	[a]	[a]
Second Specimen- Slotted Hole Pressure Plate End Boundary Condition	0.38	9.6	0.003	4.28	108.7	0.036

[a]Limit state was not reached by conclusion of test

*Note that the drift values have been adjusted for racking facility flexibility.

6.5 Conclusions Based on the Results of the Unitized Systems Tests

The objective of this testing program was to evaluate the simulated seismic performance of EN-WALL 7250 unitized curtain wall system specimens using 3M™ VHB™ Structural Glazing Tape G23F to form the structural seals. The evaluation was based on cyclic racking tests following the AAMA 501.6 test protocol. The goal was to identify any failure modes of the unitized wall system under very high drifts beyond what is expected during design earthquakes. The full-scale specimens were planar, but testing considered unrestrained planar as well as restrained boundary condition to simulate a corner or end boundary condition. The racking tests of the planar specimens without any restraint at the stack joint showed no damage to glass, structural glazing tape and structural sealant weatherseal under maximum racking facility drift capacity (6 in.), which is larger than what is expected during design earthquake. However, there was some wedge gasket pullout. Furthermore, there is also the potential for some vertical joint opening between panels, and this would only pose some serviceability issues such as air leakage. When restraints were introduced at the stack joint, besides gasket pullout, the test results showed the possibility of vertical joint opening. At very large drift values (larger than 4.25 in. or 3.5% drift index) some derailment of the top panels with respect to the bottom panels at the stack joint is also possible. It should be noted, however, that the maximum design drift index (ratio) for building structural design is 2.5%. Therefore, the drift corresponding to the potential derailment issue under special boundary restraint conditions is at least 40% higher than the maximum drift ratio allowed by the building code.

Of course, the restraints introduced were more severe than the real-life restraints due to the corner conditions. The intention was to determine the worst case scenario performance. However, since the wall system was unitized and the racking forces did not transfer to the glass and sealants, the tests did not reveal the performance of the structural glazing tape bond to the glass under stressed conditions. In other words, because the stack joint creates a seismic isolation between adjacent vertical panels, the glass to mullion attachment is not expected to experience much in-plane shear. Overall, the performance of this wall system under AAMA 501.6 testing protocol proved to be satisfactory for a planar system, and this study showed that the stack joint design can significantly enhance the seismic performance by creating a condition for the adjacent panels to sway or slide instead of being racked. No failures were observed in the glass panels themselves, and the unitized system as a whole did not experience any permanent damage. The horizontal stack joint failure occurred at relatively high drifts, enhancing the system's seismic capacity.

7. Fragility Development

7.1 Damage States

The drift corresponding to three damage states for fragility curve development have been identified from records of laboratory dynamic racking tests on the specimens included in this report. These damage states include: (1) gasket seal degradation, (2) onset of glass cracking, and (3) glass fallout threshold as defined in AAMA 501.6 (AAMA 2001) as the point at which a fragment of glass equal to or larger than 645 mm^2 (1 $in.^2$) breaks away from the glass panel and falls out. In curtain walls with heavier glass panels such as IGUs, glazing frame damage is also possible. Another damage state is the potential for glazing frame dislodging or derailment in unitized system under certain restraint boundary conditions and large drifts. Glass cracking and gasket seal degradation are considered serviceability failures and as such do not present an immediate life safety hazard. In contrast, glass fallout is an ultimate failure and is a life safety hazard. Furthermore, glass cracking and fallout are sequential damage states because a glass panel does not experience glass fallout until glass cracking has occurred. (Note: for all FT monolithic glass panels, many HS monolithic glass panels, and on occasion for AN monolithic glass panels, glass cracking and glass fallout are coincident.) Gasket seal damage is mutually exclusive from the other two damage states. The frame dislodging or derailment as discussed in detail earlier would be possible under certain extreme boundary conditions and excessively large drifts.

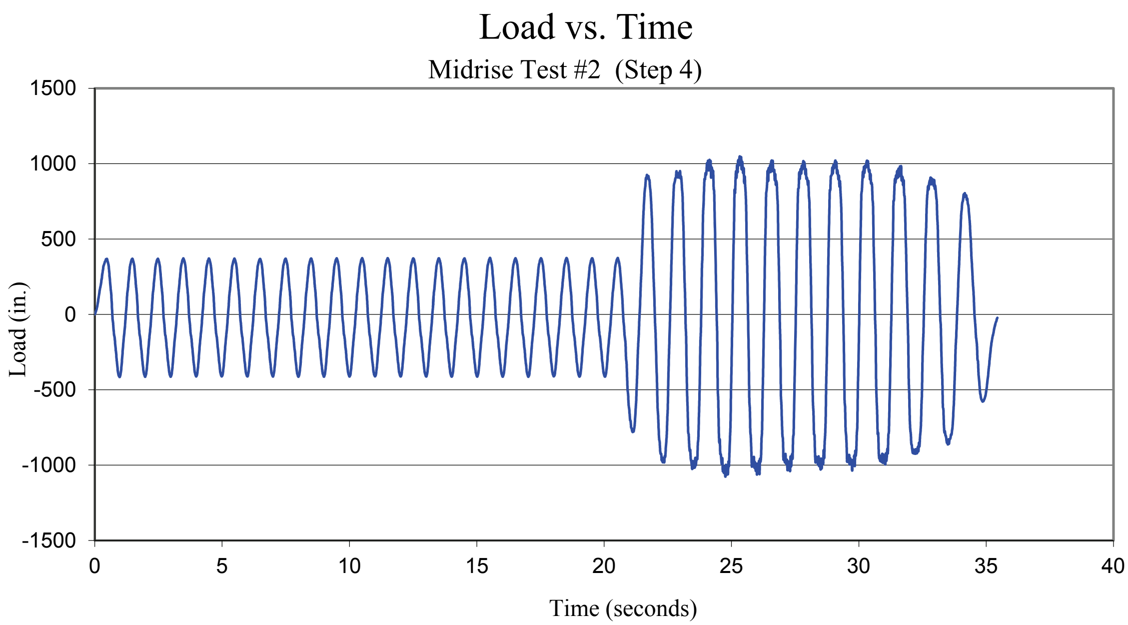
For certain IGU configurations (3-5) analyses were conducted for the glass cracking and fallout damage states for each glass pane and the overall glass panel. The analysis consisted of computed results and fragility curve plots for cracking (serviceability) for the inner (AN mono) pane, outer (laminated) pane, and the overall panel, which was recorded as the drift value associated with the onset of glass cracking in either pane. Analysis of the computed results and fragility curve plots for glass fallout (ultimate) for these data sets included fallout for the inner (AN mono) pane and fallout for the entire unit. While all of these separate fragility curves can be found in the appendices, only the overall glass cracking (onset of glass cracking in either pane) and overall glass fallout drift limits are reported in the tables that will be used for the fragility software.

7.1.1 Cracking Damage State

Although a glass panel with cracking may still retain sufficient rigidity to avoid a breach in the building envelope in its vicinity, potential hazards associated with future crack growth (including subsequent glass fallout) necessitate its replacement. Cracked glass does, however, represent a breach in the building envelope weatherseal. In the case of a monolithic glass panel, substantial air leakage and the potential for water infiltration through the crack can lead to higher energy costs for a building and potential water-induced damage to other aspects of the building envelope or the building interior. If both plies of an insulating glass panel crack, these same air leakage and water infiltration potentials exist. However, if only one ply of an insulating glass (IGU) panel exhibits cracking, and in most cases when one or both plies of a laminated glass panel exhibit cracking, air leakage and water infiltration potentials are diminished, but the loss of IGU fill gas will diminish its overall thermal performance.

Past laboratory studies identified the cracking limit state as the drift amplitude coincident with the observation of a through-thickness crack in the vision region of the specimen under test. However, more recent laboratory studies conducted to evaluate the effects of corner geometry and edge finish on glass damage states (Memari 2006a) used view windows in the glazing frame pressure plates to more accurately track damage at the corners of the glass panels. During these tests, the origin of through-thickness glass cracks that ultimately extend into the glass vision area (i.e., the area of the glass panel uncovered by perimeter anchorage means) for glass panels constructed with annealed glass were tracked. This revealed that: (1) glass crushing zones that are generated at even lower drift levels than the observed cracking drift level are the initiation regions for glass cracks; and (2) through-thickness glass cracks not visible in the vision region of the glass panel are also often observed at earlier drift levels. Even though an earthquake event might not cause immediate glass cracking visible in the vision area of the glass panel, it could cause glass crushing or non-vision area glass cracks that would later lead to glass cracks extending into the vision area through various crack growth mechanisms. For this reason, it was thought necessary to reduce the reported cracking limit states from previous laboratory studies in order to develop appropriately conservative fragilities. The means chosen for this reduction was to evaluate the data sheets from previous tests wherein notes related to glass crushing were typically recorded and to evaluate the load vs. time record generated for the laboratory tests.

Review of the load vs. time data shows that the cracking damage state was reached before the visually observed displacement for some specimens. When a glass specimen reaches the cracking damage state, the load measured during the testing fluctuates in a manner that can be identified. Figure 64 shows an example comparing a load vs. time graph for a loading step for a specimen where the first graph represents a step where no failure occurred and then a second graph where cracking/crushing occurred in the following loading step. For the first graph, it can be seen that the peak amplitudes representing the measured load are consistent and similar. However, the fluctuating measured loads in the second graph indicate that the serviceability failure was being reached during the loading step. Overall, the analysis of the load vs. time graphs compliments the initial visual observations to ensure that the serviceability failure limit states were recognized when they occurred for all of the glass specimens.



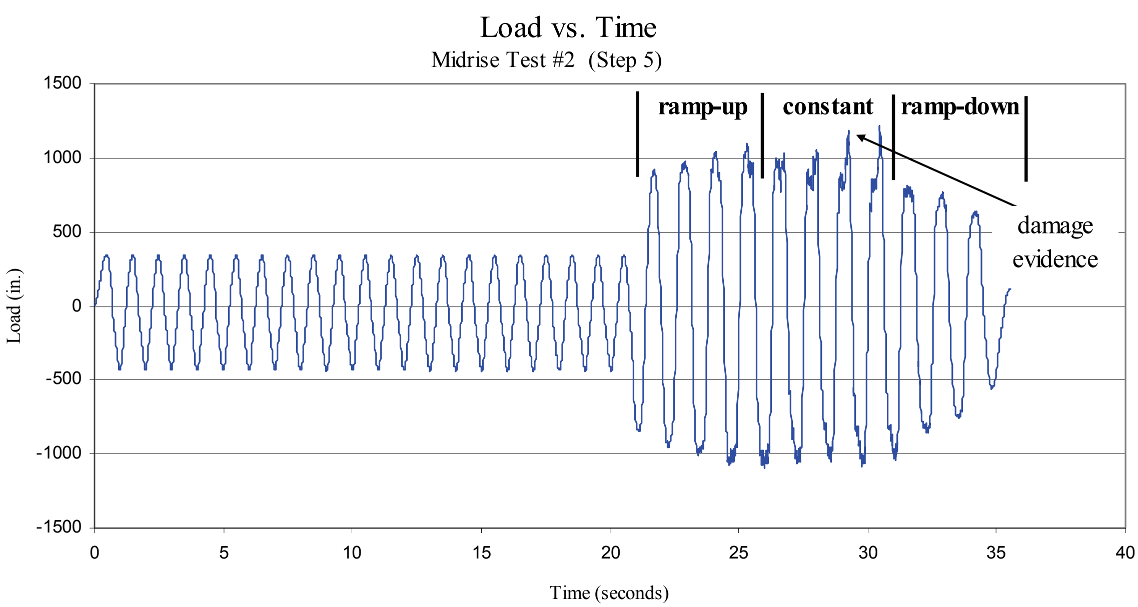


Figure 64: Comparison of load vs. time graphs between (a) a specimen where failure did not occur and (b) for a specimen where cracking/crushing occurred during the loading step, respectively.

It should be noted that more extensive cracking (than the first crack) can occur with sustained racking motions. In this case, the extensive cracking may also be considered an ultimate damage state because of the potential to lead directly to glass fallout.

7.1.2 Fallout Damage State

As previously noted, glass fallout has been recognized in AAMA 501.6 as the drift level associated with the fallout of a glass fragment larger than one square inch (625 mm^2). Aside from the most important life safety issues associated with glass fallout damage, the building envelope is breached and the interior of the building is exposed to the elements outside that can further cause building damage, building security issues and disruption of business activities in or within the vicinity of the building. Depending on the severity of the glass fallout, the entire glass panel and its remnants will need to be removed and the unglazed opening covered immediately with sheathing or some other protective barrier until it can be reglazed. Prior to the replacement of the broken glass panel, an assessment of the framing system and its perimeter anchoring system is also necessary. The racking displacement at glass fallout damage state can also cause damage to perimeter gasket, side blocking, setting blocks, gouging in the metal framing, damage to framing member connections, other cosmetic damage to the framing system, and damage to other aspects of the building interior and exterior.

Glass fallout is recognized by observation during racking experimental testing. When fallout occurs during the experiment, the time and racking step are noted. Generally, fallout failure of the glass results in the complete breakage of the glass panel. However, there can be some ambiguity in the failure limit states prior to the one square inch (625 mm^2) size threshold mandated by AAMA 501.6 because some smaller glass piece fallout due to glass corner crushing, chipping, and spalling were noted in earlier AN monolithic glass experimental testing.

7.1.3 Gasket Seal Degradation Damage State

Degradation in a dry-glazed gasket seal is another important serviceability-related damage state because it presents avenues for air leakage and water infiltration through the building envelope around the periphery of the glass panel. There are four commonly observed damage modes to gaskets during dynamic racking tests: (1) distortion, characterized by a twisted or bulged gasket that remains between the glass and the glazing pocket; (2) pull-out, characterized by a section of gasket that has pulled completely out of the glazing pocket; (3) push-in, characterized by a section of gasket that has pushed into the glazing pocket; and (4) shifting, characterized by a length of gasket that has displaced along its longitudinal axis and created an unsealed gap at one or both glass panel corners at its ends. Repair of gasket seal degradation can often be done without removing the perimeter anchorage or the glass panel depending on the severity of the gasket damage and the glazing system details. Nonetheless, it can lead to more expensive glazing system repairs if left unchecked.

Unlike glass cracking and glass fallout damage states, the drift corresponding to gasket degradation was not uniformly collected at the time of testing during previous laboratory studies. However, racking test data sheets and video footage from the racking tests have been helpful for the compilation of the gasket data. During many of the racking tests no signs of the four gasket damage modes were observed prior to the onset of glass cracking. In these instances the glass cracking drift level was implied as the gasket seal degradation drift level because at this point glass shards can begin to damage the gasket and the cracked glass panel will require replacement, which would in any case necessitate maintenance or reapplication of gaskets.

7.1.4 Framing Damage State

Still another form of damage not considered as a damage state for fragility determination is damage to the glazing frame. During the IGU experimental testing glazing frame damage was investigated. It was noticed that all instances of entire unit fallout in IGU configurations were caused by (1) a complete loss (detachment) of the bottom horizontal pressure plate, (2) extreme rotation of the horizontal member, or (3) loss of the bottom horizontal member itself. Observation of post-breakage behavior of the specimens revealed that closer spacing of pressure plate screws and perhaps a higher clamping pressure would lead to higher entire unit fallout resistance.

A cross-sectional view of a bottom horizontal at the completion of one of the IGU racking tests as shown in Figure 65 suggests other factors that could have influenced both the serviceability and ultimate drift capacities. For example, inspection of the glazing frame at the completion of a test indicated that some permanent glazing lip deformation had occurred in the corner regions of the horizontal and, at times, in the corner regions of the verticals. In general, observed deformations in heavier configuration specimens were greater than in lighter configurations. Permanent deformations in the glazing lip might have contributed to the increased serviceability drift values in some of the heavier configurations. The deformations of the lip at corners of the horizontals were typically less than 0.05 in. (1.3 mm). In those instances when rotations of the horizontals were observed, it was facilitated by bending of the shear block screws attaching the horizontals to the verticals. Moreover, in those instances where the entire bottom horizontal fell out, the fallout was attributed to pullout of the shear block screws from the vertical mullions. Rotation of the horizontals as a result of shear block and shear block screw bending in many instances caused shear block impingement in heavier configurations. In some instances, rotation of the bottom horizontal member contributed substantially to the entire unit fallout.

Framing damage was recorded for configurations 3, 4, and 5 at the completion of a given specimen's test. It was noted that the glazing pockets experienced significant damage at the conclusion of a test, and as mention is considered a serviceability damage state. Glass specimens that experienced greater frame damage failures (release of a mullion from the framing system, release of a pressure plate from the system, etc.) often had large portions of glass, if not entire glass panels, release from the glazing system intact. The data from these cases were used for the fallout limit state and will not be considered in the frame damage limit state, as the prospect of glass falling is of a greater safety risk.

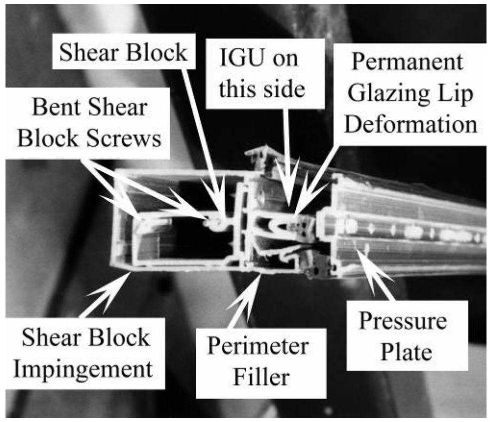


Figure 65 Cross-sectional view of a bottom horizontal of a CW frame after completion of a racking test.

Frame damage can occur in any architectural glass configuration system. Besides the insulating glass unit experiments, frame damage was also recorded in SF system testing for configurations 7, 8, and 9. For these specimens it was observed that 1/4 in. (6 mm) annealed monolithic and 1/4 in. (6 mm) annealed laminated monolithic glass units gouged into the aluminum framing corners. This was reported as a consequence of the unseamed edges of the annealed glass (Behr et al. 1995). Also SF tests that contained FT IGU glass deformed the glazing pockets. This is not a life-safety concern, but the framing should be replaced, and thus is a serviceability failure. This supports the conclusion that some configurations are more prone to frame damage due to certain details, a finding which was also noted during the IGU experiments.

Frame damage is believed to be an independent limit state, however the majority of tests evaluated frame damage (except for more severe damage like the release of a mullion from the glazing system, for example) at the conclusion of the test and therefore it is difficult to say exactly when the frame experienced enough damage to say that it has failed. It can be said for certain that frame damage does exist by the conclusion of the racking test, but at exactly what drift is yet to be determined. For the purposes of this report, framing damage will not be quantified or represented with fragility curves; however, glazing systems using heavier glass panels should check glazing pockets for damage after substantial earthquake events. If significant damage is seen to the framing, framing members should be replaced.

7.1.5 Other Potential Damage States

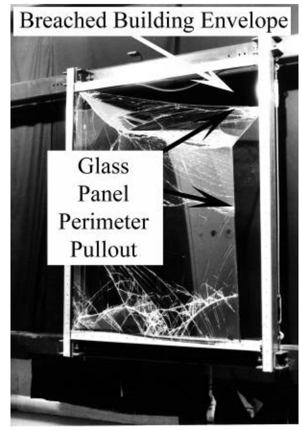


Figure 66: Laminated glass pullout behavior due to glass panel buckling shown here for a laminated glass unit.

An ultimate damage type that is specific to both monolithic laminated units and asymmetric IGUs (with an outer laminated lite) configurations that is not considered as a damage state for fragility calculation is pullout of the laminated glass unit from the glazing pocket. The glass panel pullout (Figure 66) is defined as the condition where the unit began to pull out of the glazing frame either as a result of glass panel buckling or loss of pressure plate clamping pressure. It is possible for pullout to occur without the fallout failure being reached first. Pullout is important in the context of defining when the building envelope has been breached. Glass panel buckling of the laminated outer pane in general causes pullout of a portion of the IGU perimeter as a result of substantial out-of-plane deflection. Lost clamping pressure along the bottom horizontal due to failure features such as complete pressure plate fallout also caused pullout in laboratory testing as the entire unit began to slide vertically downward and out of the frame. In these tests, pullout caused by lost clamping pressure ultimately caused the entire unit to fall from the frame during subsequent racking motion. Furthermore, in an asymmetric IGU, the AN monolithic inner pane usually experiences fallout damage state itself before the outer laminated pane reaches fallout. As a result, an entire unit fallout damage state could indicate when both panes in an IGU have experienced complete failure.

7.2 Procedure to Develop Fragility Data

In order to convert the experimental data in a form usable for seismic assessment, the data should be converted into a probabilistic form because of the many uncertainties with respect to the actual construction and the variability of seismic loadings on buildings. It is conventional for seismic assessment to express the probability of failure of a given structural and nonstructural component, element, or system in the form of fragilities, which means the probability that a given system will sustain a certain type of failure (or a more severe one) as a function of a response parameter such as drift. The material used in this section to define fragility is primarily taken from the ATC-58 35% report. However, the following references, along with many others, provide various aspects of fragility development: Abrams and Shinozuka 1997; Rosowsky et al. 2002; Deierlein and Kanvinde 2003, Porter et al. 2001, and Porter and Kiremidjian 2001.

The fragility function is defined in the form of the following lognormal cumulative distribution function:

$$F_i(D) = \Phi(\ln(D/\theta_i)/\beta_i) \quad (4)$$

Where D is the demand parameter (story drift or drift ratio), θ is the median of the test results, β is the logarithmic standard deviation (or dispersion) of the test results, subscript "i" represents the damage state of interest (e.g., initial glass cracking), $F_i(D)$ expresses the conditional probability that the glazing system under consideration will sustain the damage state "i" or a more severe damage state (e.g., glass fallout), and Φ represents the standard normal cumulative distribution function. The conditional probability for damage state "i", P[i|D], is given by the difference between the conditional probability associated with damage state "i+1", $F_{i+1}(D)$, and that for damage state "i", $F_i(D)$.

The dispersion β is a measure of the uncertainties in the actual value of demand D (e.g., drift ratio) a building may experience for the damage state to take place. This uncertainty represents that difference in the conditions of the actual construction with that of the tested laboratory specimen in addition to the differences in the actual loading a real glazing system may experience as compared to that of the laboratory loading conditions.

For cases where a fragility function is generated from a limited experimental database, a two-part β parameter can be used, such as $(\beta_r^2 + \beta_u^2)^{1/2}$. Accordingly, β_r expresses the random variability in the experimental data which is directly determined from the variability in laboratory data results. On the other hand, β_u is a measure of the differences between the actual physical construction details and loading conditions of a glazing system on the building compared to the specimen in the laboratory. β_u can also represent the uncertainty about the adequacy of the experimental database to properly reflect the variability of the specimens' behavior. The ATC-58 guidelines recommends a minimum value of 0.25 for β_u if: (a) five or fewer specimens were tested under the same loading protocol; (b) different configurations are possible for the installation of the component on the building, but the specimens tested all had the same configuration; and (c) although the laboratory specimens were tested, for example, in only one direction, but the components on an actual building could experience different loading conditions. The guidelines further recommend a value of 0.1 if such conditions are not applicable.

The ATC-58 guidelines suggest different methods to develop median (θ) and dispersion (β) values depending on the availability and nature of test results. Accordingly, the following procedures may be used:

a) Actual Demand Data – When each of the M specimens tested experienced the damage state D;
b) Bounding Demand Data – When some of the M specimens tested actually experienced the damage state D, but the maximum demand each specimen was subjected to is known;
c) Capable Demand Data – When none of the M specimens tested experienced the damage state D, but the maximum demand each specimen was subjected to is known;
d) Derivation – When modeling and analysis instead of experimental data is used to predict the demand corresponding to the damage state D;

e) Expert opinion – When the opinion of experts is used to estimate the level of demand corresponding to the damage state D.

In the case of glazing system fragilities, approaches (a) and (b) were followed most prevalently.

In cases where the fragility information is developed from actual test data, the ATC-58 guidelines require testing the data for goodness of fit. Accordingly, the demand D is calculated from the following:

$$D = max_x|F_i(d) – S_M(d)| \quad (6)$$

where $S_M(D)$ represents the sample cumulative distribution function given as follows:

$$S_M(d) = (1/M) * \Sigma H(d_i-d); i=1, M \quad (7)$$

In this equation, M is the number of specimens and H can be assumed 1.0, 0.5, or 0.0, if D_i-D is positive, zero, or negative, respectively. The guidelines define D_{crit} to be 0.775, 0.819, 0.895, or 0.995 divided by the quantity ($M^{0.5}$ -0.01+0.85$M^{-0.5}$) for significance levels represented, respectively, by quality level α values of 0.15, 0.10, 0.05, or 0.025. The guidelines define failure of the goodness of fit test (Lilliefors Test) when D>D_{crit}, where, in that case, a value of α = 0.05 is to be assigned for the quality level.

7.2.1 Fragility Derivation: Mixture

For CW and SF configurations with different details than those presented in this report for which fragility curves were developed, new fragility curves need to be derived for the performance-based seismic design analysis. Fragility mixture is a fragility derivation method developed to produce a single new fragility curve from existing fragilities for a component that shares characteristics of other configurations whose fragilities are already known. This fragility derivation method allows users to create a fragility function for their unique glass configuration when one is not available.

The method of deriving a fragility function from a mixture of fragilities is discussed in detail by Porter and Kiremidjian (2001). For this method, there are two ways to compute a fragility mixture, depending on whether the membership probability mass function (probability relationship between the configuration being considered and existing fragilities) is known or not. For the case being considered in this report, it is assumed that relationship of any given unique CW or SF configuration with respect to already developed fragilities is not known. Therefore, in this situation, Porter and Kiremidjian (2001) suggest that the option of creating a discrete uniform distribution be used. This option is only one suggested approach, and other approaches may be explored as well.

To derive a new fragility using the fragility mixture method when no information is available for a probability mass function, the following steps should be taken. First, appropriate fragility functions from the existing set developed from laboratory data need to be selected for the analysis based on the CW or SF configuration being considered. The proper existing fragilities will share most characteristics with the configuration under consideration. In most cases, only two existing fragilities will need to be selected to derive the new fragility.

After the appropriate existing fragilities have been determined, let

N = Number of existing fragility functions selected

Then:

$$i = [Nu_1]$$
$$\theta = \sigma_i \Phi^{-1}(u_2) + \mu_i$$

where i is the index for one of N types of fragilities selected randomly, u_1 and u_2 are independent samples of a uniform (0, 1) random variate, Φ^{-1} is the inverse of the standard normal cumulative distribution (Φ), σ_i is the standard deviation value at which damage occurred for i, μ_i is the mean intensity value at which damage was experienced for i, and θ is the calculated median value of demand at which the damage state is likely to occur. β is determined in the same manner as a normal fragility function, for which β represents the logarithmic standard deviation (or dispersion) of the existing fragility functions.

7.2.2 Data Organization

From the compiled archives of past experimental racking tests and additional recent tests performed on architectural glass curtain walls, 44 different CW and SF glass configurations were selected to be analyzed for the development of fragility curves. These 44 configuration types listed in Appendix A were chosen based on the amount of data already available, the most common CW systems used on buildings, and representing a range of glazing options available.

The details and characteristics for the 44 different system configurations were organized and typed into Excel worksheets as shown in Appendix A. The categories for the worksheet were created to match up with the "common data" input area in the *Fragility Function Calculator version 1.02* software, except for the first column, which is a numbering system that was used for reference in this report. The categories included the following: "Test #", "Specimen ID", "Component Description", "Describe Specimen", "Describe Excitation", "Demand Parameter", "Damage Evidence", and "Damage Measure." This was done for reference and for easy copying/pasting of the information into the software.

For this report, the worksheet in Appendix A was split up into Serviceability type failures and Ultimate type failures applicable to each glass configuration. As an example, CW configuration (1) only has cracking and fallout damage state data available. Refer to Appendix A for the complete worksheet.

The drift values (in. and mm) and drift index or ratios (D.I.) for all relevant damage state failures were then organized in a separate worksheet listed in Appendix B. The worksheet includes the new numbering referencing for this report, old numbering referencing, glass specimen characteristics, cracking drift values, glass fallout damage state values, gasket damage state values for some data sets, and other data values that were thought to be useful in future analysis. As an example, Figure 67 illustrates the test data and results that are contained in these worksheets. Refer to Appendix B for the worksheet containing a complete summary of test data and results.

ATC-58 Project Specimen ID	Original Specimen Numbering	Glass Type	Corner Shape	Edge Condition	Corner Condition	Glass Nominal Thickness (in.)
	Annealed Monolithic					
1	1-1	AN Mono	rectangular	cut	cut	0.25
1	1-2	AN Mono	rectangular	cut	cut	0.25
1	1-3	AN Mono	rectangular	cut	cut	0.25
1	1-4	AN Mono	rectangular	cut	cut	0.25
1	1-5	AN Mono	rectangular	cut	cut	0.25
1	1-6	AN Mono	rectangular	cut	cut	0.25
1	added 4/17/08	AN Mono	rectangular	cut	cut	0.25

Average Glass-to-Frame Clearance (in.)	Glass Manufacturer	Glass-to-Frame Contact			Gasket Failure		
		in.	mm	D.I.	in.	mm	D.I.
0.5	Centre Glass						
0.5	Centre Glass						
0.5	Centre Glass						
0.5	Centre Glass	0.073	1.9	0.0009			
0.5	Oldcastle						
0.5	Oldcastle						
0.5	-						

Glass Cracking						
Monolithic Pane or Inner Pane of IGU			Outer Pane of IGU			Overall Lowest of Inner/Outer (IGU)
in.	mm	D.I.	in.	mm	D.I.	D.I.
1.15	29.2	0.0142				
0.93	23.7	0.0115				
1.15	29.2	0.0142				
1.15	29.2	0.0142				
1.15	29.2	0.0142				
1.15	29.2	0.0142				
1.15	29.2	0.0142				

Glass Fallout					
Monolithic Pane or Inner Pane of IGU			Outer Pane of IGU		
in.	mm	D.I.	in.	mm	D.I.
1.88	47.7	0.0232			
2.01	51.0	0.0248			
2.21	56.0	0.0272			
2.01	51.0	0.0248			
1.36	34.6	0.0168			
1.36	34.6	0.0168			
1.79	45.6	0.0221			

Figure 67: An example of Appendix B for glass Configuration 1.

7.2.3 Data Processing

The fragility calculations are based on peak interstory drift indices for each separate damage state. However, for some glass configurations the only available damage state failure values were reported as drift in inches. To convert drift values into drift indices, the following equation was used:

$$\text{Interstory Drift Index} = \delta/h \qquad (9)$$

where δ is equal to the recorded drift experienced by the specimen and h is equal to the height between the center points of the intersection of the mullion and transom that frame the glass panel.

In the experiments carried out using the stepwise loading protocol, the racking displacements were incremented at 0.25 in. (6 mm) intervals. In most of the glass specimens, serviceability or ultimate failure occurred during the peak loading amplitudes of the racking steps. However, to ensure the accuracy of the data, the load vs. time graphs for each specimen were analyzed to see if any damage state might have occurred during the "ramp-up" interval of the loading step. If this was the case, then the result is that the actual load at which the specimen failed was less than the intended loading step and the limit value was adjusted accordingly. As an example, Figure 68 shows a load vs. time graph for a glass specimen where fallout occurred on the "ramp-up" loading interval, and the limit state value had to be adjusted. As a result of this additional analysis, the limit values have been validated or adjusted to represent the exact drift at which serviceability or ultimate failure occurred for any particular specimen.

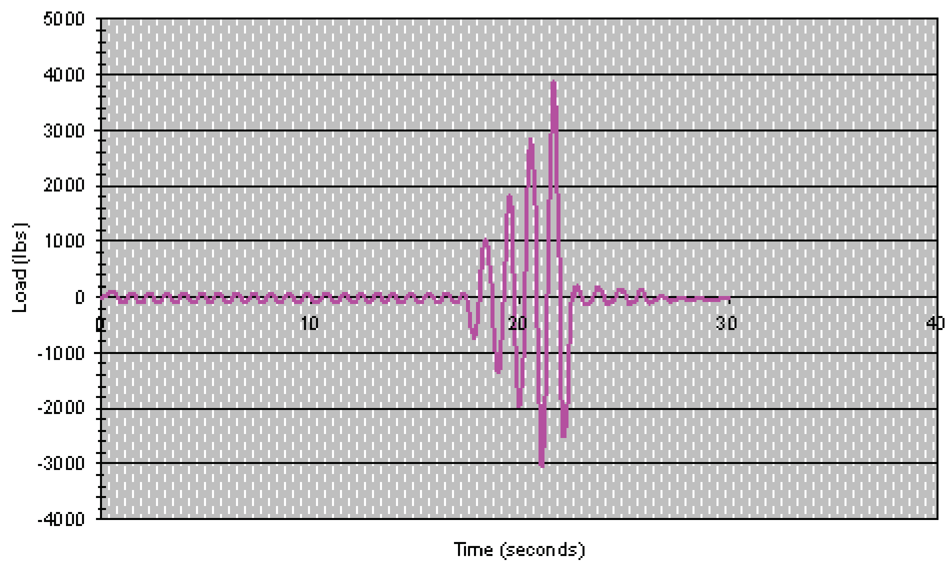


Figure 68: A load vs. time graph for a glass specimen where fallout was reached during the "ramp-up" loading interval.

The detailed information from the tables in Appendix A and data from Appendix B for each configuration was then input into the *Fragility Function Calculator Version 1.2* software. The "Method A" analysis option was used for most of the configurations and damage limit states. This is the analysis option to be used when actual damage state parameters are known for all specimens tested. For configurations where some of the specimens did not reach failure and the facility drift capacity was used as their failure drift, "Method B" was the analysis option used. The program then produces an output containing the values of M (# of specimens), θ (median), β_r (dispersion value), and whether the fragility function passes the Lilliefors goodness-of-fit test at a 5% significance level. As an example, Figure 69 and Figure 70 show a frame of the computed results for the cracking serviceability-type failure and glass fallout ultimate-type failure, respectively, for glass configuration (3). The complete results are included in Appendix C. It should be noted that for select configurations where Method B was chosen, the θ and β_r values determined by the calculator are not realistic. The problem could be the way Method B is programmed in the Calculator. This issue is further discussed subsequently.

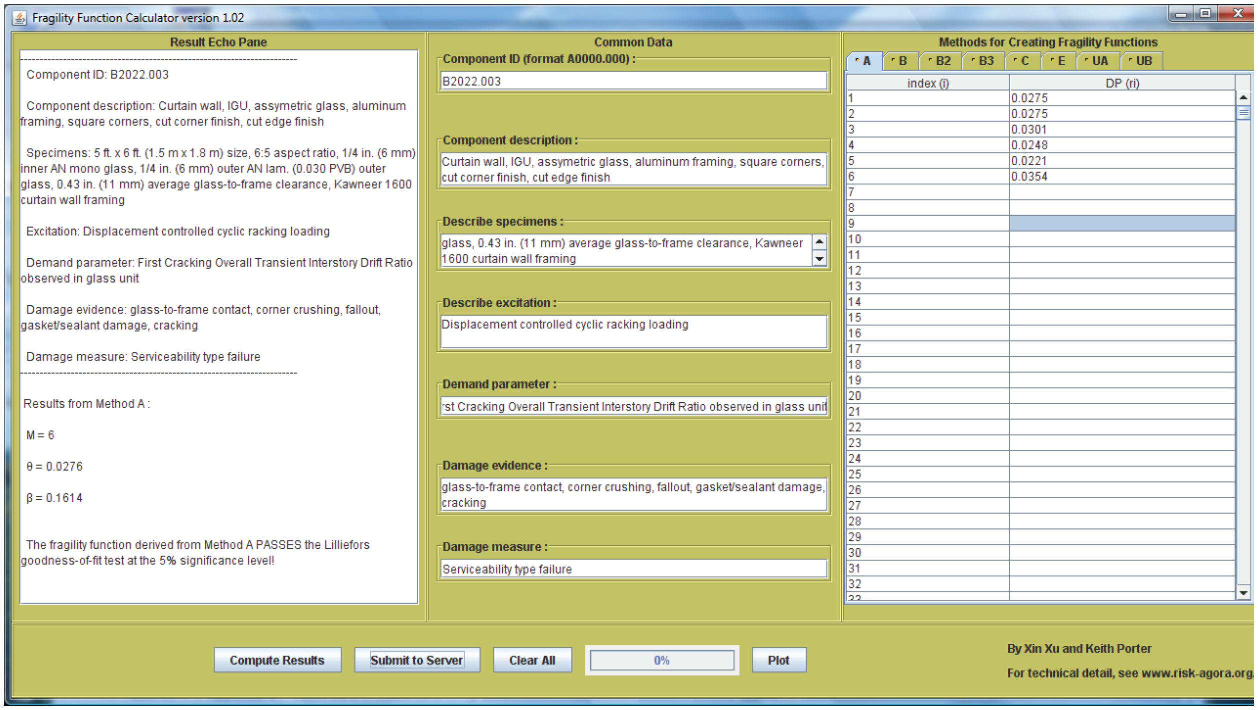


Figure 69: Computed results for glass configuration (3) for cracking failure.

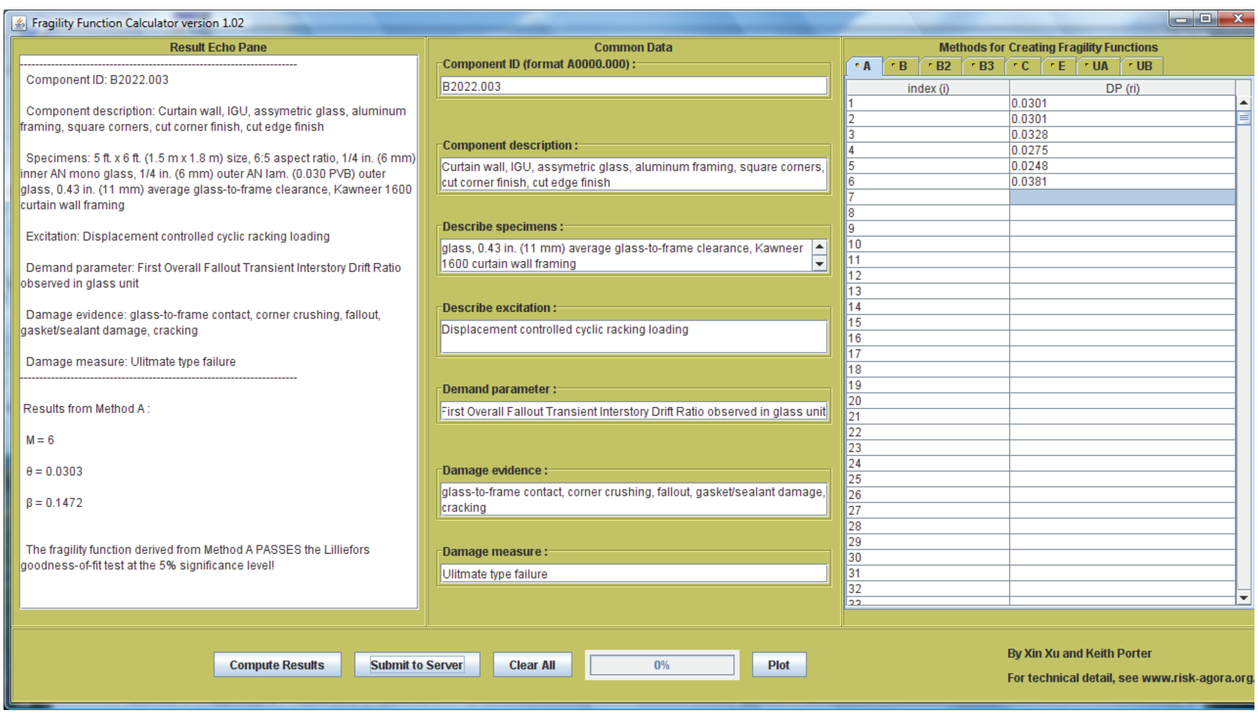


Figure 70: Computed results for glass Configuration (3) for fallout failure.

Once the two fragility parameters of θ (median) and β_r (dispersion value) were computed, the dispersion parameter β had to be determined for fragility function development based on β_r and β_u and using equation $(\beta_r^2 + \beta_u^2)^{1/2}$. According to the guidelines, β_u should be have a minimum value of 0.25 if certain criteria are met. For testing conditions of the database employed, two conditions applied: (1) in an actual building, the CW could be installed in a number of different configurations; however, all test specimens had the same configuration; and (2) all specimens were subjected to the same loading protocol. Therefore, the dispersion values were computed using a β_u value of 0.25. All resulting dispersion values were above the 0.2 mark. The resulting dispersion values along with the median and additional information related to consequences of failure and cost of repair are presented in Appendix D, and a summary of both fragility parameters can be found in Table 10a for Configurations 1-31, Table 10b for configuration 32 and Table 10c for configurations 33-44.

Select data points derived using Method B analysis yielded unrealistically high results (e.g. drift indexes well above the facility limits). A new analysis method was used for these data points presented in Tables 10 (a, b, and c) that used an arithmetic average (sum of drift indexes divided by the number of specimens tested). For specimens that did not experience the given damage state, a drift index value equal to that of the facility limits was used (shown with an asterisk in parentheses). This new method of analysis yields more realistic conservative results. All original data, including the values that are deemed unrealistic, are present in the appendices.

Table 10a: Cracking, Fallout, and Gasket Damage Fragility Parameters for Configurations 1-31. (*Probabilistically derived values yielded unrealistic results. Values shown in parentheses are derived through arithmetic methods.)

	Cracking		***Fallout***		***Gasket***	
ID	Θ	β	Θ	β	Θ	β
1	0.0138	0.262	0.0219	0.315		
2	0.0234	0.300	0.0310	0.295		
3	0.0276	0.298	0.0303	0.290	0.0270	0.320
4	0.0266	0.322	0.0299	0.346	0.0262	0.317
5	0.0268	0.289	0.0339	0.268	0.0260	0.272
6	0.0156	0.343	0.0561	0.311		
7	0.0413	0.284	0.0510	0.290	0.0303	0.492
8	0.0590	0.258	0.0665	0.253	0.0423	0.303
9	0.0567	0.289	0.0800 (0.0724*)	0.990	0.0290	0.514
10	0.0088	0.252	0.0108	0.251		
11	0.0084	0.261	0.0107	0.359		
12	0.0147	0.252	0.0164	0.262		
13	0.0142	0.250	0.0221	0.250		
14	0.0181	0.262	0.0212	0.250		
15	0.0220	0.277	0.0257	0.271		
16	0.0288	0.258	0.0400	1.021		
17	0.0273	0.283	0.0286	0.277		

18	0.0434	0.250	0.0434	0.250
19	0.0417	0.298	0.0417	0.298
20	0.0392	0.289	0.0434	0.250
21	0.0347	0.260	0.0200	1.021
22	0.0514	0.250	0.0540	0.250
23	0.0513	0.254	0.0540	0.250
24	0.0240	0.286	0.0250	0.284
25	0.0285	0.293	0.0285	0.293
26	0.0328	0.250	0.0328	0.250
27	0.0272	0.256	0.0290	0.257
28	0.0201	0.261	0.0232	0.280
29	0.0239	0.250	0.0274	0.317
30	0.0263	0.297	0.0267	0.296
31	0.0314	0.255	0.0314	0.255

Table 10b: Vertical and Horizontal Joint Dislodging Fragility Parameters for Configuration 32. (*Probabilistically derived values yielded unrealistic results. Values shown in parentheses are derived through arithmetic methods.)

ID	***Vertical Joint Dislodging***		***Horizontal Joint Dislodging***	
	Θ	β	Θ	β
32	0.53 (0.028*)	1.0211	0.0397	0.3067

Table10c: Loss of Seal, Gasket Degradation, Frame Damage, Glass Damage, and Sealant Damage Fragility Parameters for Configurations 33-44. (*Probabilistically derived values yielded unrealistic results. Values shown in parentheses are derived through arithmetic methods.)

ID	***Loss of Seal***		***Gasket Degradation***		***Frame Damage***		***Glass Damage***		***Sealant Damage***	
	Θ	β	Θ	β	Θ	β	Θ	β	Θ	β
33	1.38 (0.044*)	1.0211	0.04	1.0211	0.05	0.2881	0.16 (0.0592*)	1.0211		
34	0.0203	0.5004	0.01	0.3202	0.054	0.2805	0.16 (0.0592*)	1.0211		
35	0.01	0.3202	0.01	1.0211	0.0528	0.2822	0.0592*	1.0211		
36	10.0 (0.06*)	0.3202	10.0 (0.06*)	0.3202	10.0 (0.06*)	0.3202	10.0 (0.06*)	0.3202		
37	0.13 (0.058*)	1.0211	0.0262	0.2745	0.0551	0.2872	10.0 (0.06*)	0.3202		
38	0.15 (0.0497*)	1.0211	0.0191	0.5235	0.0548	0.3177	10.0 (0.06*)	0.3202		

39	0.16 (0.053*)	1.0211	0.0217	0.4622	0.0549	0.3027	10.0 (0.06*)	0.3202		
40	10.0 (0.06*)	0.3202	0.1 (0.054*)	1.0211	0.09 (0.0577*)	1.0211	10.0 (0.06*)	0.3202		
41	0.09 (0.06*)	0.9727	0.01	1.0211	0.06	0.25	0.03	1.0211	0.02	1.0211
42	0.0354	0.2692	0.01	1.0211	0.0424	0.5502	0.05	1.0211	0.29 (0.0513*)	1.0211
43	0.03	1.0211	0.01	1.0211	0.0522	0.3982	0.03	1.0211	0.05	1.0211
44	0.01	1.0211	0.0158	0.6945	0.0363	0.7522	0.05	1.0211	0.016	0.2652

After the parameters of a fragility function were calculated as shown in Tables 10a, 10b, and 10c with more complete information in Appendix D, the fragility curves were plotted. Note that the θ values derived using arithmetic methods in Tables 10a, 10b, and 10c were not used to plot fragility curves; rather, the values determined by the software were used. The curves were plotted with the provided software through the available "plot" function. These plotted fragilities from the software can be seen in Appendix E-1. It was noted that the software skews the curves. To show an alternative way of plotting the fragilities, fragility curves were also plotted using Excel software, with the θ parameter as calculated by the software and β as determined based on the approach discussed. The fragilities plotted with Excel can be seen in Appendix E-2. A detailed discussion on how to plot a fragility curve using the Excel software is found in the *Guidelines for Seismic Performance Assessment of Buildings 35% Draft* (ATC 2005). An example of plotted fragility curves for the fallout damage state of glass configuration (3) can be seen in Figures 71 and 72, where the first figure shows a plot from the software and the following figure a plot from Excel. As noted earlier, configurations for which Method B was used to generate mean and dispersion values, resulted in unrealistic values for θ and β parameters and led to fragility curves with incorrect shapes. However, corrections to these curves have not been made in this report in order to present the results as generated by the software.

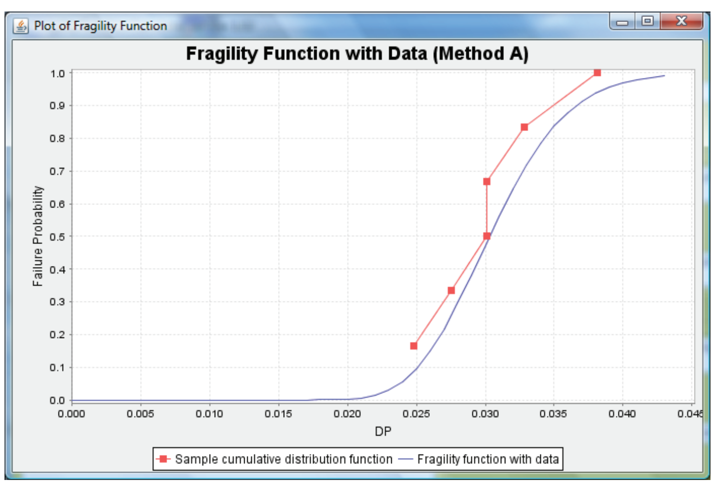


Figure 71: Fragility curve as plotted by the software for the fallout damage limit state of glass Configuration 3.

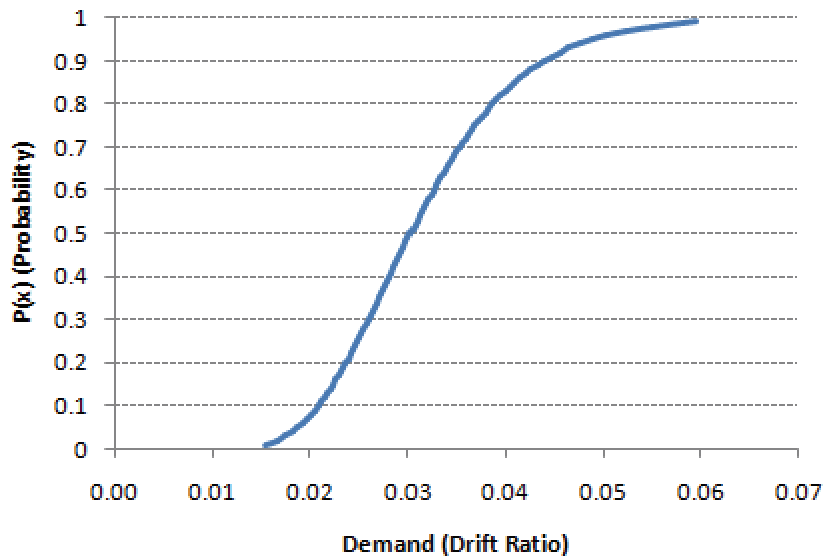


Figure 72: Fragility curve as plotted in Excel for the fallout damage limit state of glass Configuration 3.

8. Fragility Applicability

The fragility data presented in this report can in general be applied directly to a given building if the CW system has the same general framing system glazing details, glass type, approximate glass panel size, aspect ratio, thickness and glass-to-frame clearances. Otherwise, the use of mixed fragility (Porter and Kiremidjian 2001) might be one option or the fragility functions can be modified if certain conditions are met. In this mixed fragility process, as discussed in Section 5.2.1, initially known probability functions are characterized as probability functions. A simulation technique is then used to determine the preferred probability distribution and to create the new mixed fragility function. Applicability of these options, along with associated procedures, are outlined below.

8.1 Framing System

As previously mentioned, the mid-rise CW configurations used to develop the fragilities presented in this report used either the Kawneer 1600™ Curtain Wall System and the SF configurations used either the Kawneer TriFab II® 451, Oldcastle BuildingEnvelope™ systems FG-3000, FG-2000, or the 3000 Thermal MultiPlane framing systems. There are numerous aluminum wall systems manufactured by other companies that are similar to both Kawneer and Oldcastle BuildingEnvelope™ systems used in these laboratory tests. However, there are many parameters of the aluminum framing that could differ from one manufacturer to the next. These parameters include the width, depth, and gasket detailing (i.e., dry vs. wet glazing), which can affect racking behavior and structural properties such as cross section area and moment of inertia. Framing details such as glass-to-frame clearance and glass bite dimensions are determined by the designer and not necessarily the manufacturer.

To determine how to apply fragility parameters to CW framing systems with different manufacturers other than Kawneer and Oldcastle BuildingEnvelope™, the details of the framing system that have the largest effects on the seismic performance of the glass panels need to be identified. Figures 73 and 74 illustrate the behavior of two different CW framing systems before and after being subjected to the same lateral (racking) displacement. Type 1 has aluminum cross-section properties of area = A, moment of inertia = I, and width = W, while Type 2 has aluminum cross-sectional properties of area = 0.5A, moment of inertia = 0.3I, and width = 0.75W. Even though the flexural stiffness will differ between the two systems, because the stiffness of the building structural system is so much greater than the stiffness of any CW system, the two frame types will displace the same amount if they have the same connection system to the building frame and if the mullions are continuous.

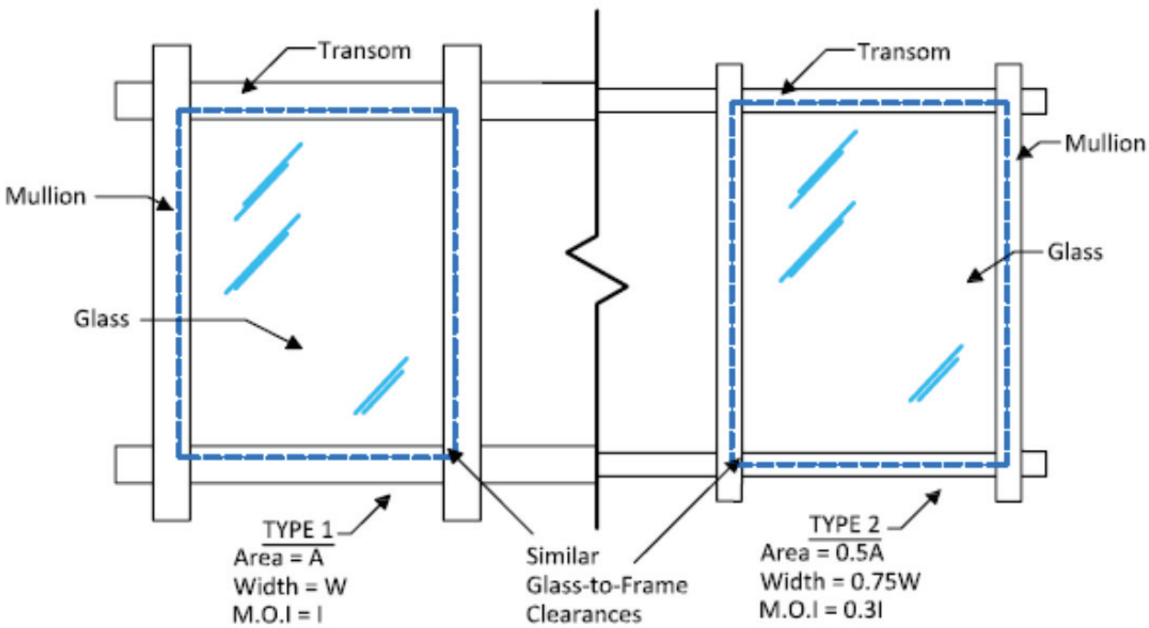


Figure 73: Comparison of two CW framing systems with different cross section properties, but with similar glass-to-frame clearances, before a racking displacement is applied.

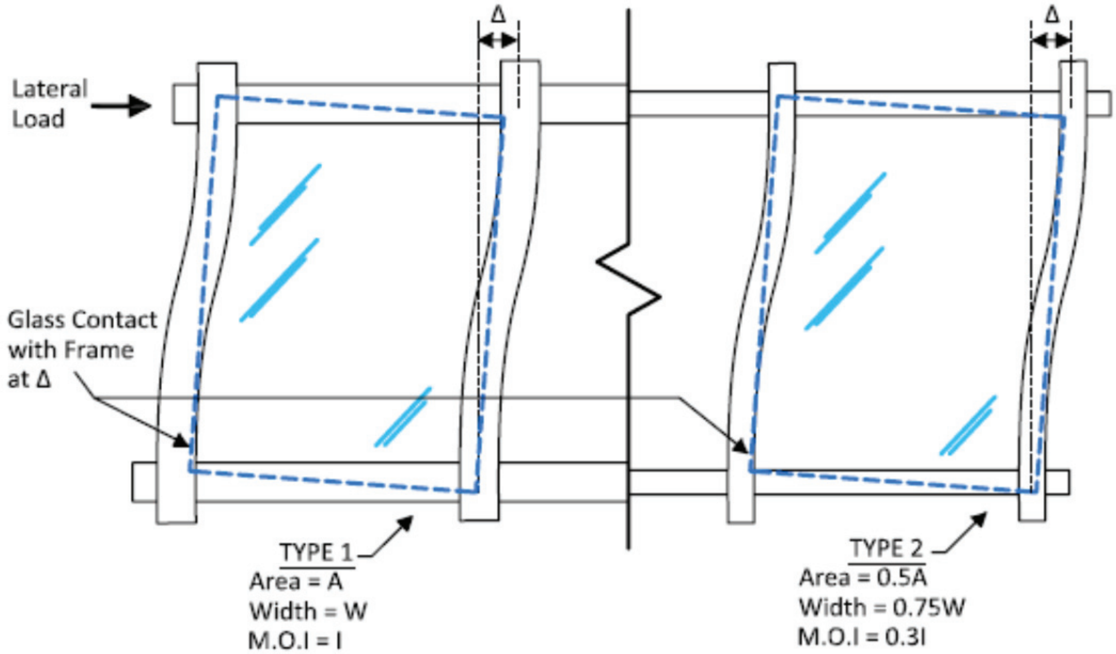


Figure 74: Comparison of two CW framing systems with different cross section properties, but with similar glass-to-frame clearances, after a racking displacement is applied.

Since different types of CW framing systems will displace the same amount if subjected to the same racking displacements imposed by the primary structural system of the building, then the most important framing detail affecting the seismic behavior of glass is the glass-to-frame clearance and, consequently, the bite as well where the glass bite is the distance between the edge of the mullion to the edge of the glass (refer to Figure 5). Therefore, these fragilities can be used for framing systems from other manufacturers. However, the connection details of the framing system to the structure need to be comparable to Kawneer 1600™, TriFab II® 451, or the Vistawall storefront framing systems even though the framing member properties mentioned above may differ. Examples of different framing systems found that are comparable to the Kawneer 1600™ are Vistawall CW-250 and YKK AP America YCW 750 OG. For reference, Figure 75 shows the cross-sectional details and component detailing, respectively, of the Kawneer 1600™ curtain wall system. Also, Figure 76 shows the cross-sectional details of the Vistawall CW-250 and YKK AP America YCW 750 OG systems that are comparable to the Kawneer 1600™ curtain wall system.

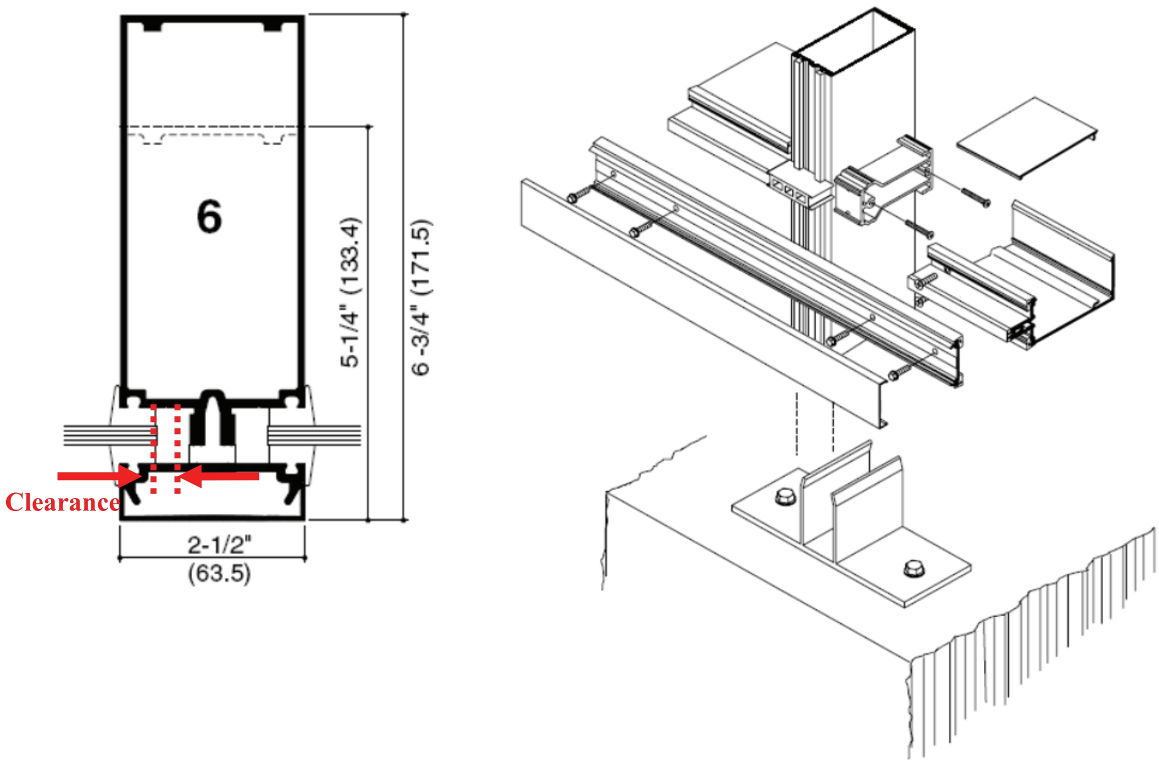


Figure 75: Drawings showing (a) cross-section details and (b) component details from the Kawneer 1600^{TM} curtain wall system (www.kawneer.com).

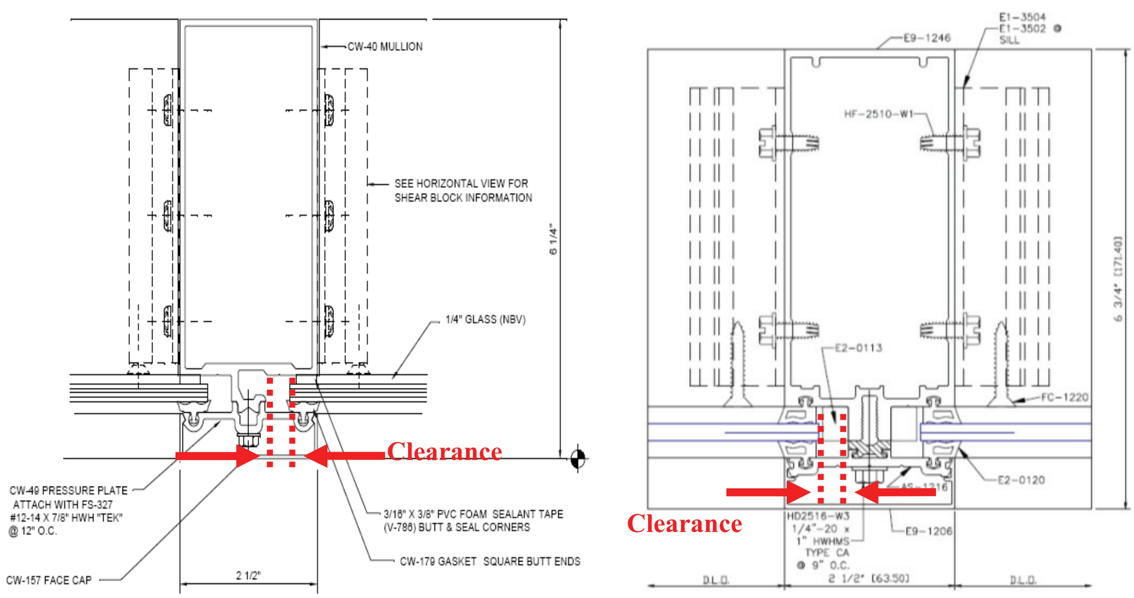


Figure 76: Depictions showing (a) Vistawall CW-250 and (b) YKK AP America YCW 750 OG curtain walls, which are comparable to the Kawneer 1600^{TM} curtain wall system (www.vistawall.com and www.ykkap.com).

8.2 Whole Exterior Glass Systems on a Building

Each of the fragilities (except for the unitized system) in the report represents one glass panel with surrounding aluminum framing. In general, the response of glass panels within CW systems on a building depends on many parameters that could be different from those in the individual laboratory test specimens. These parameters include type and flexibility of the connection of glazing frame to the structural frame, continuity of the glazing frame over multiple stories, actual clearances between glass edges and glazing frame pockets, age of the glass (the strength will be lower in highly weathered glass), and gasket conditions, which is also a function of type and age. The test results and subsequent fragilities are for standard (new construction based on industry recommendation) conditions. With respect to some parameters, such as connections to structural system, it is likely that more rigid attachments exist in the laboratory condition than compared to the glazing frame attachment to the real building situation. As a result, the damage state capacities of the glass configurations based on the laboratory testing is likely most conservative compared to the CW capacity on an actual building.

The other important factor in the failure of a large glass CW on buildings as compared to laboratory test results is the racking displacement loading condition. Even if all physical conditions are the same in the laboratory as on the actual building, one still cannot predict exactly the racking displacement loading conditions that an actual wall system panel will experience during an actual earthquake. However, many of the uncertainties mentioned, and the applicability of the test results to actual buildings, are considered to some extent by the fragility model development parameters such as β values.

With respect to glass size and aspect ratios, for a large CW system where the framing system is designed for abnormally large glass panels, the results from the 5 ft x 6 ft (1.5 m x 1.8 m) specimens tested may not be directly applicable. A discussion on glass aspect ratios is presented subsequently that will be useful in considering glass panels with different aspect ratios.

For a building, the drift ratio (drift index) for a section of a CW is equal to the drift ratio for the glass pane within that CW section. However, the drift that is expected to cause damage may differ when considering a single glass panel versus a section of CW or building story. Figure 77 shows two panels, one with an individual (isolated) glass panel and the other a section from a large CW system. Let's define the drift of the glass panel by δ, the height of the glass panel by h, the height of the section of CW by H, the drift of the section of CW with height "H" by Δ, and the drift of the glass pane and height of the glass pane on the CW section by δ' and h', respectively. Equation (10) expresses the equality of the drift ratios for the two systems:

$$\text{Interstory Drift Ratio} = \Theta = \Delta/H = \delta/h = \delta'/h' \qquad (10)$$

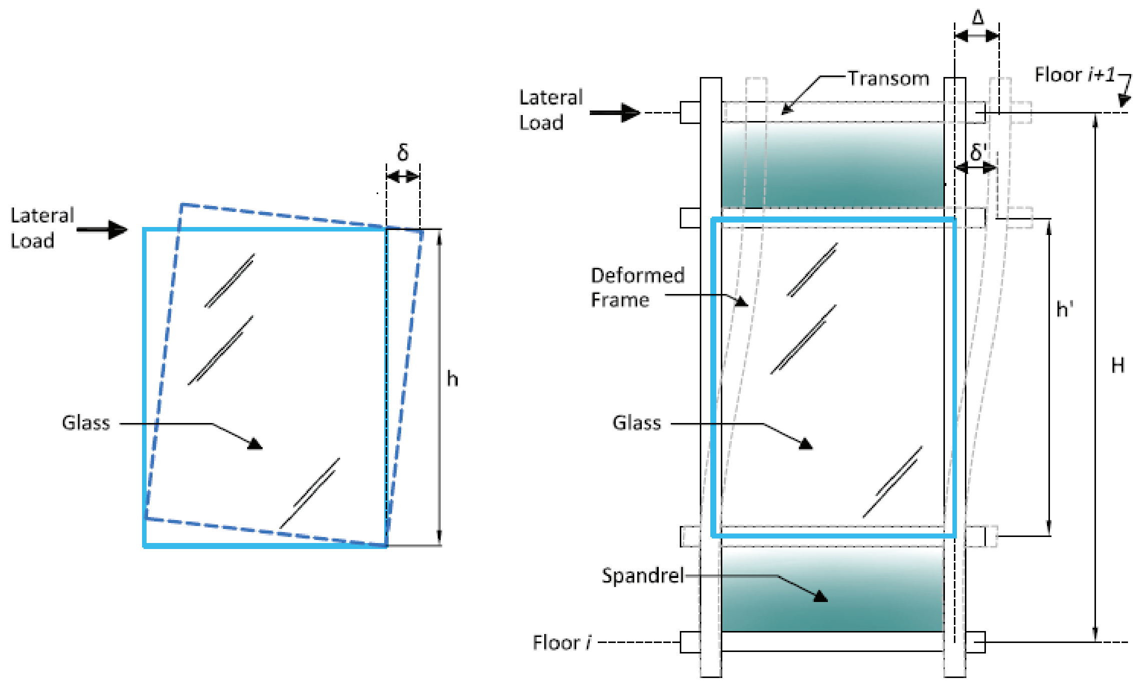


Figure 77: Interstory drift comparison and parameters for an individual glass panel and a larger section from a CW system.

A situation may arise where a failure drift displacement (δ') is needed to be determined for a particular glass panel within a CW on a building. In this case, the lab experimental results for that glass panel will be applied to the building, and then the failure drift over the glass height (h') on the CW will be determined. From the experimental data, a predicted failure drift ratio ($\Theta_{failure}$) is known for the glass of a particular configuration. Using the relationship that the interstory drift ratio for a section on a CW is equal to the interstory drift ratio for an individual glass panel, it can be stated that the failure building drift ratio is equal to $\Theta_{failure}$, which when combined with Equation (10) will yield the following:

$$\text{Bldg. Drift Ratio} = \Delta/H = \Theta_{failure} \rightarrow \delta'/h' = \Theta_{failure} \rightarrow \delta' = \Theta_{failure} \cdot h'$$

Therefore, the failure drift for a particular glass panel on a building can be assumed to be equal to the predicted failure interstory drift ratio for that type of glass panel multiplied by the height of the glass panel.

For example, Figure 78 shows a section of CW on a building with a floor height of 12 ft (3.65 m). The interstory drift expected to cause cracking of the glass panel highlighted on the figure is desired. The CW system is the same as type (4), which is a Kawneer 1600™ or comparable MR with an IGU composed of an inner AN monolithic 1/4 in. (6 mm) thick pane and an outer annealed laminated unit with two 1/8 in. (3 mm) thick lites with 0.060 in. (1.52 mm) PVB in between. Also, it is dry-glazed and the glass-to-frame clearance is the standard 0.43 in. (11 mm).

The predicted failure drift ratio (Θ) for CW type (4) is found from Table 4, where $\Theta_{cracking}$ is equal to 0.0266. Then, it can be stated that the building drift ratio that will cause the selected glass pane to crack is also equal to 0.0266. Next, using Equation (10), we can determine the interstory drift expected to cause cracking for the highlighted panel as follows:

$$\text{Bldg. Drift Ratio} = \Delta/H = \delta'/h'; \text{ and } \Theta_{cracking} = \delta'/h' = 0.0266$$

$$\text{Then, } \Delta_{floor\text{-}i} = \delta'/h' \cdot (H) = 0.0266(12 \text{ ft}) = 0.0266(144 \text{ in.})$$
$$= \mathbf{3.83 \text{ in. } (97 \text{ mm})}$$

Therefore, if the building interstory experiences a lateral drift displacement of 3.83 inches (97 mm) or greater, then it is expected that the glass pane will experience a cracking failure. It should be noted that full-scale experimental testing needs to be carried out to validate and confirm this simplified and damage prediction approach.

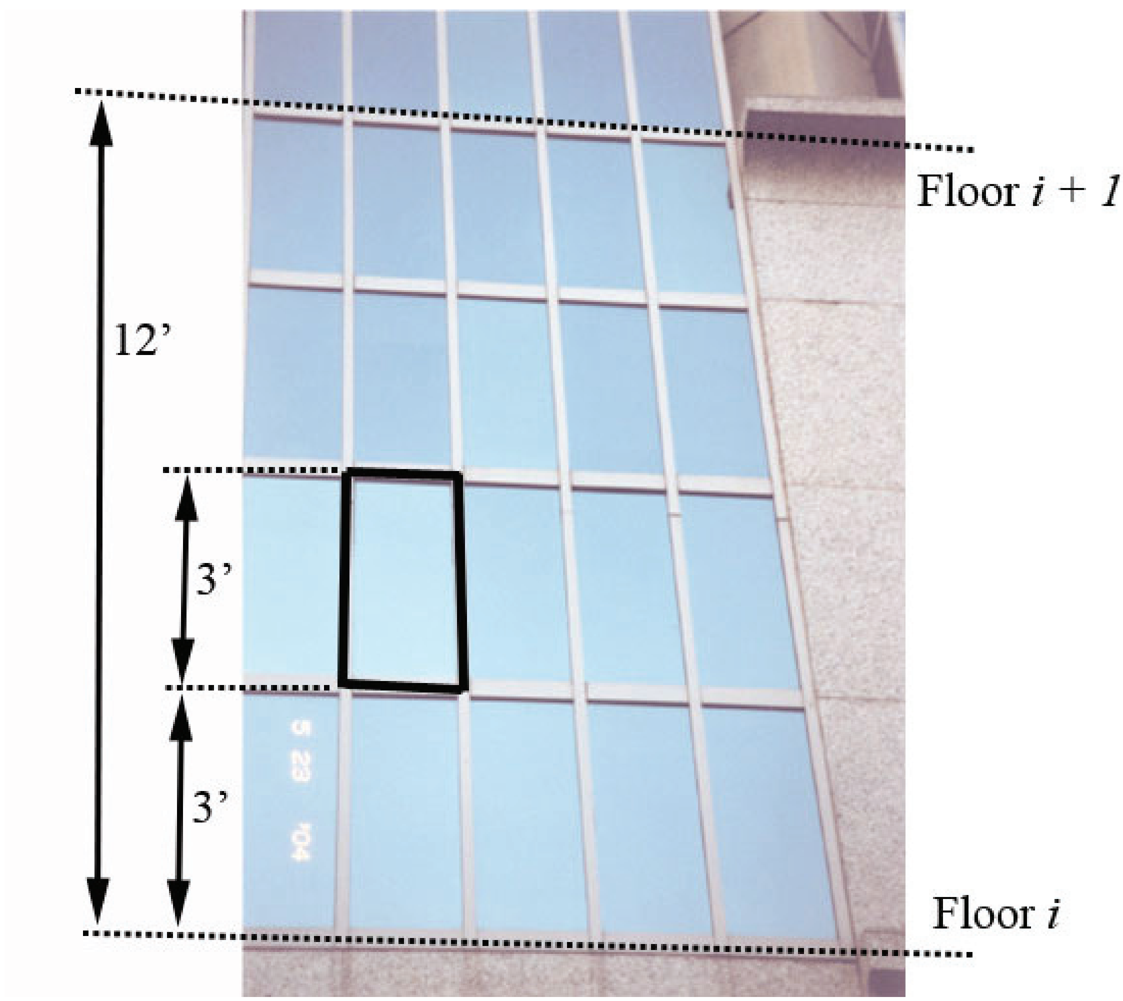


Figure 78: A section of CW with dimensions for the above example.

8.3 Glass-to-Frame Clearance

In addition to the existing data, additional data became available through recent testing to help understand the seismic behavior of architectural glass with different glass-to-frame clearances. This is particularly of interest since even under moderate seismic activity some glass damage has occurred. An example is shown in Figure 79 where glass damage has occurred in a Magnitude 4.2 earthquake in the San Francisco Bay area (epicenter in the Oakland Hills) on July 20, 2007. Storefront wall systems appear to be particularly vulnerable to earthquake-induced glass damage.

It was mentioned above that for all of the 5 ft by 6 ft (1.5 m by 1.8 m) glass specimens racked cyclically in the test programs underlying this report, the clearance between the glass and aluminum frame has been approximately 1/2 in. (13 mm). Therefore, it was not previously known how varying glass-to-frame clearances would affect the behavior of glass in an imposed racking displacement situation. If the standard annealed monolithic glass configuration was tested with different clearances, then the drift values for the service and ultimate damage states could be developed statistically. For example, if it was of interest to evaluate the performance of glass with a sub-standard glass-to-frame clearance (which could occur in the field), then the fragility parameters determined in this report can be useful. These parameters include the peak interstory transient drift ratio expected to reach cracking or fallout, and the associated dispersion values.

Figure 79: Broken windows at (a) Safeway grocery store and (b) Dream Fluff donut shop (Tucker, J., and Lagos, M. "4.2 Temblor shakes stuff off shelves, but no major damage", San Francisco Chronicle, 20 July 2007.)

For the laboratory testing, three different clearances were chosen to complement the available database: 1/4 in. (6 mm), 1/8 in. (3 mm), and 0 in. (0 mm). These clearances were chosen to incrementally reduce to zero glass-to-frame clearances from the value of 0.43 in. (13 mm) used in most other tests. Kawneer 1600™ aluminum curtain wall framing systems were built for racking tests of each glass-to-frame clearance. Then each frame was glazed with an annealed monolithic glass panel, approximately 60 in. x 72 in. (1.5 m x 1.8 m) in size. Once the glass was set with temporary plates, a caliper was used to measure the exact glass-to-frame clearances around the glass panel. Two specimens with a glass-to-frame clearance of 0 in. (0 mm), two specimens with 1/8 in. (3 mm) clearance, and three specimens with a 1/4 in. (6 mm) clearance were tested.

The results from these tests are summarized in Figure 80. The average drift capacities for cracking and fallout damage states are compared for the glass-to-frame clearances of 0 in. (0 mm), 1/8 in. (3 mm), 1/4 in. (6 mm), and typical 0.43 in. (1 mm). Figure 80 shows that from the typical 0.43 in. (1 mm) clearance, the drift capacities for both damage states generally decrease across the clearances to the 1/8 in. (3 mm) clearance. However, the drift capacities slightly increase for the 0 in. (0 mm) clearance from the 1/8 in. (3 mm) clearance. This appears counterintuitive, except that during laboratory testing a phenomenon was noticed with the 0 in. (0 mm) clearance that could explain the change in the general trend. Viewing slots that were milled in the corners of the gasket plates as shown earlier in Figure 23 allowed observations on the conditions of the glass corners throughout cyclic racking tests. It was noticed that in the absence of a gap between the glass and aluminum frame, cyclic impacts between the glass and the aluminum frame did not take place. Rather, the corners of the glass slowly crushed as racking displacements increased, resulting in a more gradual corner rounding action, as shown in Figure 81, which depicts such corner crushing progressing through subsequent load steps for a 0 in. (0 mm) clearance specimen. Figure 81 has three photographs showing the damage that occurred for an actual specimen through progressive loading steps, and drawings below each photograph illustrating the damage and subsequent corner rounding action to the glass with the framing excluded for further clarity. This behavior can be attributed to increasing the drift capacity in the glass panels until cracking finally occurred. It is not clear that the application of hard putty to the glass perimeter would change the test results because the frame deformation would override any small effects the putty might have. When larger glass-to-frame clearances are present, cracking usually occurs before extensive corner crushing and rounding can take place.

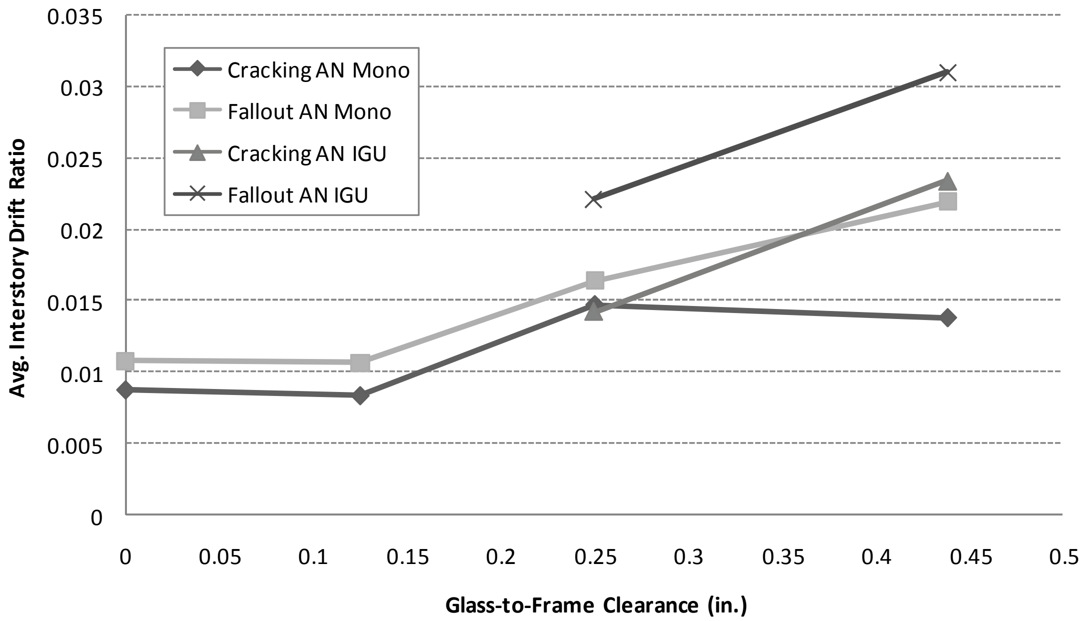
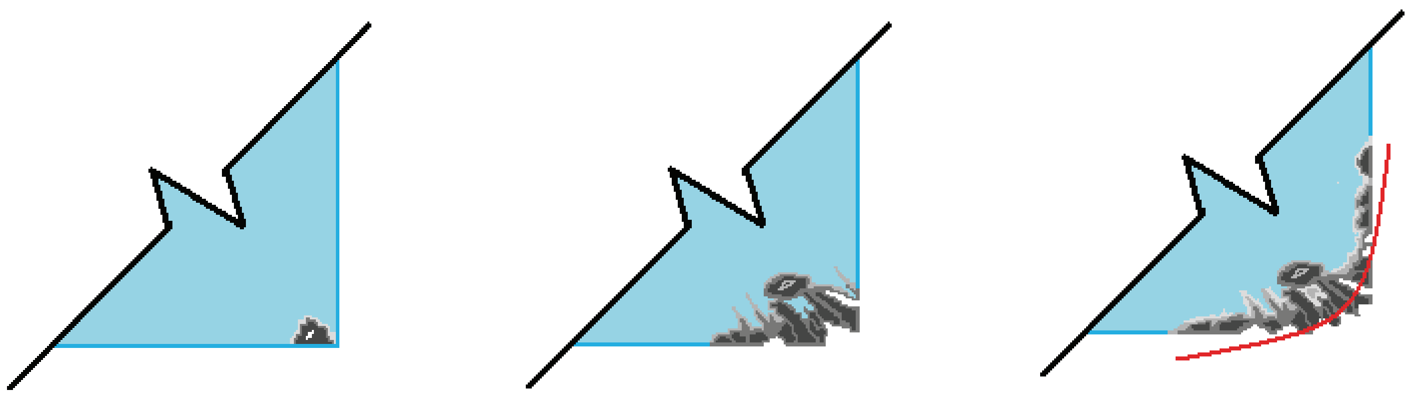


Figure 80: Comparison of drift capacities for cracking and fallout damage states of AN Mono and AN IGU configurations with 0 in. (0 mm), 0.125 in. (3 mm), 0.25 in. (6 mm), and 0.43 in. (1311 mm) glass-to-frame clearances.

(a) (b) (c)



(d) (e) (f)

Figure 81: Photographs (a, b, c) of corner crushing progression observed through the viewing slots of AN mono 0 in. (0 mm) clearance specimen with drawings (d, e, f) underneath depicting graphically the spalling and crushing the glass experiences.

From the laboratory test data fragility parameters were developed for cracking and fallout damage states. These values are summarized in Table 11. As discussed before, these parameters can either be used directly to develop a fragility curve, or mixed with other fragilities for desired CW configurations with matching glass-to-frame clearances. Overall, the more recent test data have widened the applicability of the fragilities in this report to include more CW configurations, and in this case curtain walls with different glass-to-frame clearances.

Table 11: Cracking and fallout damage state fragility parameters for various glass-to-frame clearances of AN monolithic and AN IGU glass configurations.

Glass Type	Glass-to-Frame Clearance	*Cracking*		*Fallout*	
		ϴ	β	ϴ	β
AN Mono	0 in. (0 mm)	0.0088	0.252	0.0108	0.251
AN Mono	1/8 in. (3 mm)	0.0084	0.261	0.0107	0.359
AN Mono	1/4 in. (6 mm)	0.0147	0.252	0.0164	0.262
AN Mono	7/16 in. (11 mm)	0.0138	0.262	0.0219	0.315
AN IGU	1/4 in. (6 mm)	0.0142	0.250	0.0221	0.250
AN IGU	7/16 in. (11 mm)	0.0234	0.300	0.0310	0.295

8.4 Aspect Ratio

If a CW system is similar in every aspect to one of the configurations presented in this report, except that the glass panel has different dimensions and a different aspect ratio, then other fragility parameters will need to be used that have been developed for certain CW configurations with different aspect ratios. The aspect ratio of a glass pane is calculated by dividing the height of the glass by the width. Testing has been done on CW systems with varying glass panel aspect ratios, and these data have been used for fragility development. Table 12 summarizes the fragility parameters for the varying glass aspect ratios. Figure 82 shows the drift capacities for 4 ft x 8 ft (1.2 m x 2.4 m) and 8 ft x 4 ft (2.4 m x 1.2 m) glass panels as compared with the 5 ft x 6 ft (1.5 m x 1.8 m) panels, where the results are presented as an aspect ratio represented as height to width (height: width). The figure shows that for the cracking damage state, the glass configurations with 2:1 and 1:2 aspect ratios had greater experimental failure drift ratios than the glass configuration (1) with a standard 6:5 aspect ratio. For the fallout damage state, though, there appears to be a potential linear relationship between the aspect ratio and drift capacity. The fallout experimental drift ratio is greatest for the 1:2 aspect ratio and then decreases in capacity to the 1:2 aspect ratio. It would be desirable to have additional laboratory data including a greater number of glass panel aspect ratios. After additional data values are acquired, it is then possible to recommend a formula to relate the median fragility values of glass configurations with varying aspect ratios.

Table 12: Cracking and fallout damage state fragility parameters for various glass aspect ratios of AN monolithic glass dry-glazed in a mid-rise CW system.

Aspect Ratio (H:W)	*Cracking*		*Fallout*	
	Θ	β	Θ	β
2:1	0.0181	0.262	0.0212	0.250
6:5	0.0138	0.262	0.0219	0.315
1:2	0.0220	0.277	0.0257	0.271

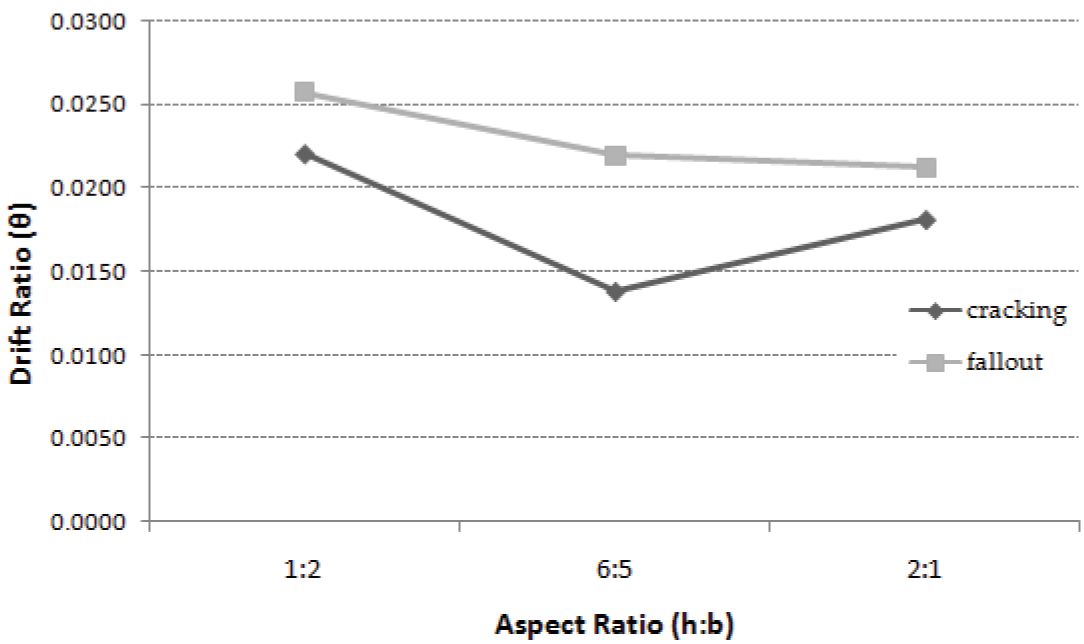


Figure 82: Average drift capacities for cracking and fallout damage states for varying aspect ratios (width/height) for AN monolithic CW configurations.

The fragility parameters in Table 7 can be used directly if the aspect ratio and all the other details of the CW configuration are similar. If this is not the case, then further analysis will have to be performed to produce the desired fragility parameters. As an example, assume a fragility analysis is needed for an annealed laminated glass unit CW system with the same characteristics as configuration type (6) in this report but the glass panel size is 6 ft x 12 ft (1.8 m x 3.7 m) instead of 5 ft x 6 ft (1.5 m x 1.8 m) and thus an aspect characteristic of 2:1 is present. Unfortunately, laboratory testing for this specific configuration is not available. However, two types of related data are available: (I)

Laboratory test data and fragility parameters for configuration type (6) with the standard glass panel aspect ratio; and (II) Laboratory test data and fragility parameters for an annealed monolithic glass with an aspect ratio of 2:1 and other details similar to configuration type (1). Since (I) and (II) have certain shared configuration details with the said configuration, the fragility parameters for (I) and (II) can be mixed for new fragility parameters that can be used for the desired CW configuration. The reference to create a mixed fragility function have been mentioned earlier in the report. If fragility data is not available for a particular aspect ratio, then maybe using the fragility parameters of the next conservative aspect ratio in the analysis could be looked at.

As an illustration of a potential situation stated above, assume that a fragility function is desired for a custom CW system on a commercial building. The CW system framing is Kawneer 1600™, and the glass is composed of insulating glass units (IGU) with a 1/4 in. (6 mm) inner AN monolithic glass pane and a 1/4 in. (6 mm) outer AN laminated glass unit (0.030 PVB). The glass has an average 0.43 in. (11 mm) glass-to-frame clearance, is 6 ft (1.8 m) wide by 4 ft (1.2 m) high, and is sealed by dry gaskets. Since the dimensions are 6 ft x 4 ft (1.8 m x 1.2 m) the aspect ratio is 2:3. Due to this varying feature from glass configuration (3), the fragility parameters from configuration (3) cannot be directly used. Also, laboratory testing has not been executed for glass configurations with an aspect ratio of 2:3; therefore, fragility parameters will need to be manually computed.

It is known that the damage state capacities for the custom CW will be lower as shown in Figure 41 with an aspect ratio of 2:3 than if the aspect ratio was higher (such as the standard 6:5). However, how much lower is not exactly known because laboratory testing has not been executed for varying aspect ratios for glass configuration (3) or even any glass configuration with a glass configuration of 2:3. The method of mixing known fragilities is an option that can be used to create a new fragility function tailored to the glass configuration under consideration. For this procedure, fragilities that share the most characteristics with the configuration being considered need to be identified, and then those will be used to be mixed. For the example, the fragilities for the following configurations have been deemed as appropriate and will be mixed:

I) Glass configuration (3) : asymmetric IGU
II) Glass configuration (15) : AN monolithic with 1:2 aspect ratio

The fragility (I) was selected because glass configuration (3) shares all of the same characteristics with the considered configuration except the aspect ratio (6:5). The fragility (II) was selected because it shares a varying aspect ratio characteristic such as the configuration being considered from the standard aspect ratio of 6:5. Since there is no fragility based on laboratory testing for glass with an aspect ratio of 2:3, the next conservative option was selected, which was (II) with an aspect ratio of 1:2. This logic is based from the laboratory results on glass with varying glass aspect ratios which showed that as the aspect ratio decreases the damage state capacities of the glass declines. Using the damage state and fragility parameter values from glass with an aspect ratio of 1:2 is a conservative approach compared to glass with an aspect ratio of 2:3.

Mixing the fragilities (I) and (II) yields fragility parameters that can be used for the custom CW system for the performance-based engineering analysis. Table 13 shows a summary of all of the fragility parameters chosen in this example and the results for the CW configuration being considered.

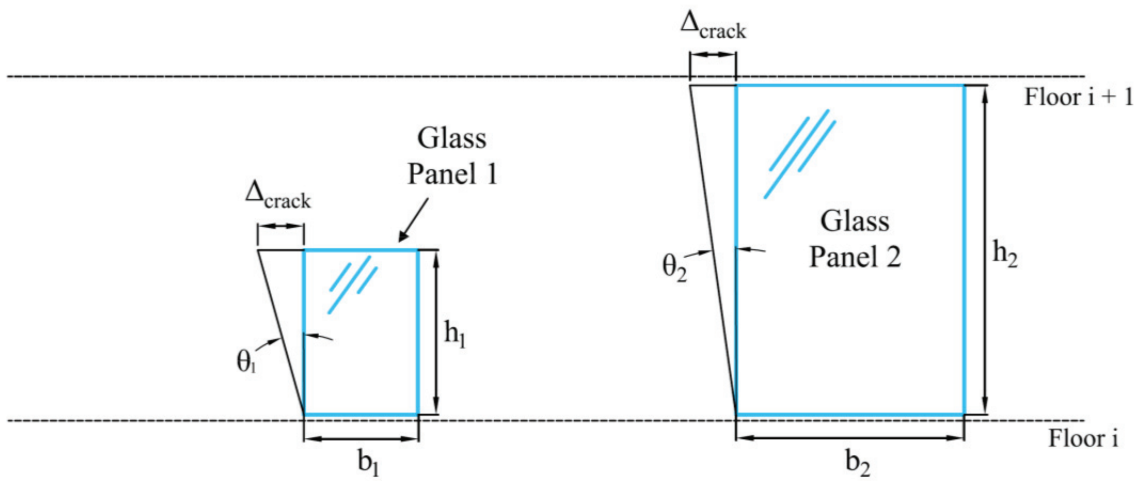
Table 13: Summary of fragility parameters from above example.

Configuration	***Cracking***		***Fallout***	
	ϴ	β	ϴ	β
IGU (3)	0.0351	0.297	0.0372	0.284
AN Mono – Aspect Ratio 1:2	0.0220	0.277	0.0257	0.271
Custom	*0.0278*	*0.414*	*0.0318*	*0.385*

8.5 Glass Panel Dimensions

Two hypothetical glass panels with similar system configuration details including aspect ratios but different panel dimensions will have the same seismic failure capacities in terms of drift (Δ), but different failure capacities in terms of drift ratio (θ). This condition exists because the glass-to-frame clearance and aspect ratio determines the drift (Δ) that a glass panel can withstand before experiencing failure. While varying glazing details such as glass type alters the damage capacity as well, two panels which both have the same glazing characteristics like the examples given previously will have their drift capacity altered to the same degree. Consequently, in this scenario both glass panels will have the same capacity in terms of drift, a condition that is supported by the ASCE equation that would predict the same failure drift ($\Delta_{failure}$) for the two panels. However, when this drift capacity is translated into interstory drift ratio, the glass panel that has a smaller height will have a greater drift ratio capacity than the panel with a greater height. This is because the failure drift for smaller glass panel is equivalent to the failure drift of the larger glass panel, but is divided by a height that is smaller when it is translated into drift ratio.

This condition is illustrated in the following example. Consider glass panel (1) and glass panel (2), as shown in Figure 83**.** It is assumed that the two glass panels are mid-rise CW systems with comparable Kawneer 1600™ framing, have an AN-Mono glass configuration, a 6:5 glass aspect ratio, and a glass-to-frame clearance of x in. ($x \cdot 25.4$ mm). Also, it is assumed that the height (h_1) and width (b_1) dimensions of glass panel (1) is less than the height (h_2) and width (b_2) of glass panel (2).



Clearance:	x	x
Glass Type:	AN	AN
Configuration Type:	Mono	Mono
Aspect Ratio:	6:5	6:5
System:	CW	CW

Figure 83: Characteristics assumed for glass panel (1) and glass panel (2).

The following definitions and relationships between the glass panels are known, where (1) is defined from Equation 10 and (2) is derived from the information given in Figure 83:

(1) $Drift\ Ratio = \theta = \frac{\delta}{h}$ (2) $\frac{h_1}{b_1} = \frac{h_2}{b_2} = 1.2$

To determine the cracking drift ratio capacity (θ_{crack}) of either glass panel, the cracking capacity in terms of drift (Δ_{crack}) is first found through the use of the code ASCE 7-05 equation (ASCE 2006).

With this information, the following can be calculated:

$$\Delta^1_{crack} = 2x\left(1 + \frac{6x}{5x}\right) = 4.4x$$
$$\Delta^2_{crack} = 2x\left(1 + \frac{6x}{5x}\right) = 4.4x$$

$\therefore\ \Delta^1_{crack} = \Delta^2_{crack} = 4.4x$

With the ASCE equation, it is determined that glass panel (1) and glass panel (2) both have equal predicted cracking drift capacities. To find the cracking capacity of either panel in terms of drift ratio, the drift ratio definition (see known (1)) is applied such that:

$\theta^1_{crack} = \frac{\Delta^1_{crack}}{h_1} = \frac{4.4x}{h_1}$ $\theta^2_{crack} = \frac{\Delta^2_{crack}}{h_2} = \frac{4.4x}{h_2}$

Since it is known that:

$$h_1 < h_2$$

It can be concluded:

$$\therefore \; \theta^1_{crack} > \theta^2_{crack}$$

Given that the dimensions of a glass panel have an effect on its drift ratio capacity, it can then be concluded that the fragilities only reflect the capacity of glass panels that have similar dimensions as the glass configurations each function represents. If a user's glass panel has dimensions different from those of the glass panel from which a fragility function was developed, the fragility needs to be modified to reflect the increase or decrease in drift ratio capacity that the user panel has. As a result, a method has been created so a user can modify the drift ratio values of a fragility curve to reflect the capacity of a glass panel that has dimensions different from those listed in Appendix A. It should be noted that while this method applies to glass panels that have different dimensions, the aspect ratio of the user glass panel is assumed to be equivalent to the glass panel of a developed fragility. If the aspect ratio varies, then further fragility adjustments will be needed as detailed in Section 6.4.

The method for modifying a fragility in this scenario is straight-forward; a user multiplies the median value of demand (θ) of the parameter of the fragility by a calculated modification factor (r) to create a new median demand value for the users modified fragility. For the derivation of the r factor, consider two glass panels depicted in Figure 84, a user glass panel (x) and a similar glass panel (*exp.*), which could be any given glass configuration that was experimentally studied. It is assumed that both glass configurations have similar framing, glass configuration and glass types, the same aspect ratio, and the same glass-to-frame clearance. Furthermore, it is assumed glass panel (x) has a height (h_x) and width (b_x) that is not similar to the height (h_{exp}) and width (b_{exp}) of the experimental glass panel.

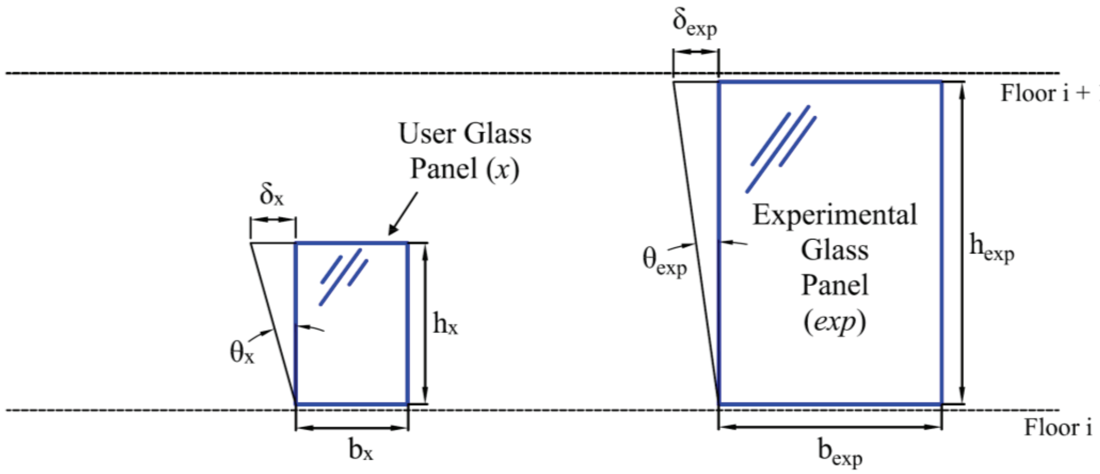


Figure 84: Characteristics of the user glass panel (*x*) and considered experimental glass panel (*exp*).

To start the analysis, the following relationships are known where (a) and (b) are derived from the given information, and (c) is known from the previous analysis (see Figure 42) since the two panels have similar clearances, aspect ratios, and all other glazing characteristics besides similar glass dimensions.

$$(a)\quad h_x \neq h_{exp}\ ;(b)\quad \frac{h_x}{b_x} = \frac{h_{exp}}{b_{exp}}\quad ;\ (c)\quad \Delta_{failure}^{capacity} = \delta_x = \delta_{exp}$$

where for known (c) $\Delta_{failure}$ denotes the drift causing failure, δ_x the failure drift of a given user glass panel *x*, and δ_{exp} the failure drift of an experimentally tested glass specimen.

Then, the drift ratio capacity (θ) for each glass panel can be defined:

$$\theta_x = \frac{\delta_x}{h_x} = \frac{\Delta_{failure}^{capacity}}{h_x}$$

$$\theta_{exp} = \frac{\delta_{exp}}{h_{exp}} = \frac{\Delta_{failure}^{capacity}}{h_{exp}}$$

Now it is desired to relate θ_x and θ_{exp}. With the use of known (a), the following can be stated:

$$\theta_x \neq \theta_{exp}$$

Then, let us define the relationship for the heights of the glass panels with the following Equation (11).

$$r = \frac{h_{exp}}{h_x} \tag{11}$$

where *r* denotes a ratio value relating the heights of a user panel (*x*) and an experimental panel (*exp*), and the variables h_x and h_{exp} were defined previously.

Next, rearranging Equation (11) we have:

$$h_x = \frac{h_{exp}}{r}$$

and,

$$\theta_x = \frac{\delta_x}{h_x} = \frac{\Delta_{failure}^{capacity}}{\frac{h_{exp}}{r}} = \left(\frac{\Delta_{failure}^{capacity}}{h_{exp}}\right) \cdot r = \theta_{exp} \cdot r$$

Therefore, it is derived that:

$$\therefore \quad \theta_x = \theta_{exp} \cdot r$$

With the *r* factor derived, it can be redefined for general use. To modify a fragility function so that the predicted performance of a given glass panel is altered to account for different glass dimensions, the *r* factor needs to be applied to the median value of demand (θ) fragility parameter. This process is defined in Equation (12), which will be utilized by a user to modify the median value of demand:

$$\theta_i = \theta_j \cdot r \tag{12}$$

In Equation (12), θ_i denotes the user panel's median value of demand, θ_j denotes the median value of demand fragility parameter of the curve to be modified, and *r* denotes the modification factor as seen in Equation (13):

$$r = \frac{h_j}{h_i} \tag{13}$$

where h_j denotes the height of the glass panel that a fragility was derived from and h_i denotes the user glass panel's height. With the newly derived median value of demand θ from Equation (12), a user can develop a new fragility function through the use of the Performance Assessment Calculation Tool (PACT) assuming the dispersion value β has not changed. The *Guidelines for Seismic Performance Assessment of Buildings* (ATC 2005) details how a user can input a new fragility function into the PACT software.

As an example of the practical application of this fragility modification, assume that a user has a glass panel 8 ft high by 6.7 ft wide (2.4 m x 2.0 m) and desires a cracking failure state fragility function for a building analysis. The glass system consists of a 0.25 in. (6 mm) AN-Mono glass panel, has a 0.43 in. (11 mm) glass-to-frame clearance, is dry-glazed, and has comparable mid-rise CW Kawneer 1600™ framing. Essentially, it has the same glazing characteristics as glass configuration (1) analyzed in this report, except that the glass dimensions are different (but the 6:5 aspect ratio is the same). To modify the fragility of glass configuration (1) to determine a new user fragility parameter θ, Equations (12) and (13) are used as follows:

$$r = \frac{6\,ft}{8\,ft} = 0.75$$

$$\theta_i = \theta_j \cdot r = (0.0138)(0.75) = 0.0104$$

The newly determined user median value of demand and original dispersion value can then be input into the PACT software to develop a fragility curve for the user glass panel, which will reflect the drift ratio capacity for the 8 ft high by 6.7 ft wide (2.4 m x 2.0 m) glass panel.

8.6 Comparing Factors Affecting Seismic Performance

Based on existing test results, the importance of the factors affecting the seismic performance of a glass configuration can be relatively compared. The factors include the framing system, overall size of CW system, glazing size, glass-to-frame clearance, and the aspect ratio. Based on a scale of low to high, where a rating of "high" represents that a factor has the most effect on the seismic capacity and a rating of "low" represents a small effect, a relative comparison is presented in Table 14. Full-scale experimental research is needed to refine or quantify the factors. For now, it is suggested that the designers note the importance of all factors impacting the performance of a CW or SF configuration through the designing process.

Table 14: Factor Importance Comparison.

Factor	Rating
Framing System	**Low**
Curtain Wall Overall Size	**Low**
Glazing Size	**Moderate**
Glass-to-Frame Clearance	**High**
Aspect Ratio	**High**

8.7 Stick Built Vs. Unitized Curtain Wall Systems

As discussed earlier, most of the CW configurations discussed represent stick-built CW systems. This type of CW is prevalent on most buildings, but unitized CW systems are now being employed on larger, more recent building construction projects. Figure 85 shows the two different types of configurations. The fragilities reported in this document for stick-built cannot be applied to unitized curtain walls.

(a)

(b)

Figure 85: (a) Picture showing the installment of a unitized CW system (www.sierraglass.com) and (b) picture showing the construction of the framing for a stick-built CW system (www.livemodern.com).

While only a small amount of unitized system testing has been performed, initial results indicate that it is unlikely for glass damage to occur during racking. Due to the nature of unitized systems, the framing members that are "snapped" together allow for movement. The En-Wall system that was tested allowed the unitized panels to slide past one another, transferring very little load to the glass panels. End boundaries were also installed to attempt to minimize the framing system's ability to freely slide and to attempt to create a realistic boundary condition like that found at the corner of a building. Tests that utilized these boundary conditions showed that the framing of a given panel can dislodge from surrounding panels, creating a potentially dangerous situation as a fully intact panel may release from the building and fall.

9. Pricing

The "Required Results Template" and "Optional Summary Supporting Information Templates" have been attached to the end of this report. For these tables, a mini survey has been conducted to determine the current pricing for curtain walls that are required by the templates. Also, the repair durations have been considered in the survey as well.

For the survey, phone conversations were held with various glass installers in the Los Angeles and San Francisco markets. These installers represent a wide array of projects, from private to public and small to large. During the phone conversations, a series of questions were asked, aiming to get an idea of how the estimators determine a cost for a glazing project. An overview of the questions that were asked can be found in Section 10.7. Also, general prices were obtained for cost per square foot for CW configurations relevant to this report. The prices obtained from the survey were then organized, and when determining the final cost per square foot for the glass configurations each of the individual cost estimates were given equal weight.

Based on the glass type and damage state, different percentages of new installation costs were reported for the repair costs. For annealed glass, one half of the new installation costs were reported for cracking and fallout damage states because annealed glass generally damages aluminum framing to a lesser degree during failure than all of the other CW configurations with different glass types. In general, a laminated IGU is a heavier glass panel than a single annealed monolithic glass lite with conventionally used thickness (e.g., ≤ 1/4 in.), and during racking displacements it will impact and damage the framing system more. If the fallout damage limit state is reached there is a greater chance of necessitating replacement of the framing.

For the glass cracking damage state for all of the laminated and IGU configurations, one half of the new installation cost was used as well. This was a result that generally when the cracking damage state is reached, the CW components besides the glass have not yet been significantly damaged, resulting in the largest repair cost being associated with replacing the glass lite. However, for the fallout damage state for all of the laminated and IGU glass configurations, the full new installation cost was used because of there being significant frame damage. All fully tempered glass systems accounted for the cost of full new installation for both cracking and fallout as these damage states occur simultaneously.

The replacement costs for dry gaskets were also collected during the survey. As with cracking and fallout damage states, the cost per square foot quoted costs were consistent. but still differed, and for the final cost values in the table the quotes were weighted equally in an averaged calculation. Generally, gasket replacement associated with the gasket failure damage state was much cheaper than the repair costs associated with the cracking and fallout damage limit state for all of the glass configurations. The costs for all of the glass configurations can be viewed in the Supplemental Tables at the end of this report.

10. Practical Application Issues

10.1 Introduction

This section presents a discussion that was developed to specifically address certain practical application issues. The topics addressed in this section include an investigation of how a professional can identify specific characteristics of a glazing system, a data lumping analysis with corresponding new fragilities, whether a glass-to-frame clearance should be made a random variable, an update of the existing fragilities from the ones presented earlier, an expanded discussion on the fallout limit state section, and ratings of data used to develop the report.

10.2 Glass System Identification

One of the requirements in using the existing fragilities developed in the report is that all of the glazing and configuration details would need to be known if the fragilities were to be applied for use in an analysis of an existing system. These details include glass system type (CW or SF), glass type (AN, HS, or FT), configuration type (monolithic, laminated, asymmetric IGU, or symmetric IGU), glass-to-frame clearance, glass panel aspect ratio, and glass thickness. However, the information on such an existing exterior architectural glass system may not be readily available, for reasons such as misplacement of the original design documents that would contain the needed information. As a result, a professional may need to investigate the glass CW or SF system to acquire the desired information. The following discussion is meant to explain the methods that can be used to obtain configuration information on existing exterior glass systems.

According to Runkle (Runkle 2008), a building forensics professional, one method that a professional may use to be able to determine glazing and configuration details is through various visual inspection techniques. The first is peering at a glass panel at different angles and distances, and searching for a "rolling wave" light reflection pattern. If this described pattern is spotted, then it can be assumed that the glass panel has received a heat treatment and is therefore most likely HS or FT. The second visual technique is locating an etched or stamped inscription in the corner region of a glass panel. This stamp will give the standard to which a glass panel was tempered to. These stamps will be present on FT glass types because of ANSI, SGCC, and CPSC labeling requirements, and may be present on laminated glass panels. Thirdly, a professional will generally be able to determine from visual inspection the configuration type of a glass panel. Specifically, an inspection will determine whether a glass panel is an IGU versus other glass configuration types (monolithic or laminated unit). Although, it would be difficult to determine if an IGU configuration was an asymmetric or symmetric unit with only a brief visual inspection. Symmetric IGU's are characterized by a similar inner and outer pane, while asymmetric IGU's are composed of an interior monolithic panel and an exterior laminated pane. Finally, a professional can roughly estimate the aspect ratio of a glass panel through visual inspection.

A second method a professional can use to determine glazing and configuration details is through the use of different instruments available. There are non-destructive gauges that will give the glass thickness, coatings present, lamination present, and for an IGU the gas fill and space dimension between glass panels. Furthermore, a laser instrument is available that will determine the residual strength of a glass panel. The Grazing Angle Surface Polarimeter (GASP®) is a commonly used portable laser instrument (see Figure 86) which measures the residual stress of treated glass panels in a nondestructive manner. (Feingold 2008)

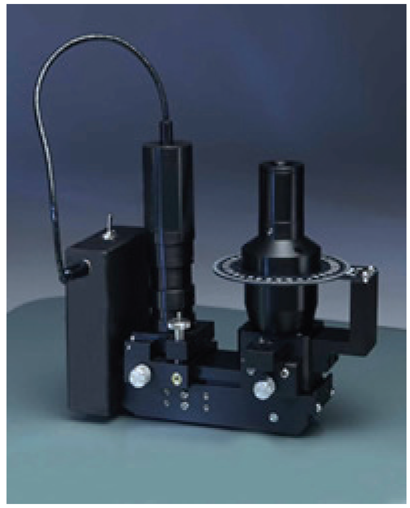


Figure 86: The Grazing Angle Surface Polarimeter (GASP®) (Feingold 2008).

The above methods are ways that professionals can determine the details of a glass system nondestructively. Unfortunately, none of the nondestructive techniques can find the glass-to-frame clearance of a glass configuration. To determine this information, the gaskets will need to be removed and a rough estimate can be taken with a measuring device. Also, if a rubber spacer can be removed, sometimes information on the spacer can be gathered that includes whether the glass was replaced, the date of manufacture, and the company that produced the glass panel.

10.3 Data Lump and Analysis

A new analysis was conducted to group the data of certain glass configurations together based on the amount of information that is available as a result of the possibility that certain glazing and configurations details of an exterior glass CW or SF system may not be known. Note that Records from the commissioning of a building will contain the information on the glass systems used throughout a building, and should be sought after if it is desired to determine the glass and framing details for the purpose of a PBSD analysis. However, the records may be unattainable or take awhile to acquire. Furthermore, the glass and framing will vary across the façade of a building where certain areas may not be easily accessible for an inspection. Therefore, the data from the configurations presented earlier in the report were lumped together to various degrees and followed with a fragility analysis to make fragilities available for users as a function of the amount of glass configuration information known.

The data will be lumped to varying degrees according to levels defined in Table 15, where the data will be kept separated for CW and SF configurations. Table 15 is offered as a way to infer the guidance to how the different data groupings represented by levels will be created. In the table, Level 1 is considered the option for a user that has the least amount of information known for a glass system, and from there the levels increase incrementally to Level 4, which is the option that represents the fragilities presented earlier in the report where all CW or SF system information is known.

The levels were determined based on the availability of glass system information. For the most part, any given glazing detail (such as glass-to-frame clearance) is assumed to be either known or unknown to a user. However, for glass configuration type it is assumed that with a simple visual inspection, a professional will be able to determine whether a glass panel is an IGU or not. From this point, if the configuration is identified as IGU, it may not be known whether it is a symmetric or asymmetric unit. Otherwise, if the configuration is determined to not be an IGU, from this point it may not be known whether the panel is a monolithic or Lami unit. For a given level in the table, the configuration information that is unknown to the user is highlighted in yellow (lighter shade in black and white print). If partial information is known for a parameter, such as for glass configuration type, then the area in the table is highlighted orange (darker shade in black and white print). The following assumptions were made in developing different levels:

General:

- A professional will be able to distinguish between a CW and SF system. Therefore, the data for these systems will be kept separate.

Level 1:

- Only the aspect ratio is known
- A professional will be able to indentify an IGU from other configuration types (with simple visual observation). However, a user will not know whether an IGU is symmetric or asymmetric, or whether a configuration is monolithic or laminated if the glass panel is deemed not to be an IGU.

Level 2:

- The aspect ratio and glass type is known
- A professional will be able to indentify an IGU from other configuration types (with simple visual observation). However, a user will not know whether an IGU is symmetric or asymmetric, or whether a configuration is monolithic or laminated if the glass panel is deemed not to be an IGU

Level 3:

- The glass configuration, type, aspect ratio, and thickness are known, while only the glass-to-frame clearance is unknown.

Level 4:

- All glass configuration information is known

Table 15: Matrix that guides the different data groupings according to four levels which is based on the types of information known to users on a glass system.

	System (CW/SF)	**Configuration** (Mono, IGU, Lami)	**Type** (AN)	**Clearance**	**Aspect Ratio**	**Thickness**
Level 1	CW or SF	*IGU (asymmetric or symmetric)*	*unknown*	*unknown*	known	*unknown*
	CW or SF	*Mono or Lam*	*unknown*	*unknown*	known	*unknown*
Level 2	CW or SF	*IGU (asymmetric or symmetric)*	AN	*unknown*	known	*unknown*
	CW or SF	*Mono or Lam*	AN	*unknown*	known	*unknown*
Level 3	CW or SF	known	AN	*unknown*	known	known
Level 4	CW or SF	known	AN	known	known	known

All of the fragilities presented earlier in the report are considered as Level 4 characterization. With Table 15 as a guide, the configurations were inputted into the different levels, and sublevels were created within the context of each level based on the known and unknown information characterizations. A sublevel is defined as a specific grouping of different glass configurations and the subsequent data conforming to the limitations in Table 15 that a new fragility function is based on. Higher levels (such as Level 3) will have more sublevels than lower levels (such as Level 2), because sublevels are created when the information for a glazing detail is assumed to be *known* for a user. For example, for Level 3 it is assumed that a user knows the configuration type of a glass system, which means that the glass configurations are grouped based on whether the glass panel of a configuration is a Mono, sym. IGU, asym. IGU, or Lami configuration type, thus creating four separate sublevels for this one glazing parameter.

The result of this further breakdown is seen in Table 16 (CW) and Table 17 (SF), which specify the applicable configurations for each grouping and known glass system information. These tables only include configurations 1-31 and do not include the manufactured systems. If more than one glass configuration applies to a sublevel, then a new fragility function will be developed for the grouping of data from all applicable glass configurations. Otherwise, if only one or no glass configurations researched is applicable to a particular sublevel, then no further fragility analysis was performed for that sublevel.

This scenario is illustrated by Sublevel 3-b, where only glass configuration (6) has characteristics that fit the glazing detail limitations of the sublevel, and where it would be unnecessary to perform a fragility analysis on the data for one glass configuration if this analysis was already executed earlier in the report.

Table 16: Expanded matrix which specifies configurations applicable to each level for the grouping analysis with known information given for CW systems.

		Applicable Configs.:	**System** (CW, SF, US)	**Configuration** (Mono, IGU, lam)	**Type** (AN, HS, FT)	**Clearance**	**Aspect Ratio**	**Thickness**
Level 1	**a**	2, 3, 4, 5, 8, 13, 22, 23, 30, 31	CW	*IGU (asymmetric or symmetric)*	*unknown*	*unknown*	6:5	*unknown*
	b-1	1, 6, 10, 11, 12, 16, 17, 18, 19, 20, 21, 24, 25, 26, 27	CW	*Mono or Lam*	*unknown*	*unknown*	6:5	*unknown*
	b-2	14, 28	CW	*Mono or Lam*	*unknown*	*unknown*	2:1	*unknown*
	b-3	15, 29	CW	*Mono or Lam*	*unknown*	*unknown*	1:2	*unknown*
Level 2	**a-1**	2, 3, 4, 5, 13,22, 23	CW	*IGU (asymmetric or symmetric)*	AN	*unknown*	6:5	*unknown*
	a-2	30	CW	*IGU (asymmetric or symmetric)*	HS	*unknown*	6:5	*unknown*
	a-3	31	CW	*IGU (asymmetric or symmetric)*	FT	*unknown*	6:5	*unknown*
	b-1	1, 6, 10, 11, 12, 16, 17, 20, 21, 27	CW	*Mono or Lam*	AN	*unknown*	6:5	*unknown*
	b-2	18, 19, 25, 26	CW	*Mono or Lam*	FT	*unknown*	6:5	*unknown*
	b-3	24	CW	*Mono or Lam*	HS	*unknown*	6:5	*unknown*
	c	14, 28	CW	*Mono or Lam*	AN	*unknown*	2:1	*unknown*
	d	15, 29	CW	*Mono or Lam*	AN	*unknown*	1:2	*unknown*
Level 3	**a-1**	1,10, 11, 12, 16, 17, 27	CW	Monolithic	AN	*unknown*	6:5	1/4 in.

	a-2	18, 19, 25, 26	CW	Monolithic	FT	*unknown*	6:5	1/4 in.
	a-3	24	CW	Monolithic	HS	*unknown*	6:5	1/4 in.
	b	14, 28	CW	Monolithic	AN	*unknown*	2:1	1/4 in.
	c	15, 29	CW	Monolithic	AN	*unknown*	1:2	1/4 in.
	d	6, 20, 21	CW	Laminated	AN	*unknown*	6:5	1/4 in.
	e-1	3, 4	CW	IGU (symmetric)	AN	*unknown*	6:5	1 in. (1/4 in. inner and outer)
	e-2	5	CW	IGU (asymmetric)	AN	*unknown*	6:5	1-1/4 in. (1/4 in. AN inner and 1/2 in. AN LAM outer)
	f-1	2, 13, 22, 23	CW	IGU (symmetric)	AN	*unknown*	6:5	1 in. (1/4 in. inner and outer)
	f-2	30	CW	IGU (symmetric)	HS	*unknown*	6:5	1 in. (1/4 in. inner and outer)
	f-3	31	CW	IGU (symmetric)	FT	*unknown*	6:5	1 in. (1/4 in. inner and outer)
Level 4		See main report	CW	known	known	known	known	known

Table 17: Expanded matrix which specifies configurations applicable to each level for the grouping analysis with known information given for SF systems.

		Applicable Configs.:	**System** (CW,SF)	**Configuration** (Mono, IGU, lam)	**Type** (AN, HS, FT)	**Clearance**	**Aspect Ratio**	**Thickness**
Level 1	**a**	8	SF	*IGU (asymmetric or symmetric)*	*unknown*	*unknown*	6:5	*unknown*
	b	7, 9	SF	*Mono or Lam*	*unknown*	*unknown*	6:5	*unknown*
Level 2	**a**	8	SF	*IGU (asymmetric or symmetric)*	AN	*unknown*	6:5	*unknown*
	b	7, 9	SF	*Mono or Lam*	AN	*unknown*	6:5	*unknown*
Level 3	**a**	7	SF	Monolithic	AN	*unknown*	6:5	1/4 in.

	b	9	SF	Laminated	AN	*unknown*	6:5	1/4 in.
	c	8	SF	IGU – symmetric	AN	*unknown*	6:5	1 in. (1/4 in. inner and outer)
Level 4		See main report	SF	known	AN	known	known	known

The results of the data lumping can be seen in Appendix F, where software outputs available for the cracking and fallout limit states were developed based on the data from applicable glass configurations for each grouping indentified according to sublevels. For the analysis, the software *Fragility Function Calculator version 1.02* was used to calculate the values of the fragility parameters. For the demand input, the failure data available from all applicable glass configurations for a particular sublevel was included in the fragility analysis. The failure values input into each fragility analysis for all sublevels can be reviewed in Appendix F, where snapshots of the input screen for the fragility calculator are presented. Currently, the *Fragility Function Calculator version 1.02* (i.e. 2007-2008 version) software was used to create the data lumpings. The calculated fragility parameters were checked with manual calculations, and found to be accurate.

10.4 Glass-to-frame Clearance Random Value

In development of this report, it was assumed earlier that the glass-to-frame clearance is known. However, it is also of interest to assume the glass-to-frame clearance variable to be a random variable. It should be noted that on many existing glass systems on buildings, the glass-to-frame clearance may not be known to the professional. Therefore, if the glass-to-frame clearance was made random, then this piece of information could be disregarded by the professional as a parameter for a value which needs to be collected and used in an analysis.

Ultimately, it is determined that it would not be best to make the glass-to-frame clearance a random variable for all fragilities. The data lump analysis which was performed in the previous section assumes in several sublevels in Levels 1 through 3 that the glass-to-frame clearance is not known to a user, and is in this respect treats the clearance parameter as a random value. Furthermore, the variable substandard glass-to-frame clearance experimental testing outlined in the main ATC report showed that a glass-to-frame clearance has a significant effect on the seismic capacity of glass panels. Consequently, it would be ideal to have fragilities available for users that do not assume that the glass-to-frame clearance is not random, and therefore provide an increased degree of accuracy for professionals when the glass-to-frame clearance is known for a glass system.

10.5 Fallout Damage State

Another issue that is addressed here is to elaborate on the assumption that when one-square inch of glass falls out, defined as the fallout damage limit state, it can constitute a life-safety issue. The one-square inch value was an arbitrary metric accepted by AAMA for $\Delta_{fallout}$ for the recommended AMAA 501.6 testing of glass (AAMA 2001). While an airborne one-square inch of glass may not necessarily cause death, it does create a precarious damage state to a glass panel that presents a real life safety hazard if the significantly more fallout occurs with relatively little additional force (e.g. from wind, contact from occupants, aftershocks, etc.). The one-square inch metric is primarily an issue for systems which contain AN monolithic glass. The extensive fragmentation in HS and FT glass types leads to substantially more fallout in monolithic panes or IGUs composed of monolithic panes containing those glass types.

In previous studies that developed the data used in the main report, it was only recorded if the fallout damage state was reached by a glass specimen, and therefore data on the different fallout degrees were not originally collected. For glass configurations using AN monolithic panes, fallout can occur all at once and is completely random. However, a best estimation would be that complete fallout of a glass panel in most cases generally occurs in 1/4-1/2" drift beyond the drift that causes glass fallout limit state (i.e., 1 in^2 glass fallout).

10.6 Rating of Data Used in the Main Report

The final issue important for practical application of the results developed in the report is rating the data employed. Ratings of Superior, Average, and Marginal were given to various topics in the report, which include: Data Quantity and Quality, Relevance, Quality of Reporting, and Physical Relevance. A discussion is added for each rating to elaborate justification of the rating.

I) Data Quantity: *Average*; Data Quality: *Superior*

Overall, the data used to develop the fragilities was of Superior quality, but in some cases the quantity was lacking in certain fragilities. The ratings for the fragilities for each glass configuration are given in Table 18.

Table 18: Ratings for fragilities according to glass configuration for data quantity and quality.

ID	System	Glazing Type	Glass-to-Frame Clearance	Ratings	
				Quantity	Quality
1	MR	1/4 in. (6 mm) AN monolithic	0.43 in. (11 mm)	S	S
2	MR	1 in. (25 mm) AN insulating glass unit (IGU) [1/4 in. (6 mm) inner and outer panes]	0.43 in. (11 mm)	S	S
3	MR	1/4 in. (6 mm) inner AN / 1/4 in. (6 mm) outer AN LAM (0.030 PVB) IGU	0.43 in. (11 mm)	S	S
4	MR	1/4 in. (6 mm) inner AN / 1/4 in. (6 mm) outer AN LAM (0.060 PVB) IGU	0.43 in. (11 mm)	S	S
5	MR	1/4 in. (6 mm) inner AN / 1/2 in. (13 mm) outer AN LAM (0.030 PVB) IGU	0.43 in. (11 mm)	S	S
6	MR	1/4 in. (6 mm) AN LAM (0.030 PVB)	0.43 in. (11 mm)	S	S
7	SF	1/4 in. (6 mm) AN monolithic	0.41 in. (10 mm)	S	S
8	SF	1 in. (25 mm) AN IGU	0.59 in. (15 mm)	S	S
9	SF	1/4 in. (6 mm) AN LAM (0.030 PVB)	0.41 in. (10 mm)	S	S
10	MR	1/4 in. (6 mm) AN monolithic	0 in. (0 mm)	A	S
11	MR	1/4 in. (6 mm) AN monolithic	0.13 in. (3 mm)	A	S
12	MR	1/4 in. (6 mm) AN monolithic	0.25 in. (6 mm)	A	S
13	MR	1 in. (25 mm) AN IGU [1/4 in. (6 mm) inner and outer panes]	0.25 in. (6 mm)	M	S
14	MR	1/4 in. (6 mm) AN monolithic (2:1 aspect)	0.43 in. (11 mm)	A	S
15	MR	1/4 in. (6 mm) AN monolithic (1:2 aspect)	0.43 in. (11 mm)	A	S
16	MR	1/4 in. (6 mm) AN monolithic (6:5 aspect)	0.43 in. (11 mm)	A	S
17	MR	1/4 in. (6 mm) AN monolithic (6:5 aspect)	0.43 in. (11 mm)	S	S
18	MR	1/4 in. (6 mm) FT monolithic (6:5 aspect)	0.43 in. (11 mm)	A	S
19	MR	1/4 in. (6 mm) FT monolithic (6:5 aspect)	0.43 in. (11 mm)	S	S
20	MR	1/4 in. (6 mm) AN laminated (6:5 aspect)	0.43 in. (11 mm)	A	S
21	MR	1/4 in. (6 mm) AN laminated (6:5 aspect)	0.43 in. (11 mm)	S	S
22	MR	1 in. (25 mm) AN IGU (6:5 aspect)	0.43 in. (11 mm)	A	S
23	MR	1 in. (25 mm) AN IGU (6:5 aspect)	0.43 in. (11 mm)	S	S
24	MR	1/4 in. (6 mm) HS monolithic (6:5 aspect)	0.43 in. (11 mm)	S	S
25	MR	1/4 in. (6 mm) FT monolithic (6:5 aspect)	0.43 in. (11 mm)	S	S
26	MR	1/4 in. (6 mm) FT monolithic (6:5 aspect)	0.43 in. (11 mm)	A	S
27	MR	1/4 in. (6 mm) AN monolithic (6:5 aspect)	0.43 in. (11 mm)	S	S
28	MR	1/4 in. (6 mm) AN monolithic (2:1 aspect)	0.43 in. (11 mm)	A	S
29	MR	1/4 in. (6 mm) AN monolithic (1:2 aspect)	0.43 in. (11 mm)	A	S
30	MR	1 in. (25 mm) HS IGU (6:5 aspect)	0.43 in. (11 mm)	S	S
31	MR	1 in. (25 mm) FT IGU (6:5 aspect)	0.43 in. (11 mm)	S	S
32	US	1-1/4 in. (32 mm) FT IGU	0.43 in. (11 mm)	S	S
33	SF	1 in. (25 mm) FT IGU (1.9:1 aspect)	0.43 in. (11 mm)	A	S
34	SF	1 in. (25 mm) FT IGU (1.9:1 aspect)	0.43 in. (11 mm)	A	S
35	SF	1 in. (25 mm) FT IGU (1.9:1 aspect)	0.43 in. (11 mm)	A	S
36	SF	1 in. (25 mm) FT IGU (2.8:1 aspect)	0.43 in. (11 mm)	A	S
37	SF	1 in. (25 mm) FT IGU (1.9:1 aspect)	0.43 in. (11 mm)	A	S

38	SF	1 in. (25 mm) FT IGU (1.9:1 aspect)	0.43 in. (11 mm)	A	S
39	SF	1 in. (25 mm) FT IGU (1.9:1 aspect)	0.43 in. (11 mm)	A	S
40	SF	1 in. (25 mm) FT IGU (2.8:1 aspect)	0.43 in. (11 mm)	A	S
41	SF	3/8 in. (10 mm) FT monolithic (1.9:1 aspect)	0.5 in. (13 mm)	A	S
42	SF	3/8 in. (10 mm) FT monolithic (1.9:1 aspect)	0.5 in. (13 mm)	A	S
43	SF	3/8 in. (10 mm) FT monolithic (1.9:1 aspect)	0.5 in. (13 mm)	A	S
44	SF	3/8 in. (10 mm) FT monolithic (2.7:1 aspect)	0.5 in. (13 mm)	A	S

All of the glass configurations received a Superior data quality rating. Besides the experimental testing being consistent among the different studies over time, additionally several data adjustment analyses were performed to ensure the conservatism in the data. These data adjustments included the correction for flexibility in the racking facility, the data check for the initial cracking and crushing limit state definition, and the data check for failure during the "constant" interval portion of the loading steps.

As for data quantity, most configurations received a Superior rating. However, due to testing limitations some configurations had fewer specimens tested. If a glass configuration had between two to three specimens tested, then it received an Average data quality rating. Glass configuration (13) received a Marginal data quantity rating because there was only one specimen of its type tested.

II) Relevance: *Average*

The relevance was given an Average rating, mainly because for experimental testing only one of the possible mounting configurations for mid-rise CW and SF systems were used. As discussed earlier in the report, the vertical mullions of the CW systems were attached to pi-shaped steel anchors welded and bolted onto the steel tubes of the racking facility. This connection detailing results in a rigid connection situation, which is considered conservative because no rotation occurs during testing. However, semi-rigid connections on actual buildings will result in additional seismic capacity to the glass systems to a magnitude which is unknown. Therefore, this potential response behavior was not present in the testing, and as a result the relevance received an Average rating.

III) Quality of Reporting: *Superior*

The original ATC report provides in-depth discussions pertaining to data compilation, analysis, and application.

IV) Physical Relevance: *Not Rated*

This topic has not been rated because it is not proven whether the fragility curves will accurately model architectural glass seismic responses on actual buildings. Earthquake reconnaissance for CW and SF glass is limited, but resources such as the "Initial Survey and Audit of Glass and Glazing System Performance During the Earthquake in the Los Angeles Area on January 17, 1994" by William Lingnell and various EERI reports do exist.

10.7 Results of a Survey on Glazing Details, Practices, and Reasons for Glass Breakage in Earthquakes

To reflect the views of curtain wall installers and designers on reasons for glass damage as a result of earthquakes, a survey was conducted. A questionnaire was prepared and sent to a selected list of glazing professionals in several states, but mainly in California and Nevada in order to benefit from the experience of professionals who deal with design, installation, and repair of glazing system mostly in high seismic areas. Phone contacts were initially made to 205 companies. 96 companies expressed willingness to participate, and the questionnaire was sent to them through e-mail. However, only 15 companies responded within reasonable time frame. The questionnaire sent had three parts, each with several questions. The questions are listed below and the responses to the questions are summarized, showing the percentage of respondents giving the answers shown.

Part I

I.1 - What kind of work do you do involving glazing systems? (e.g., Installer, Designer, Manufacturer, Other?)

Installers	85.7%
Manufacturer/Fabricator	50.0%
Estimator	28.6%
Designer	28.6%

I.2 - What types of glazing systems have you worked with before? (e.g., Storefronts, Curtain Walls, Old Construction, Other?)

Storefronts	92.9%
Curtain Walls	100.0%
Old Construction	50.0%
Other (Sky Lights, Doors, Mirrors, etc.)	92.9%

Part II

Storefronts

II.1 - What are the most common frame types (e.g., wood, steel, aluminum, stick built, unitized, etc.) used in storefront systems?

Aluminum	92.9%
Aluminum and Steel	7.1%
Stick-built	21.4%
Unitized	7.1%

Curtain Walls

II.2 - What are the most common frame types used in curtain wall systems?

Aluminum	71.4
Aluminum and Steel	21.4%
Stick-built	7.1%
Unitized	14.3%
Pressure Bar	14.3%

Old Construction

II.3 - Based on your experience with existing buildings, what percentage of window/storefront/curtain wall systems have glass held in the framing with soft or hard putty?

14.5%

II.4 - Based on your experience, please give an estimate of the percentages of different frame types (e.g. wood, steel, aluminum, stick built, unitized, etc.) in existing buildings.

Wood	11.4%
Steel	6.2%
Aluminum	78.5%

II.5 - What sort of glass-to-frame clearances have been used typically in these different framed systems of older construction? Please round to nearest 1/8 in. and specify the type of glazing system and the material of the framing.

1/8	21.4%
1/4	78.6%

3/8	21.4%
1/2	21.4%
5/8	28.6%
3/4	14.3%

Part III

III.1 - What glass-to-frame clearance is generally specified today for new construction? (Please round to nearest 1/8 in.)

1/8	14.3%
1/4	28.6%
3/8	28.6%
1/2	28.6%
5/8	14.3%
3/4	14.3%
1	7.1%

III.2 - On a scale of 1 to 5 (1 being least, 5 being most), how accurately and carefully are the specified clearances actually delivered in the field?

4.25

III.3 - Assuming that specified clearances are not accurately delivered during construction, what actual clearances are typically out there in newer buildings? Please give a rough percentage (e.g., “15% actually have at least the specified 1/8 in. clearance”)

No uniform response, many refrained from responding, some responded vaguely

III.4 - Are glazing panel side blocks typically used in the field? If yes, how many? Where? (e.g. “mid-height,” “corner,” etc.)

YES		42.9%
	1	7.1%
	4	28.6%
	6	7.1%
NO		57.1%

III.5 - Are sill area setting blocks always used in the field? If yes, how many? Where? (e.g., “quarter points,” “third points,” etc.)

YES 92.9%

2 at minimum, number increases if panel is large,

Generally, at 1/4 points, minor variation on location

III.6 - Some field observations show that larger glass panels have a greater chance of failure in earthquakes. Would you agree with this? If so, why so you think larger glass panels can break more easily than smaller panels?

Agree	92.9%
Disagree	7.14%

III.7 - Some field observations show that placing glass panels together at a corner without capturing the glass edges in a corner frame increases the possibility of earthquake-induced glass failure. Would you agree with this? If so, why do you think this would happen?

Agree	42.9%
Disagree	14.3%
Mixed	42.9%

Based on the results of the survey, the following conclusions can be suggested with regard to glazing details in existing systems and possible reasons for damage during earthquakes:

- The most common glazing frame type is aluminum.
- In about 15% of existing glazing systems glass is held with soft or hard putty.
- While most clearances are over 1/4 in., in at least 21% of the existing buildings and 14% of the new buildings, the clearance is 1/8 in.
- On a scale of 1-5, on average the respondents chose 4.25 to indicate great care and accuracy being exercised in installation to provide the specified clearances.
- 57% of the respondents say that side blocks are not used.
- About 93% of the respondents say that setting blocks are used.
- About 93% of respondents agree that glass panels have a greater chance of failure in earthquakes. As for reasons, below are some of the respondents' explanations:
    - The taller the glass lite, the less movement is required to come into contact with the glazing frame pocket that causes the breakage.
    - When heavier glass shifts, there is greater chance of breakage.
    - Larger panels will have larger deflection and flex more. Smaller pieces do not flex as much and are less likely to break.
    - Thickness is a factor as well as less support at the bottom of larger panels near center.
    - Larger glass pieces are more susceptible to movement.
- While about 43% agree that lack of use of corner mullion increases the chances of glass failure, the same percentage also had mixed responses. Below are some of the responses.
    - In most application the silicone that is used often used to seal the joint provides a cushion if properly installed. In cases where the glass may experience larger movement, depending on the opening size, breakage may be more.

- Silicone at corner locks the joints together. A system with all silicone joint is better than a framed system.
- Glass to glass contact is not good.
- Damage occurs since the joint is not captured and panels can move.
- In such cases with butt joint, glass is usually tempered.
- Due to seismic induced movement, glass panel can shift and hit the side of the (perpendicular) glass and cause it to break.
- The caulk joint at corner acts as a setting block. Should provide at least ¼" gap, preferably 3/8" to allow for the movement.
- Glass edge within a frame allows for movement, but glass edge against glass without much room for movement causes breakage.

Besides answering the specific questions, the respondents were asked to add any other comments with regard to minimizing glass damage in earthquakes. Below are some of the comments.

- Use of setting blocks or anti-walk blocks effectively prevents glass breakage.
- Use of polycarbonate sheets instead of glass eliminates the glass damage issue.
- Use of laminated glass is desirable.
- Glass performance also depends on the construction of the building itself.
- If the structure is not built stiff enough, the glazing frame will be affected more seriously.
- Larger glass-to-frame clearances in the pockets help prevent glass damage.

11. Summary and Conclusions

In this report, fragility functions were developed to support the prediction of probable earthquake performance of glazing systems within the context of seismic performance assessment of buildings as part of a Performance-Based Design (PBD) approach. This report was developed for the Applied Technology Council (ATC) for the ongoing ATC-58 project to develop next-generation performance-based seismic design criteria. The development of the fragility functions and accompanying modification procedures have provided the means to evaluate the response of curtain wall (CW) and storefront (SF) wall systems to earthquake-induced movements in terms of the probability of damage, the amount of damage, and the consequences of such damage.

In all, probabilistic fragility functions were developed for forty-four different glass configurations as listed in Table 1. The defined damage states included gasket degradation, initial cracking and crushing, and glass fallout as well as frame dislodging for the unitized curtain wall system (Configuration 32). Data was provided by past studies (Behr 1996, Behr 1998, and Memari et al. 2003) and new experimental testing that was performed on glass configuration with varying glass-to-frame clearances.

The fragility functions can be directly used if a glass system has the same glazing details and characteristics that the fragility represents. These details include glass-to-frame clearance, system type, configuration type, glass type, glass panel dimensions, glazing type, and a comparable framing system. If not, then procedures are offered to modify the fragilities to account for varying glass dimensions, glass-to-frame clearances, or aspect ratio.

Section 10 of this report, which contains some additional discussion relevant to practical applications, provides information on how a glass professional can identify certain glazing characteristics on an existing exterior glass system on a building. Furthermore, the data from various glass configurations were lumped and analyzed according to various degrees to offer fragility parameters of groupings as a function of glazing information which may or may not be known to a user. The quality of certain aspects of work in this report was rated. Finally, the results of a survey conducted to reflect the views of curtain wall (glazing) professionals and installers on current practice and reasons for glass damage are presented.

From the experimental testing of glass configurations with varying glass-to-frame clearances, it is concluded that:

- As the glass-to-frame clearance of a configuration decreases, the failure capacity of the system decreases as well.

- Natural corner rounding action displayed by glass specimens during testing with the substandard clearances is credited to giving additional seismic failure capacity to those systems than what would otherwise be expected.

- If glass panels for a system are slightly oversized and lead to a glazed glass-to-frame clearance that is unknowingly lower than designed for, the seismic capacity of the system will be lower. Based on the results of some laboratory experiments, in some cases, the capacity may not be as low as originally expected. For simplicity of evaluation, clearances between 0 and 0.125 in. (3 mm) can be assumed to have a clearance of 0.125 in. (3 mm).

- Flexibilities found in the racking facility were generally determined to influence the failure of glass panels.

From the experimental testing of the manufactured storefront systems, it is concluded that:

- Primary failure modes observed during racking tests of these storefront wall system mockups are seal loss via gasket movement or sealant damage and frame damage.

- Glass damage did occur on occasion, but was not extensive.

- Repair of frame damage could be much more costly because in most instances glass panels would need to be removed and the damaged framing components replaced.

- The design of the storefront systems tested is adequate for seismic regions because damage to glass was minimal and could occur only at large drift ratios well beyond the code maximum value of 2.5%.

From the experimental testing of the manufactured unitized systems, it is concluded that:

- The horizontal stack joint is susceptible to dislodging from the lower panels under certain boundary conditions and racking displacements.

- The vertical joints are also vulnerable to some separation under some boundary condition and racking, leaving a pathway for air and water penetration.

- The design of the unitized systems tested is adequate for seismic regions because damage to glass was nonexistent and failures occurred only at large drift ratios well beyond the code maximum value of 2.5%.

From the development of the fragility functions, it is concluded that:

- Greater than half of the glazing configurations analyzed in this report, as listed in Table 1, would be expected to experience no cracking or fallout damage in an earthquake that subjects the panels to an interstory drift ratio demand of 0.02.

- Gasket failure generally occurs at a drift ratio demand 25% less than the demand expected to cause cracking damage.

- In terms of PBSD it is important to make prompt repairs to damaged gaskets, otherwise a building risks high indirect economic losses and loss of function.

- Fallout damage results in nearly double the direct economic consequences than losses associated with the cracking damage of glass panels.

For the practical application of the fragility curves, it is concluded that:

- In the design of a glass system, moderate differences between framing members are not critical to the seismic capacity of glass panels.

- One way to directly increase the interstory drift ratio capacity of glazing systems is to reduce the size of glass panels.

- Rotational flexibility as a result of semi-rigid mullion-to-structure connections on actual buildings can add seismic capacity to those glass systems.

- Since the fragility functions were developed from laboratory experiments with rigid connection detailing, the predicted performance on actual buildings are conservative.

- For exterior systems on buildings that have continuous vertical framing members and components not degraded from the weathering, the results from the fragilities can be easily applied.

The survey conducted was quite limited. However, the results of the survey at least point out to several issues including the following that may need to be further considered for follow-up studies:

- In about 15% of existing glazing systems, glass is held with soft or hard putty. This can be a concern as glass held in hard putty has sustained more damage compared to modern dry glazed or structural sealant glazed systems.

- The glass-to-frame clearance in at least 21% of existing buildings and 14% of the new buildings is 1/8 in. This again should be a concern as smaller clearances have higher chance of glass damage.

- In over half of the glazing construction, side blocks are not used. This should be considered a serious concern in terms of glazing component resistance to earthquake-induced building motions.

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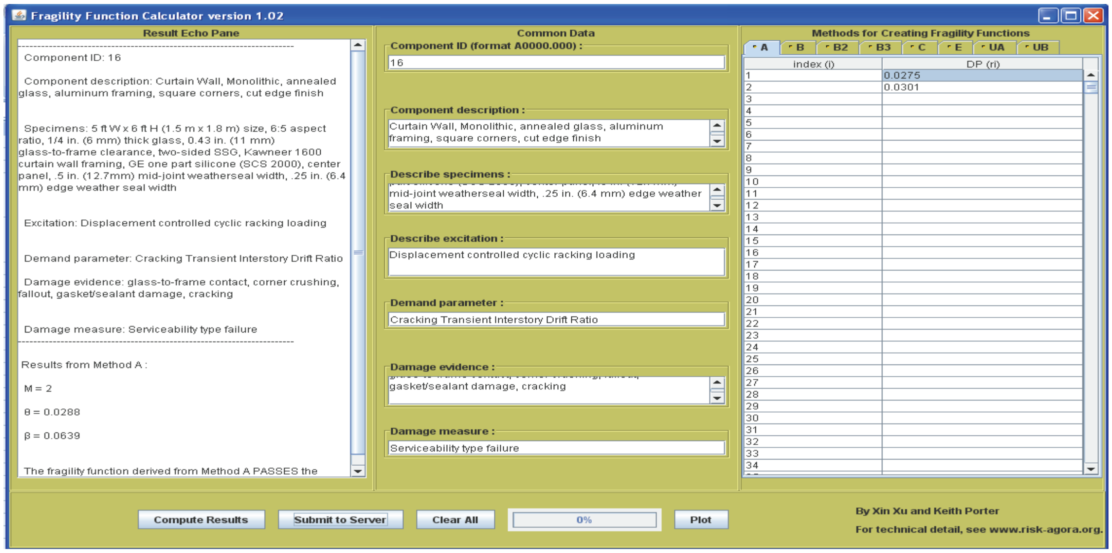

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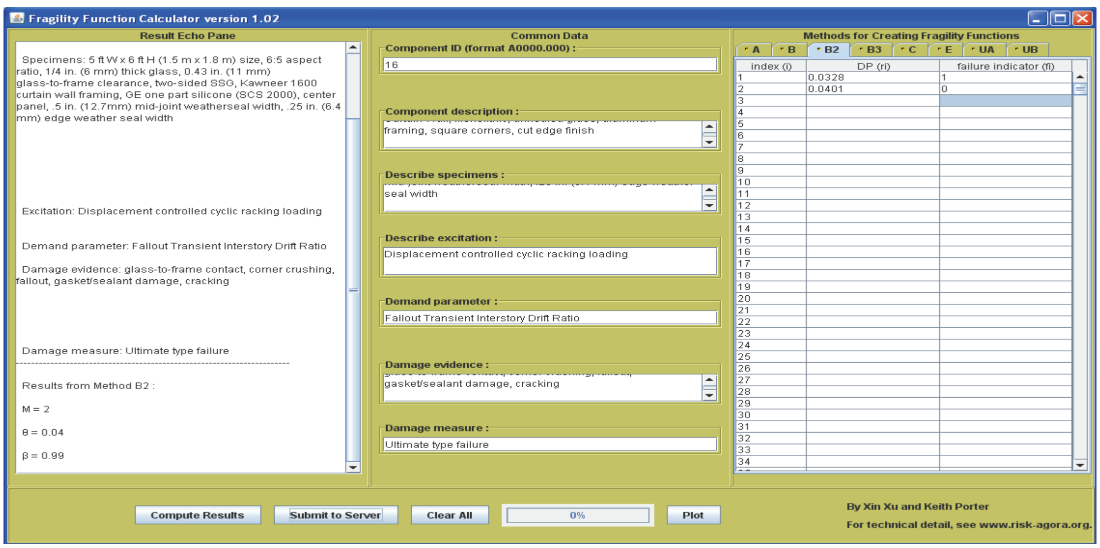

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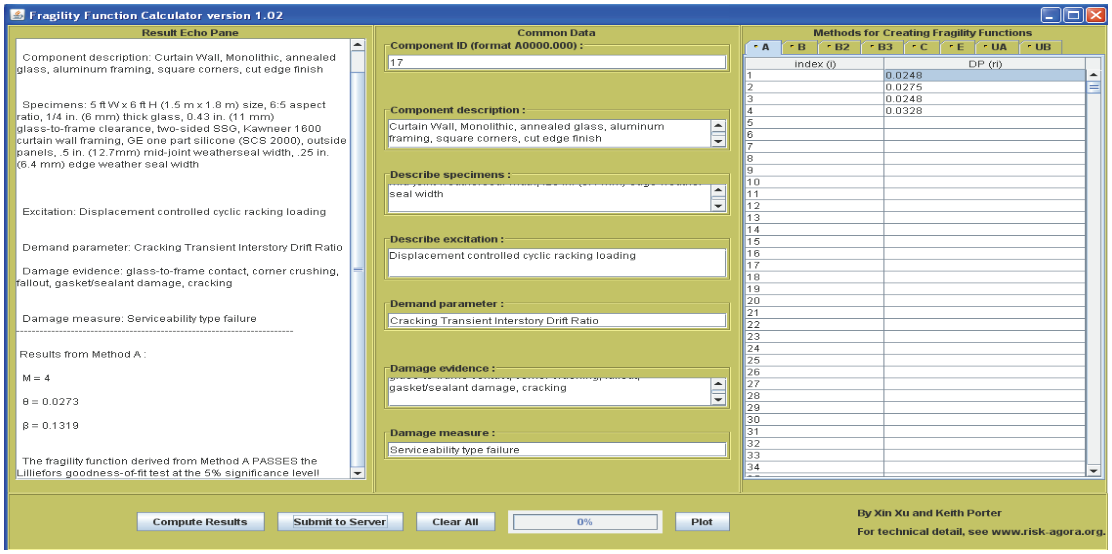

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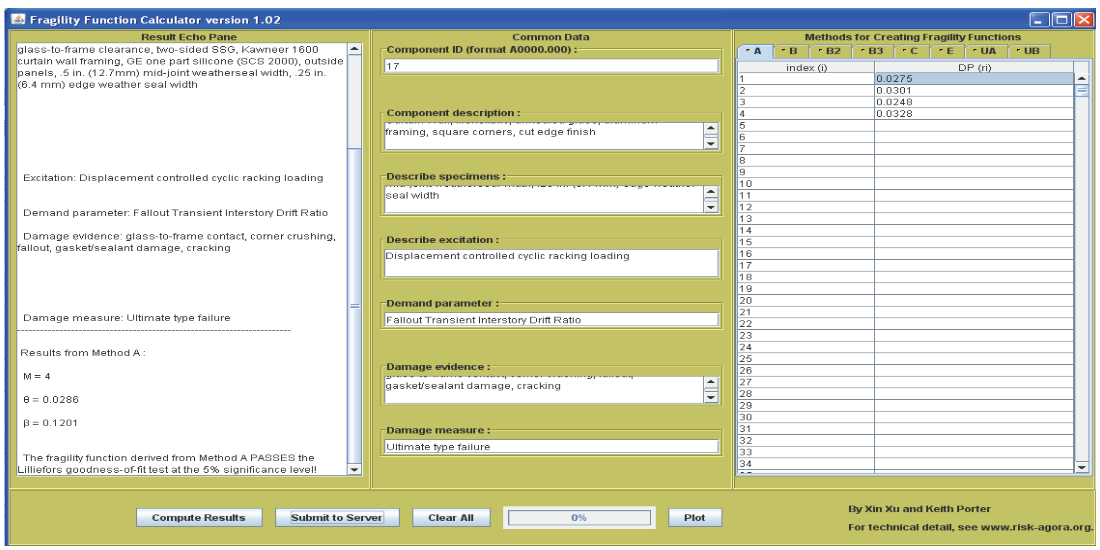

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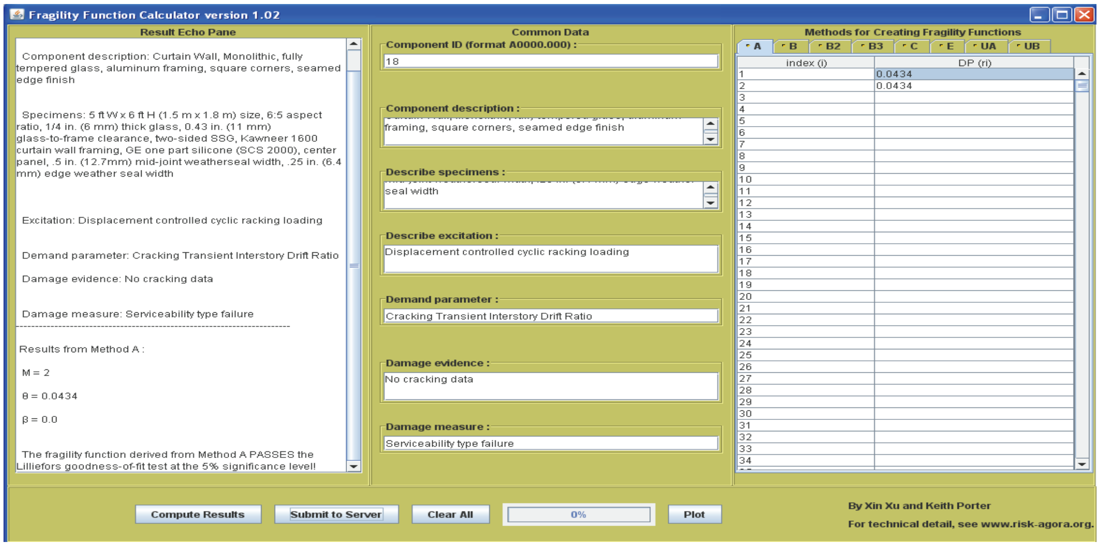

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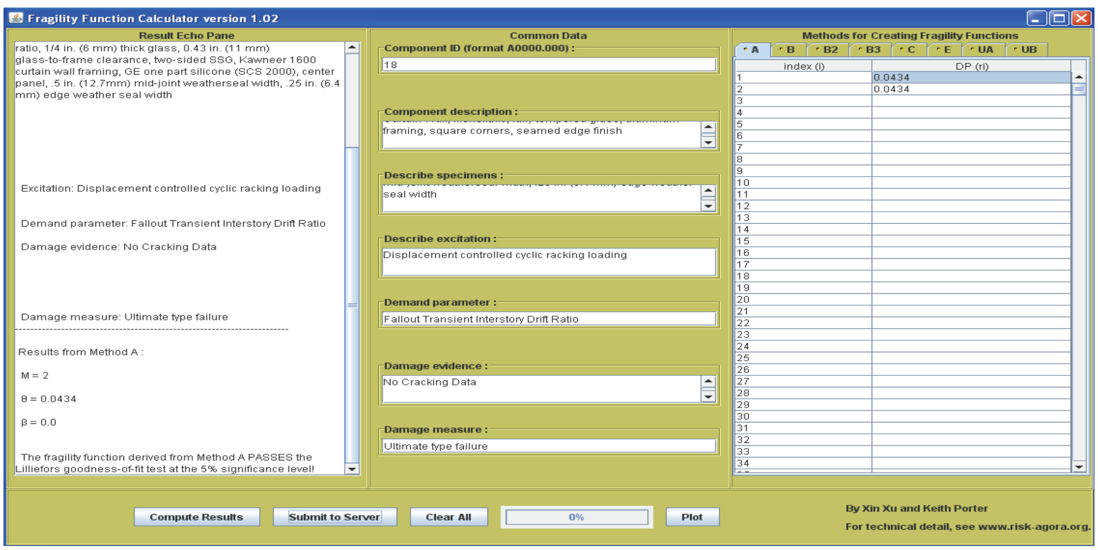

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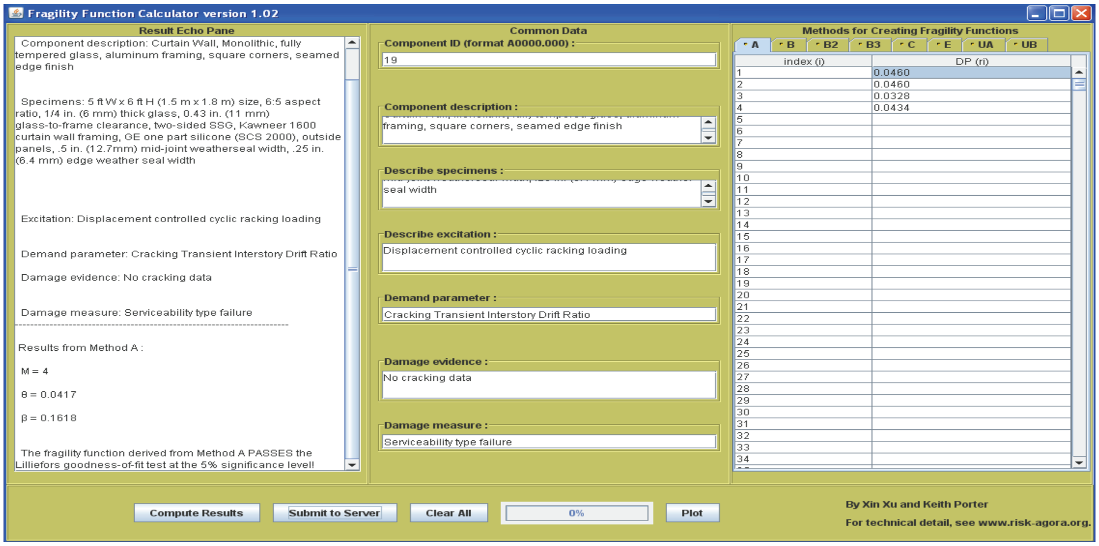
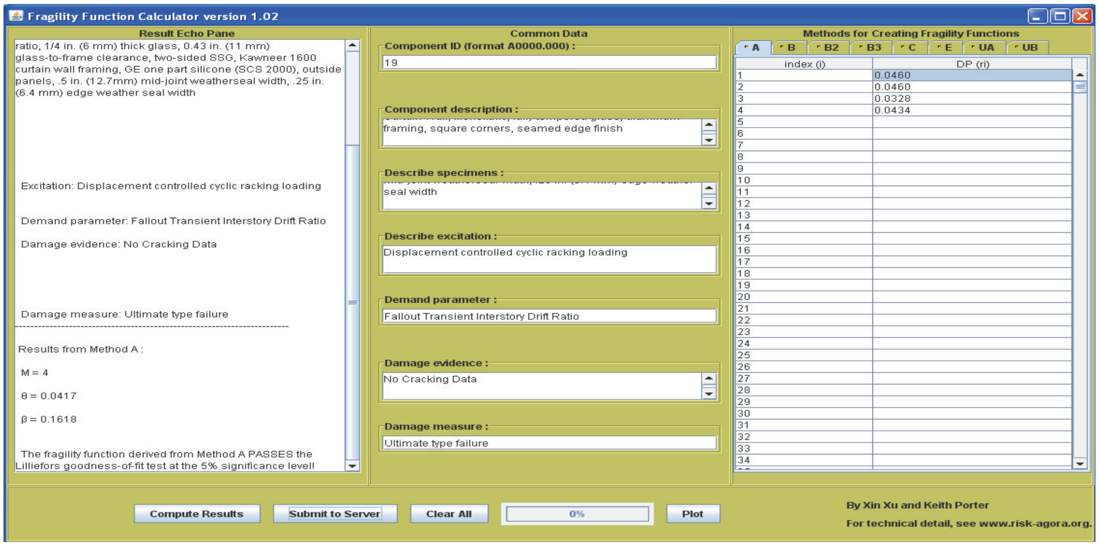
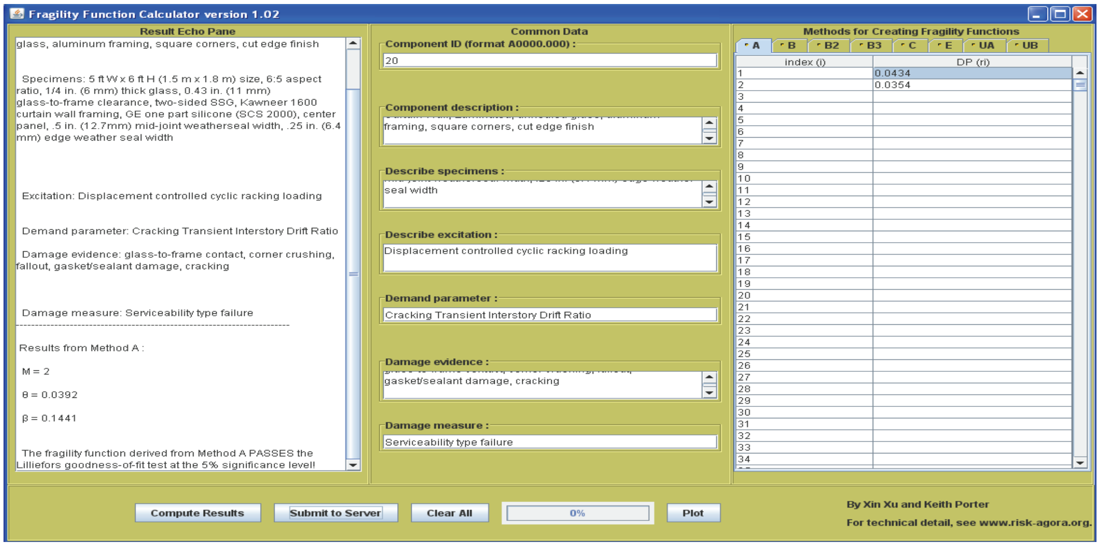


#19 FALLOUT



#20 CRACKING



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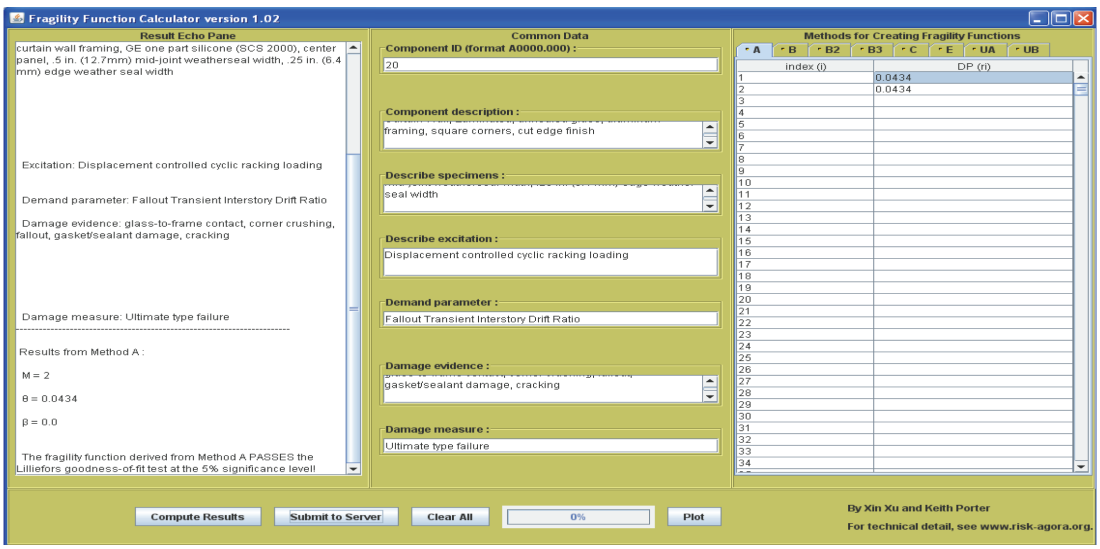

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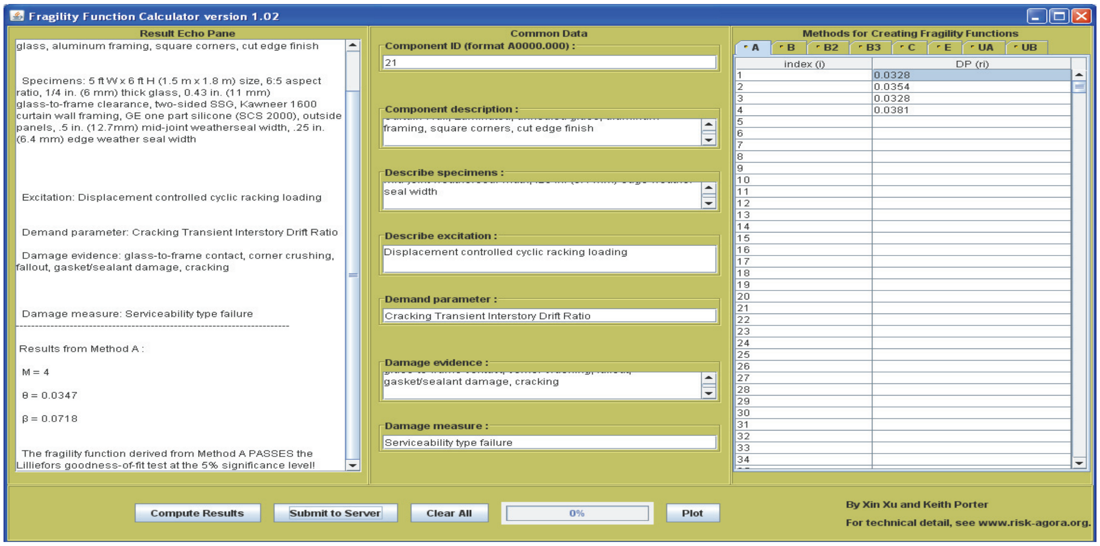

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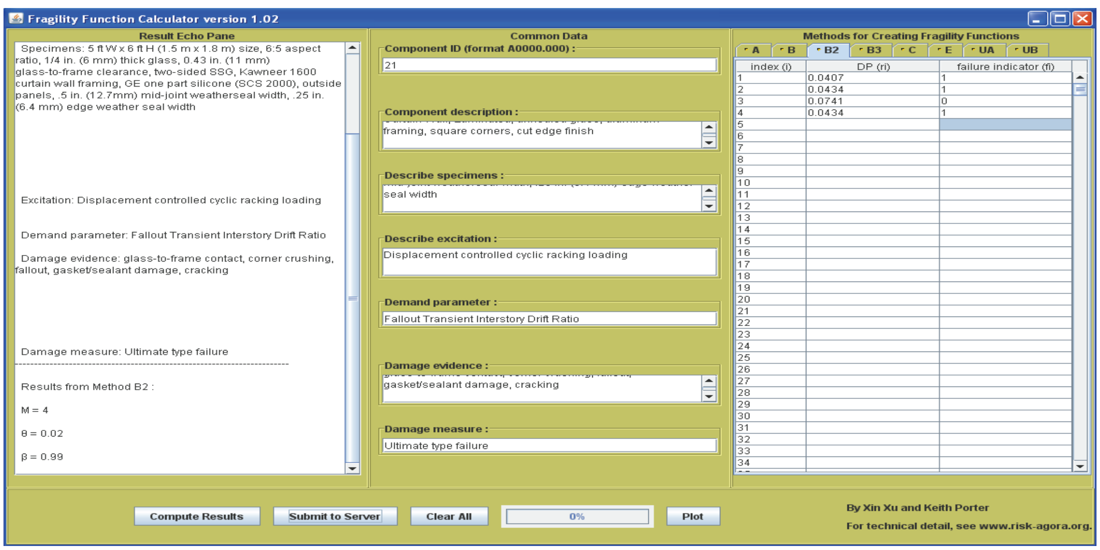

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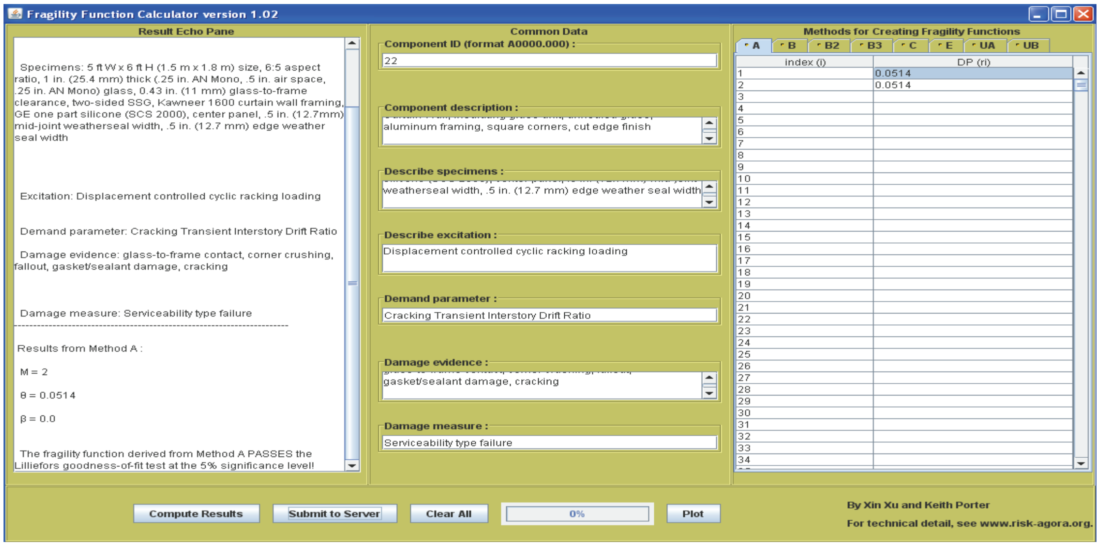

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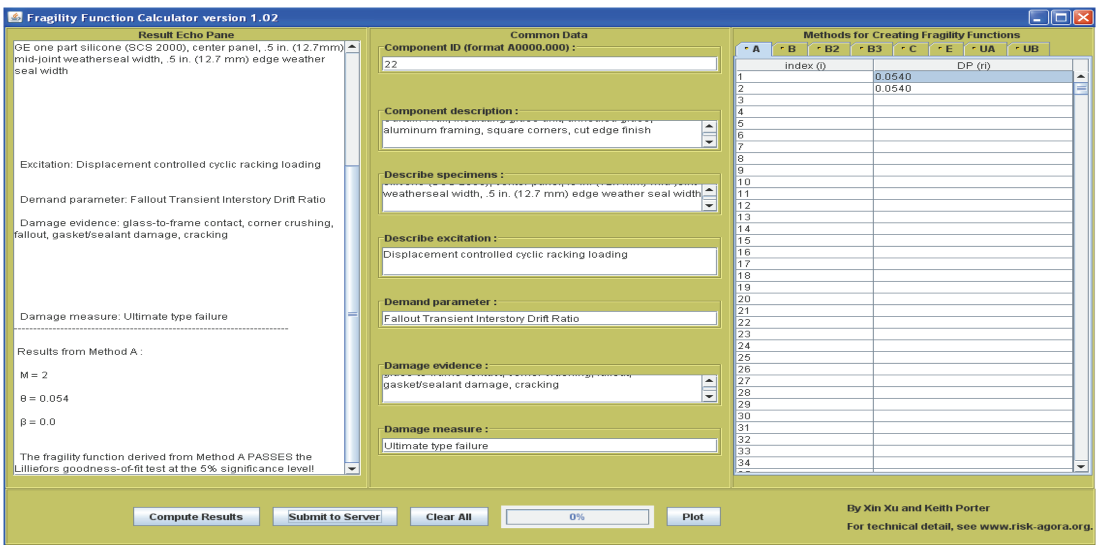

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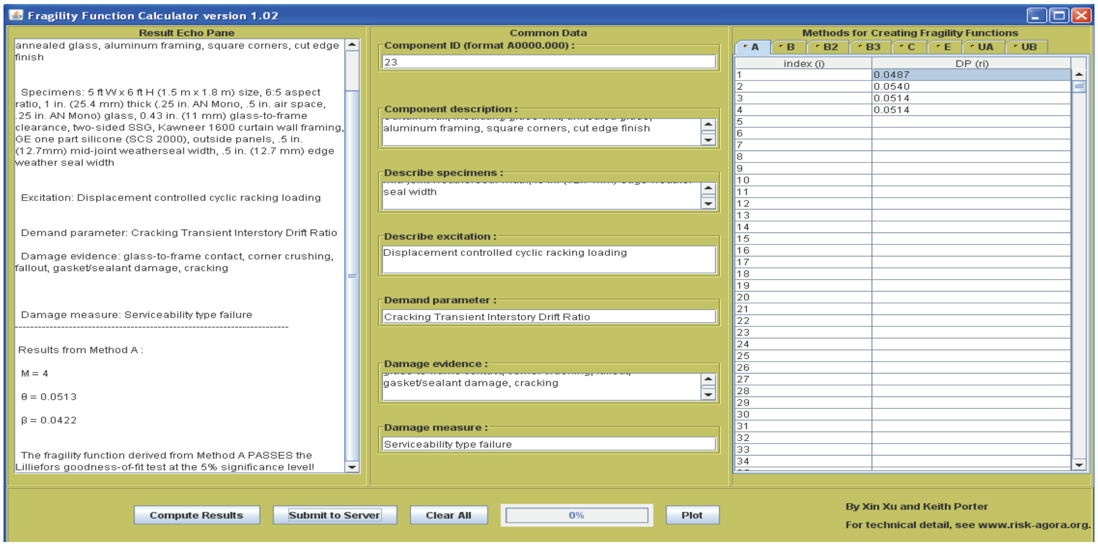

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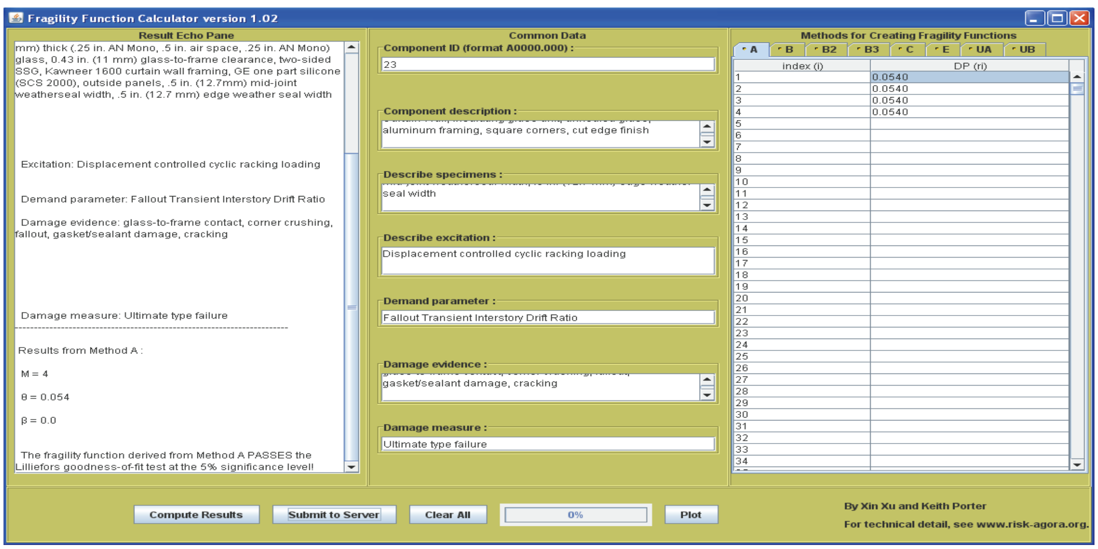

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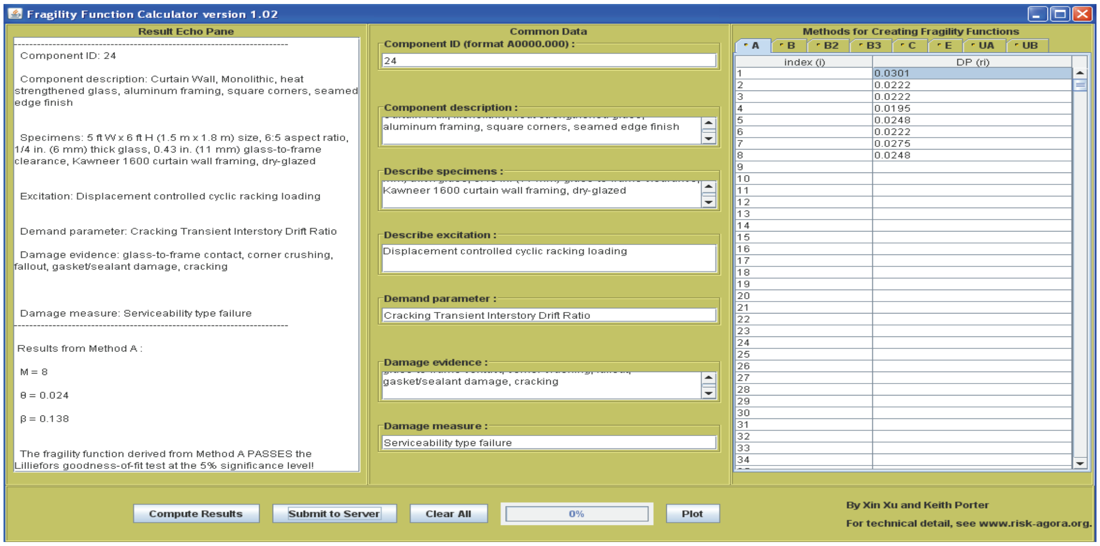

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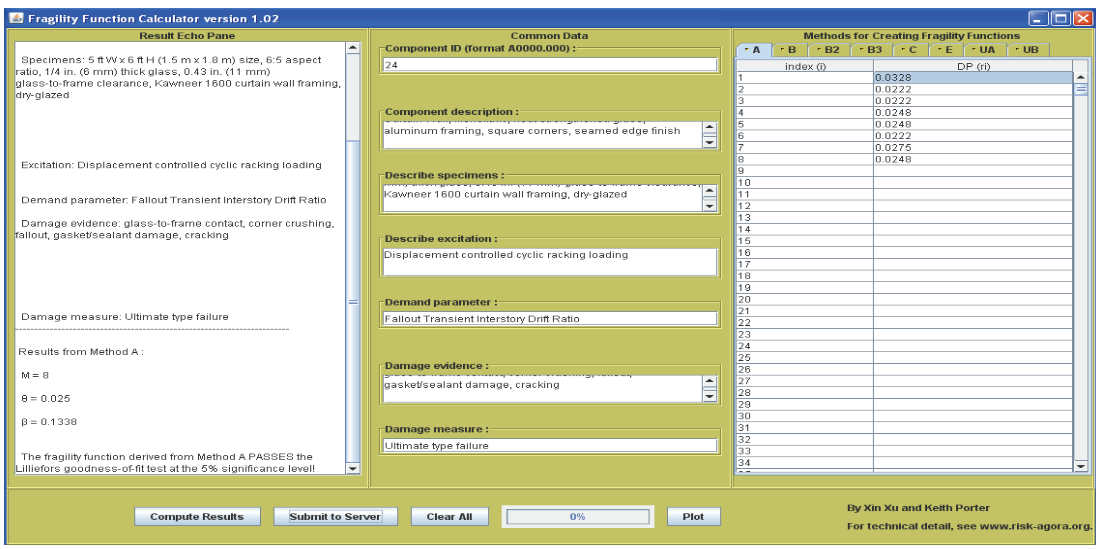

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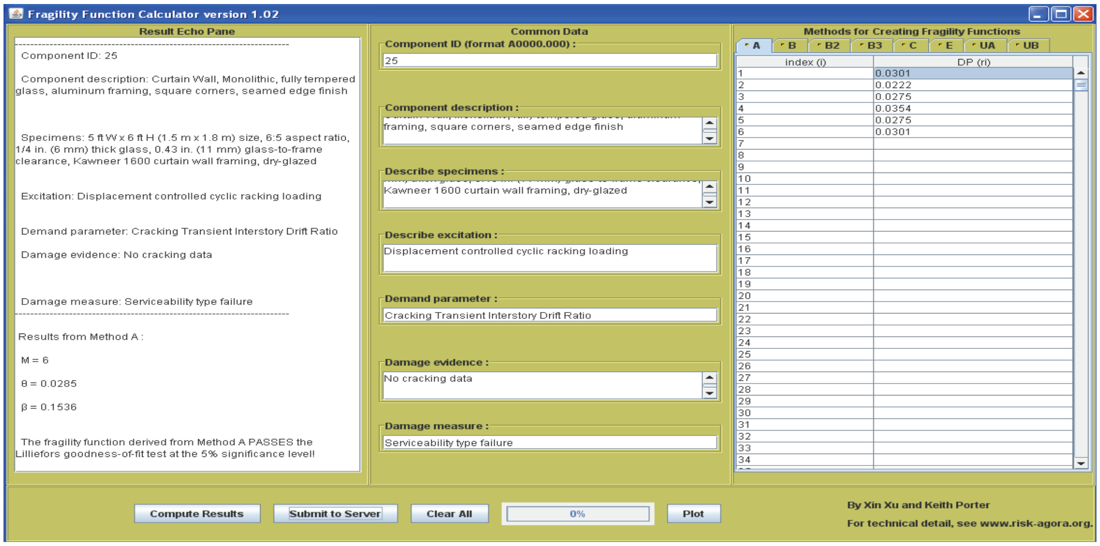

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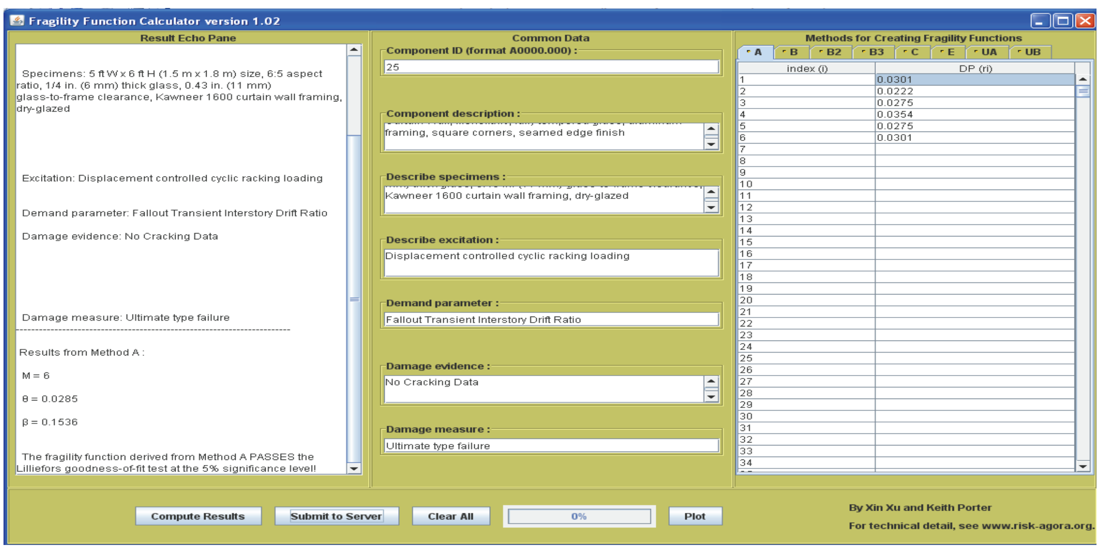

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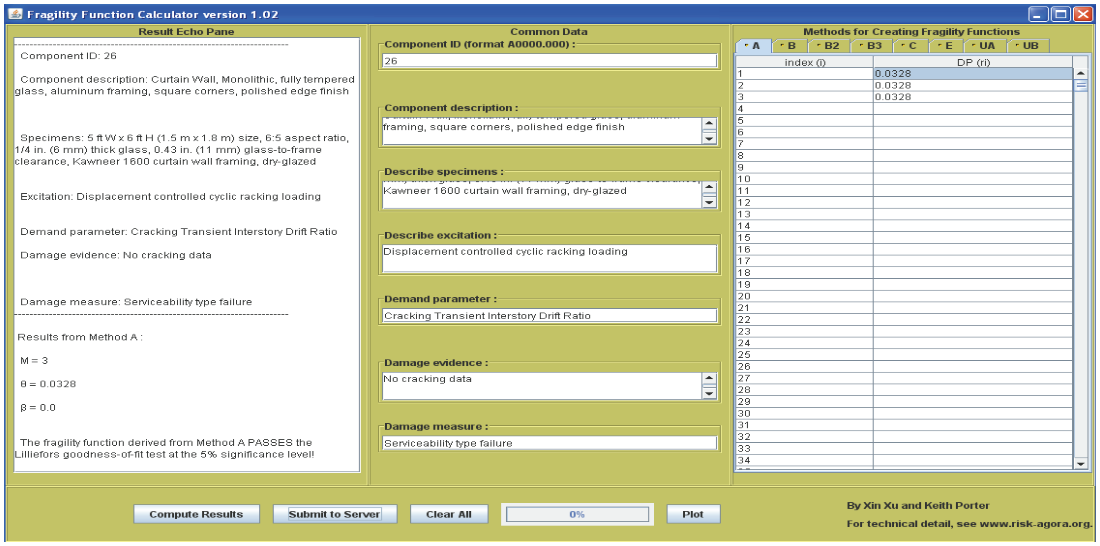

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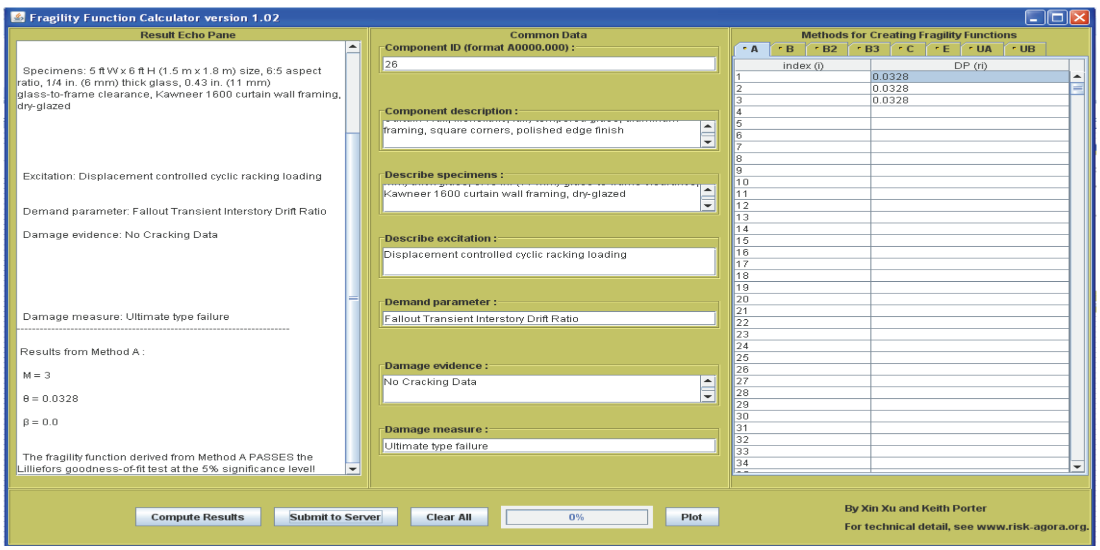

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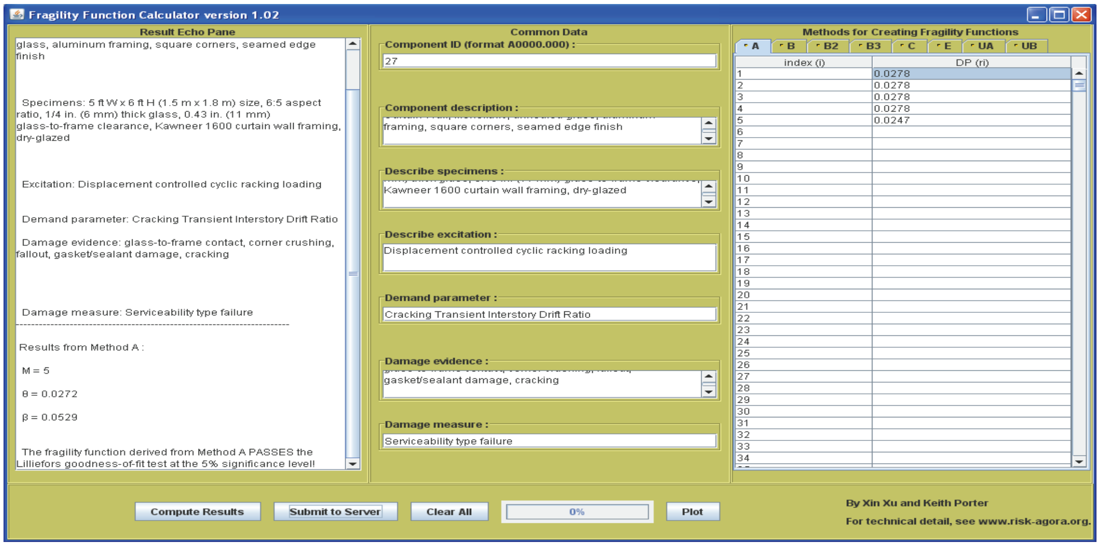

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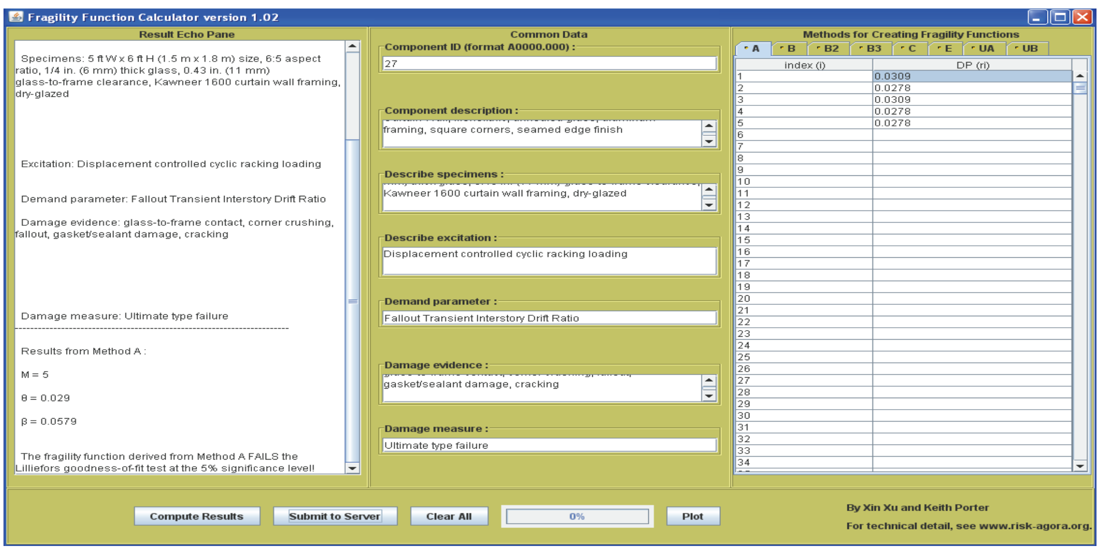

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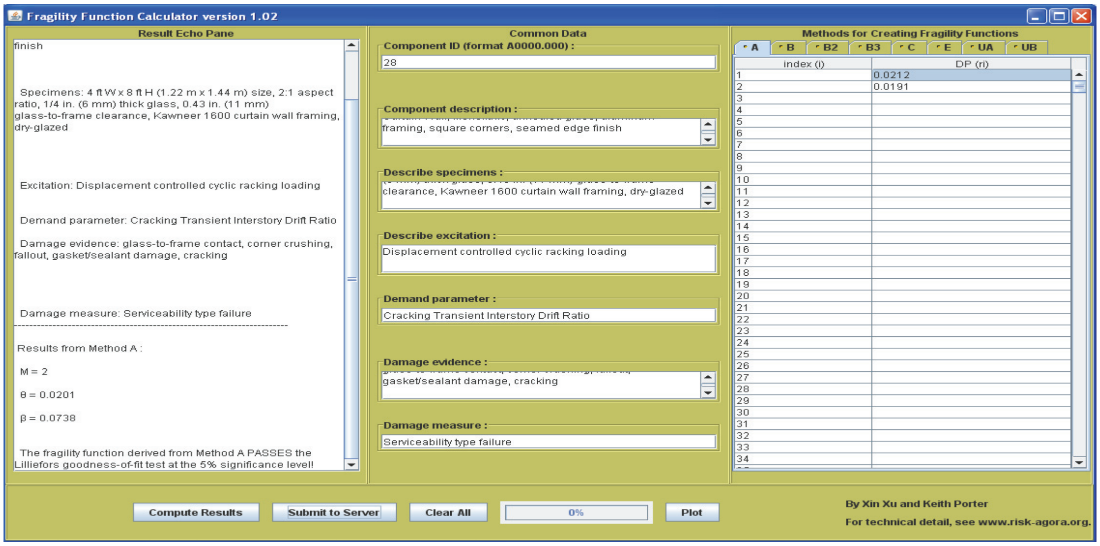

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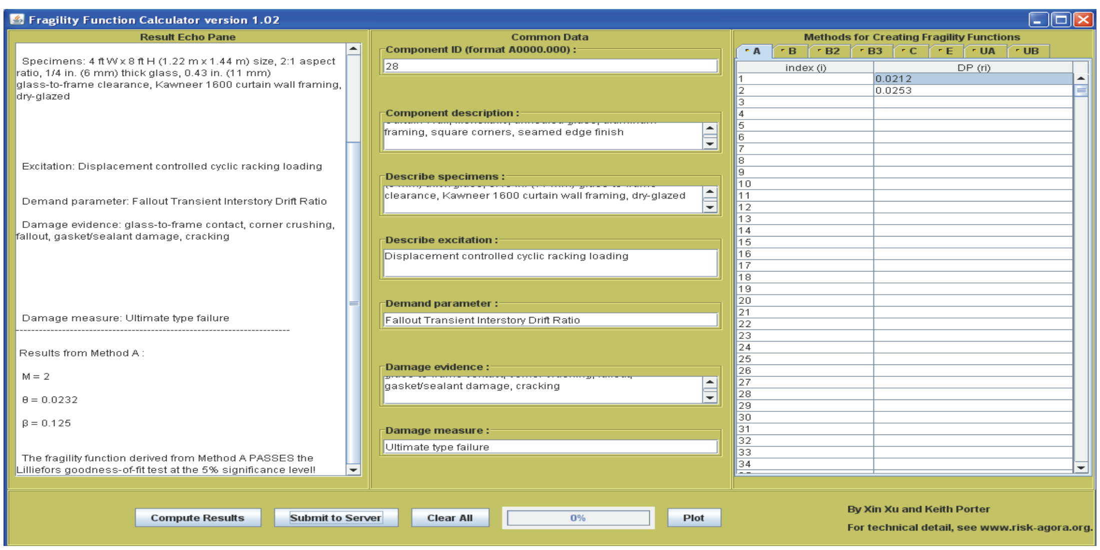

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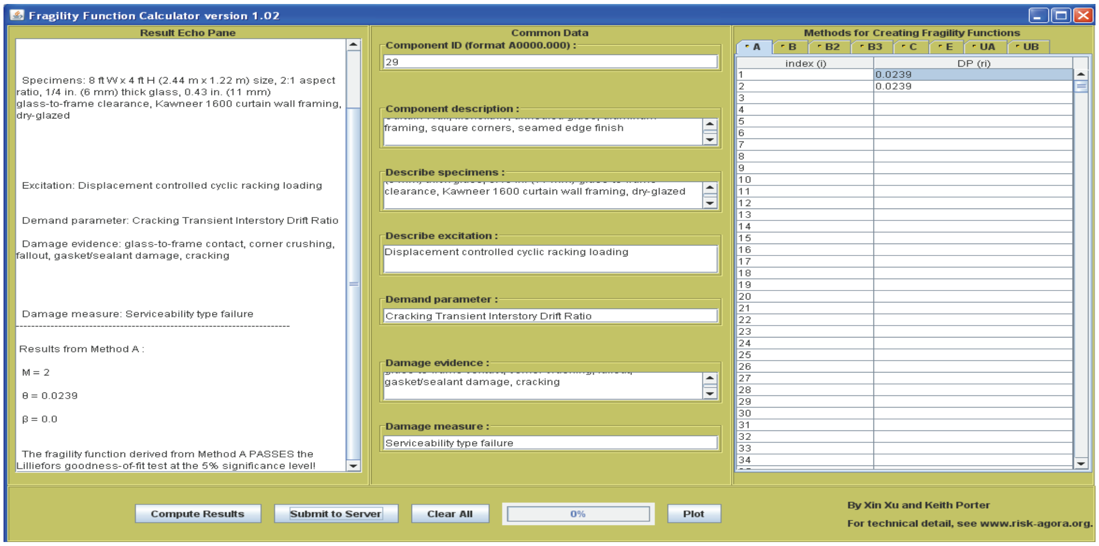

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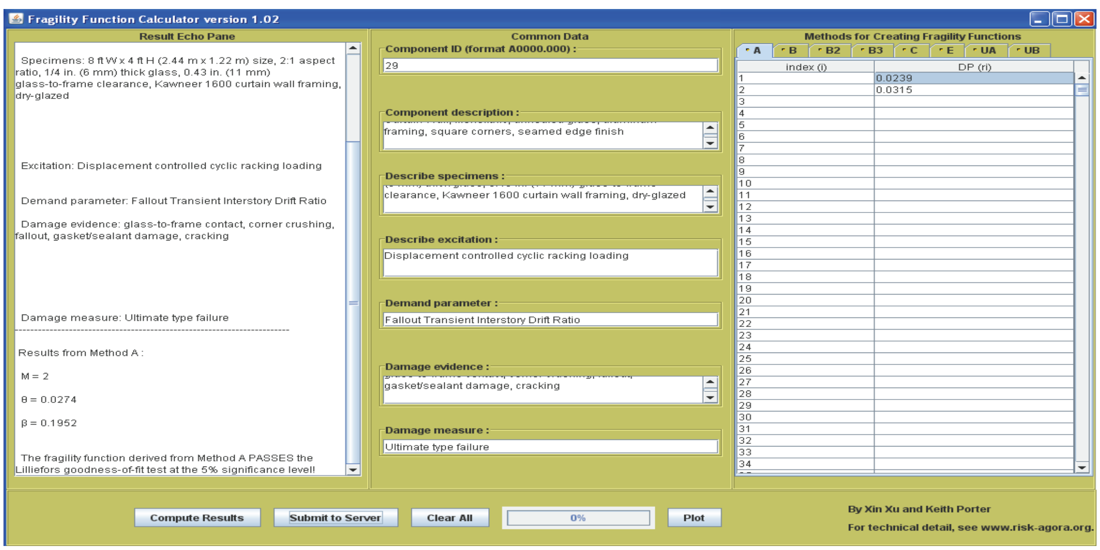

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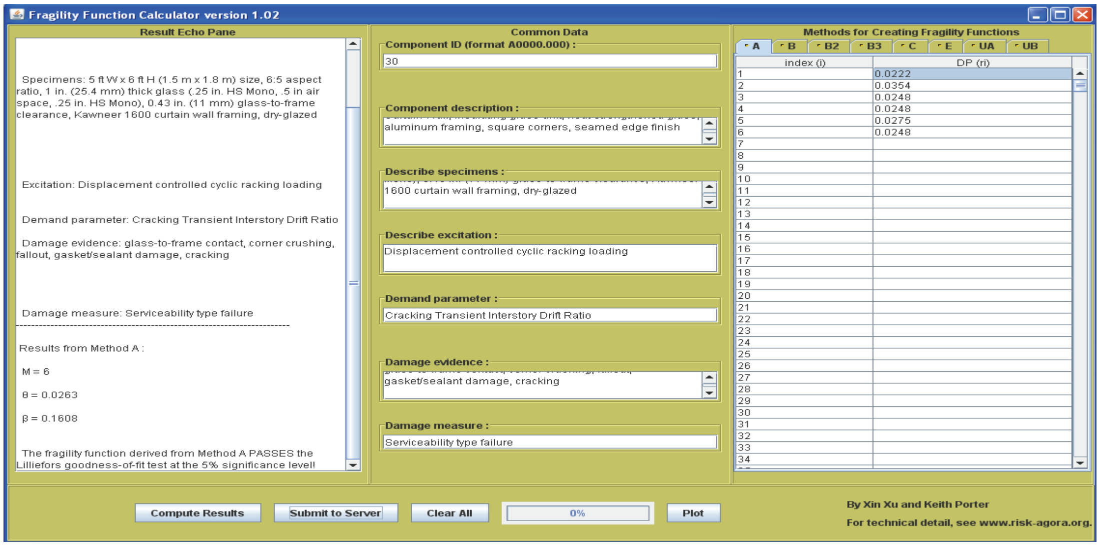

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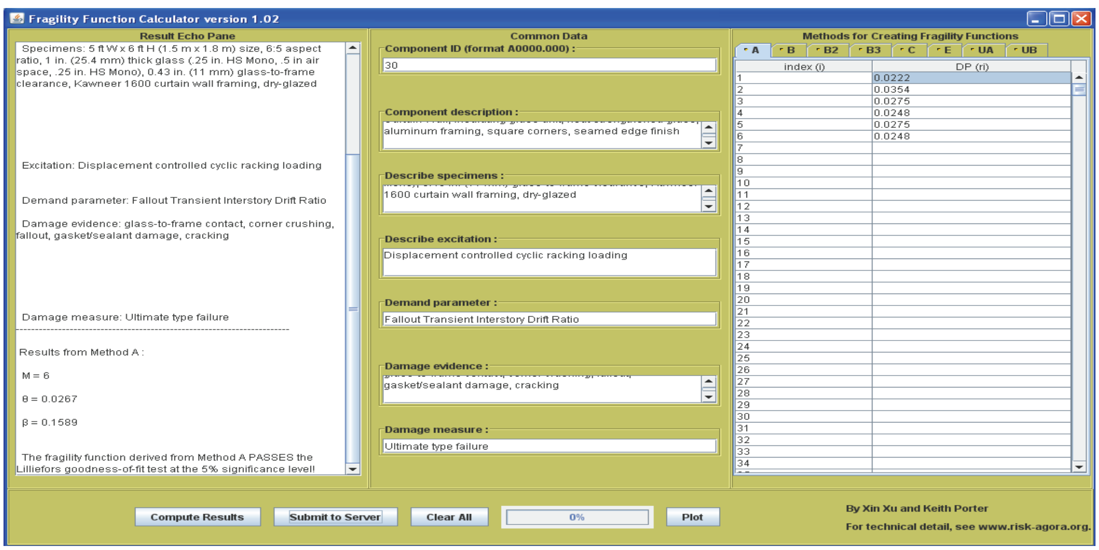
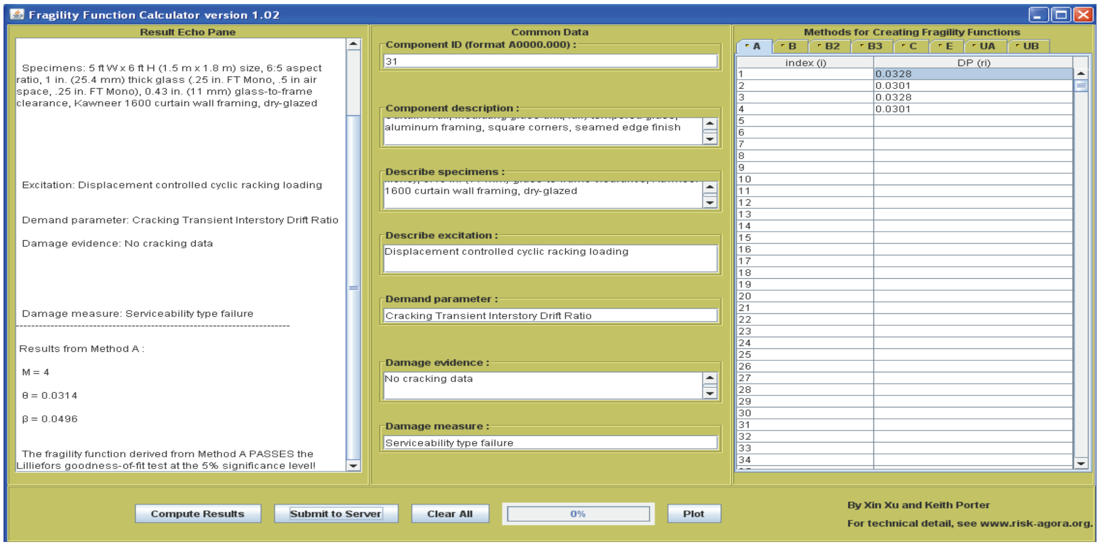


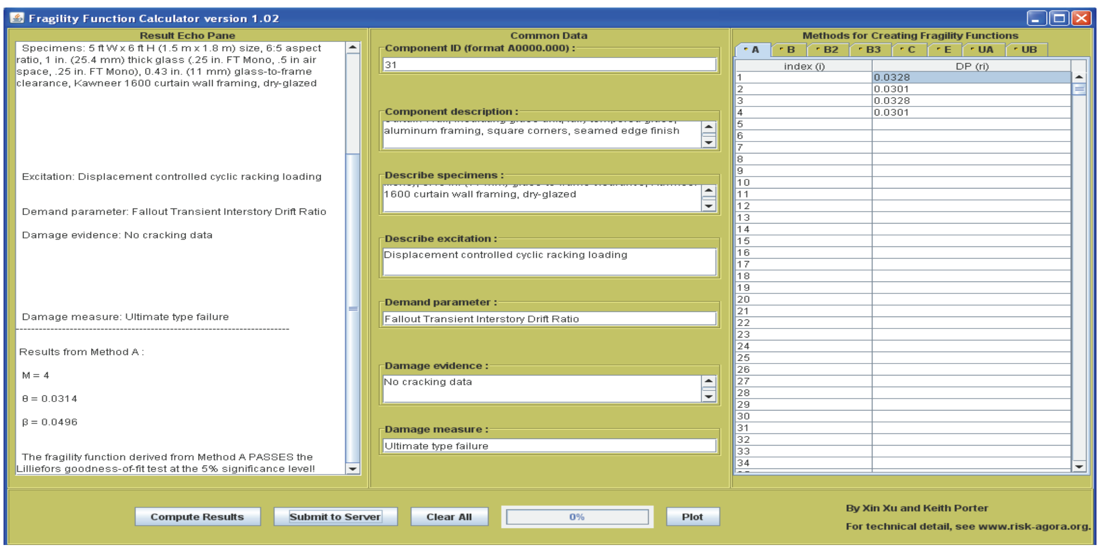
#31 CRACKING

#32 VERTI



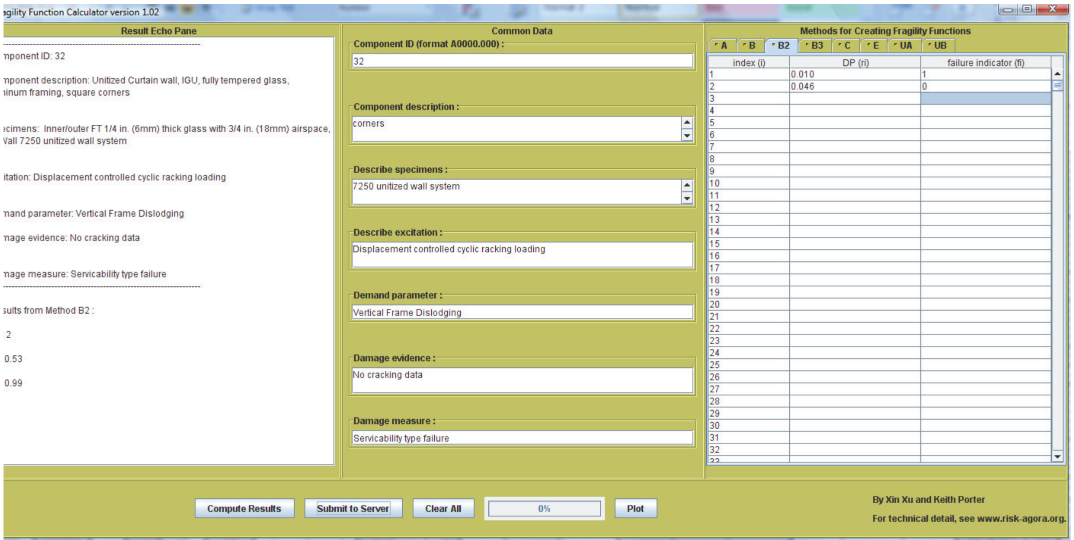
#31 FALLOUT

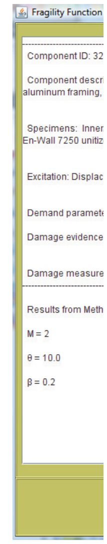
#32 HORIZ



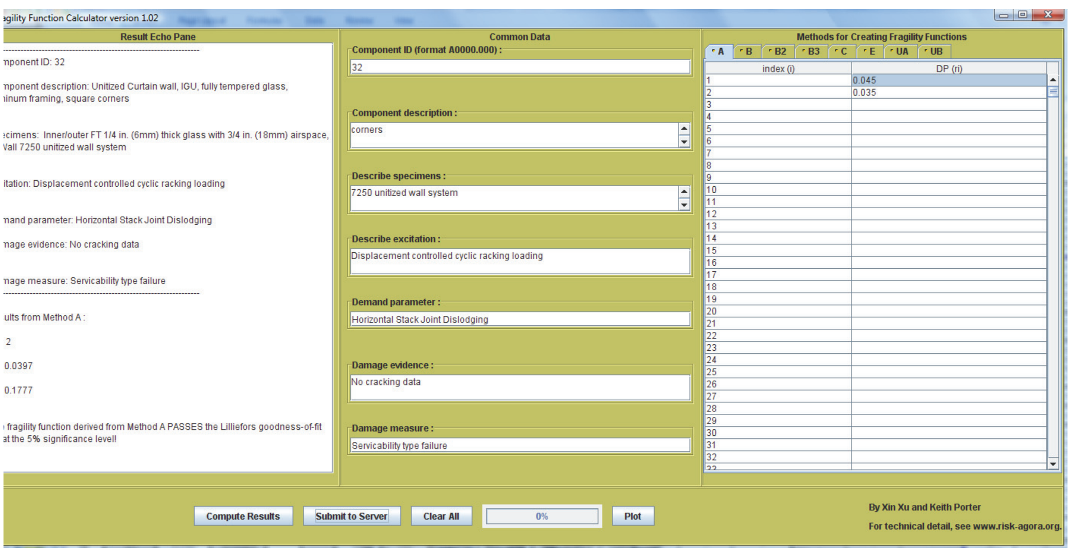
CAL JOINT DISLODGING

#32 GLASS DAMAGE

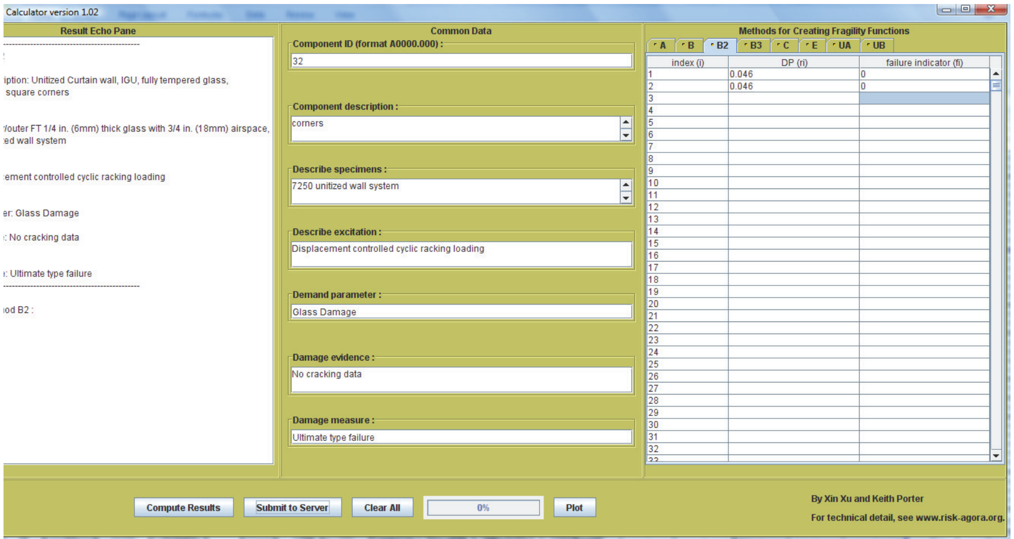


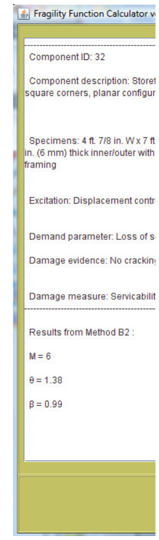


ZONTAL STACK JOINT DISLODGING

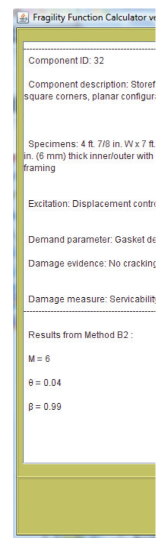


#33 LOSS OF SEAL

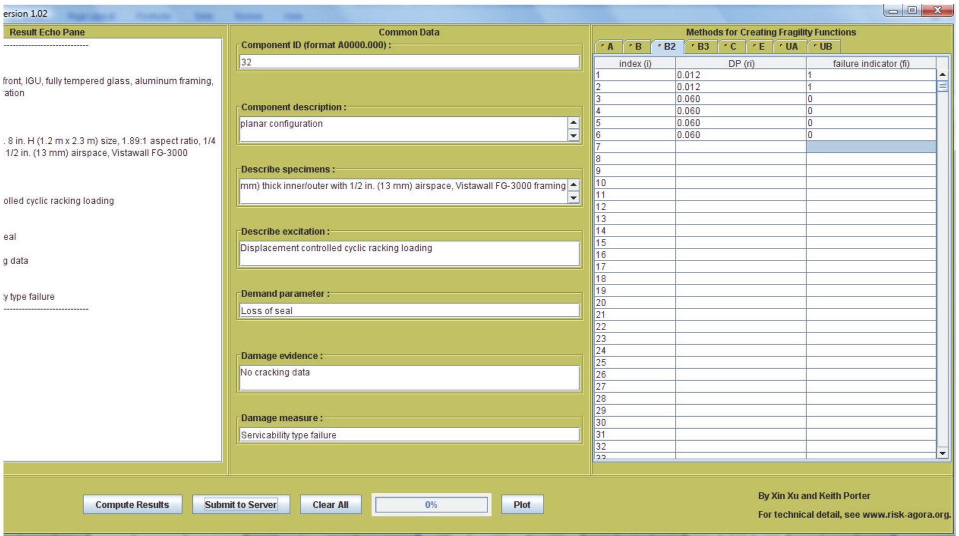


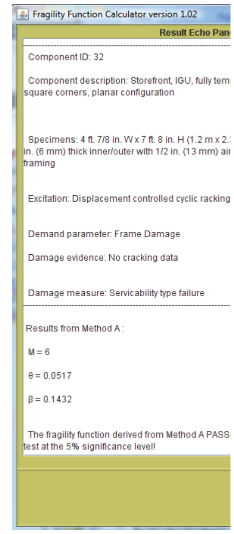


#33 GASKET DEGRADATION

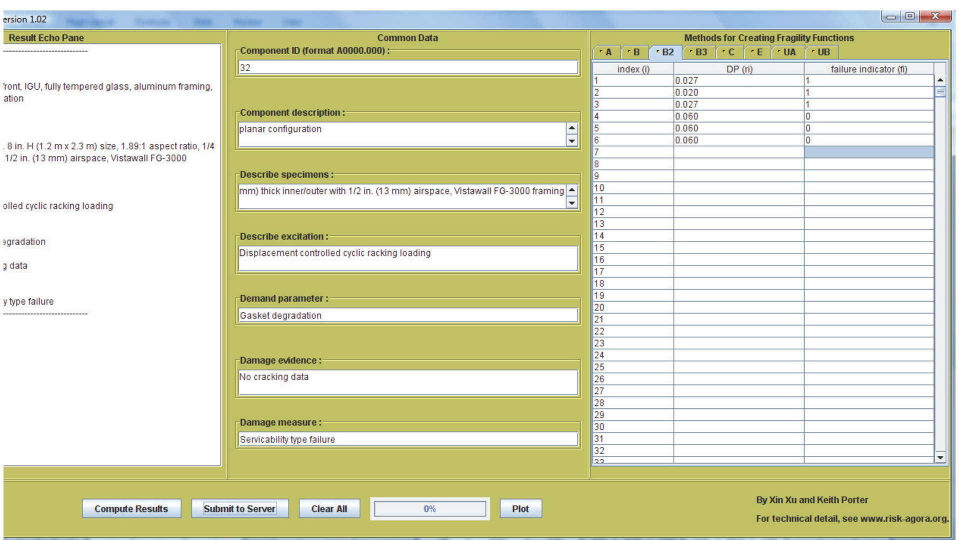


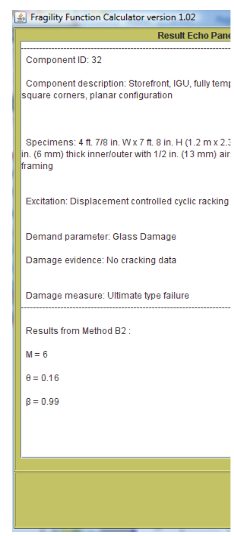
#33 FRAME DAMAGE



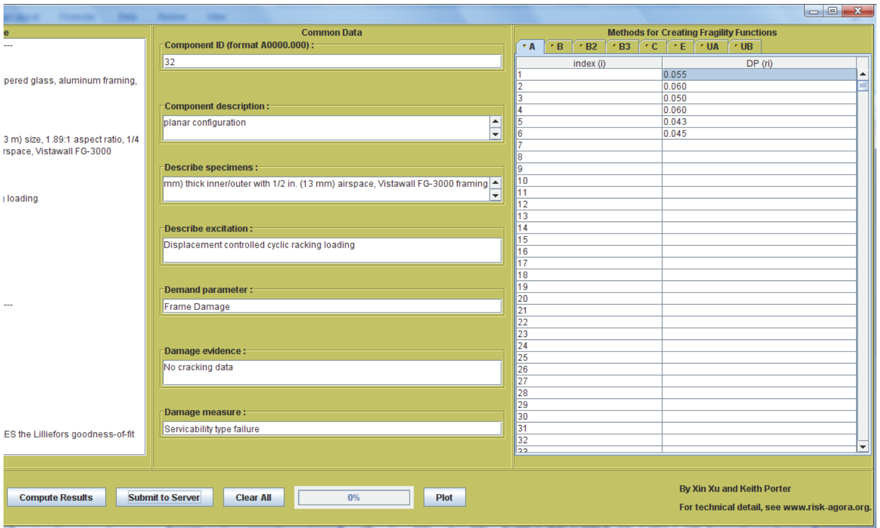


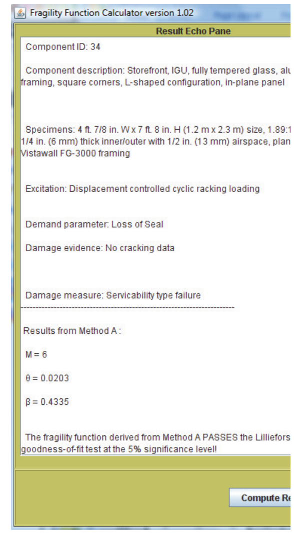
#33 GLASS CRACKING/FALLOUT





#34 LOSS OF SEAL





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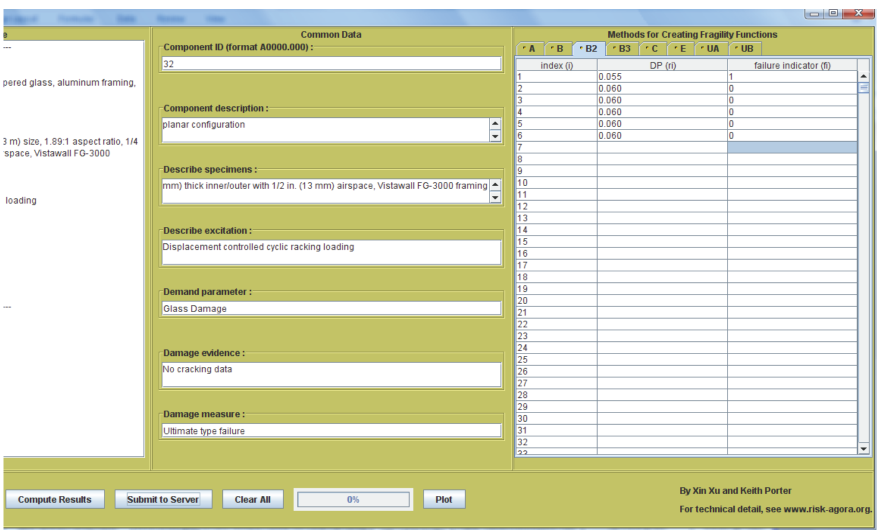

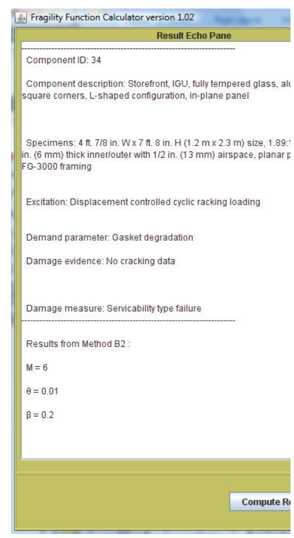

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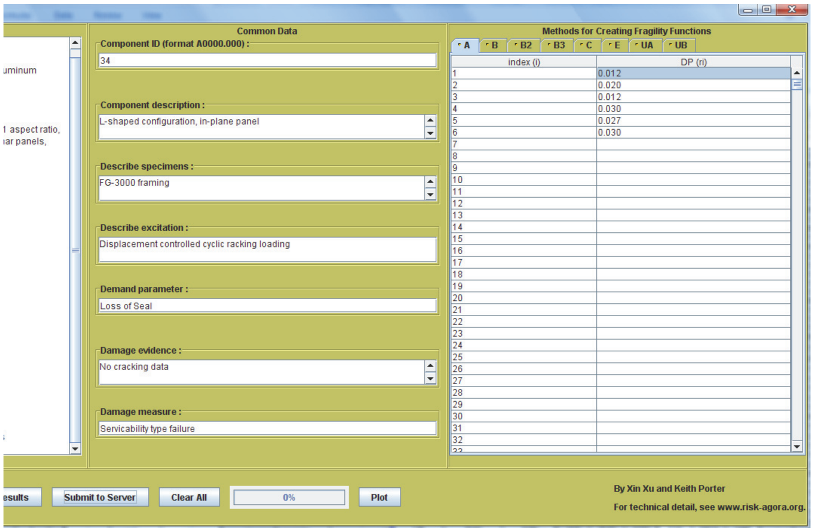

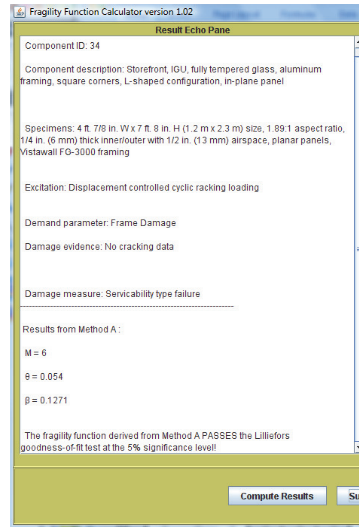

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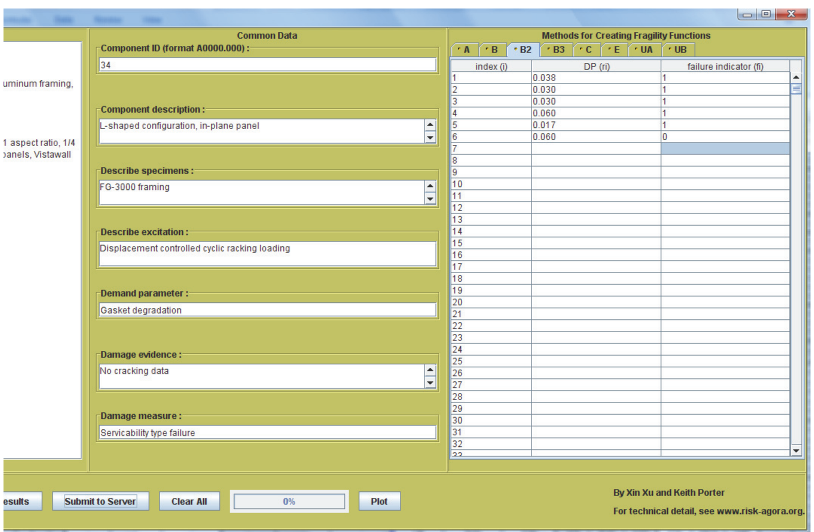

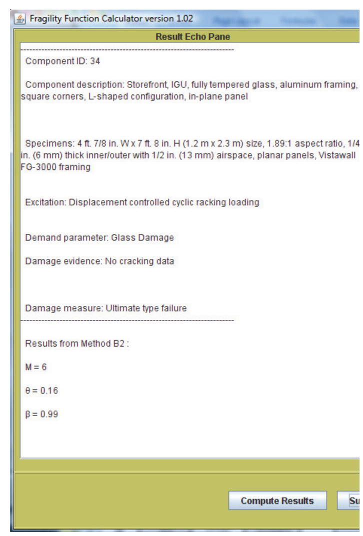

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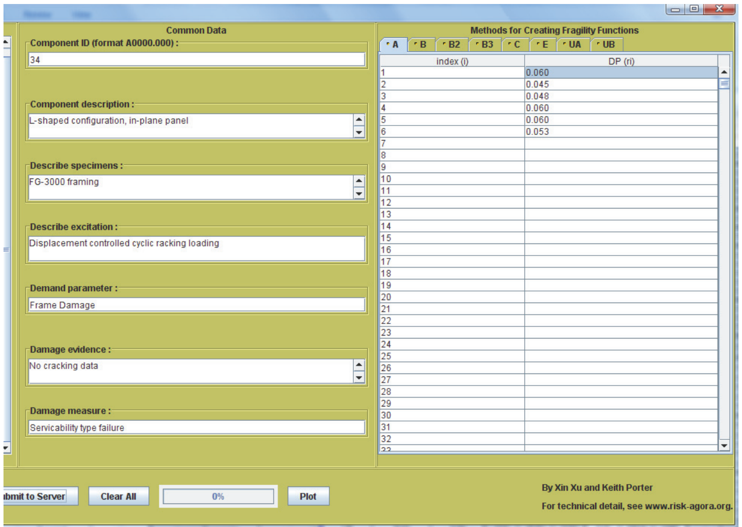

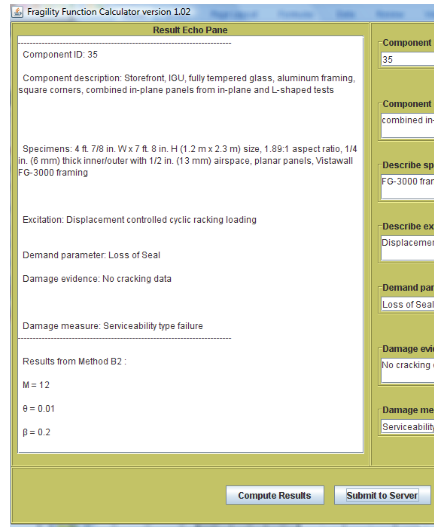

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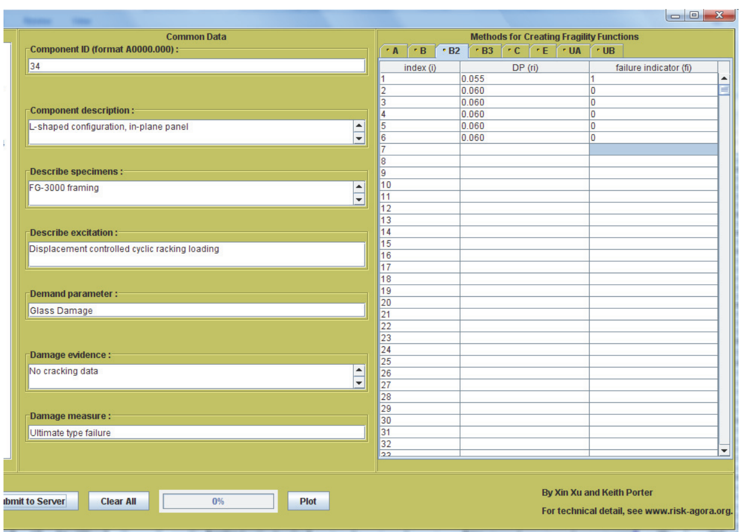

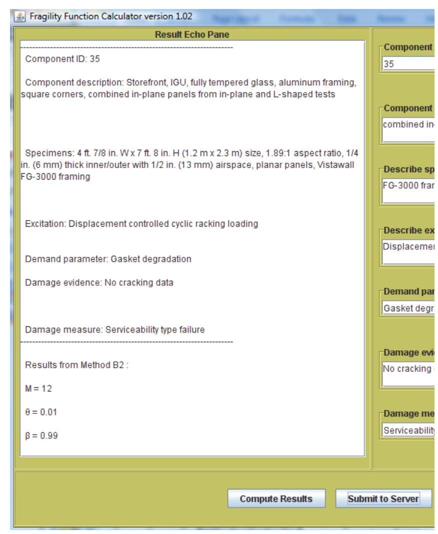

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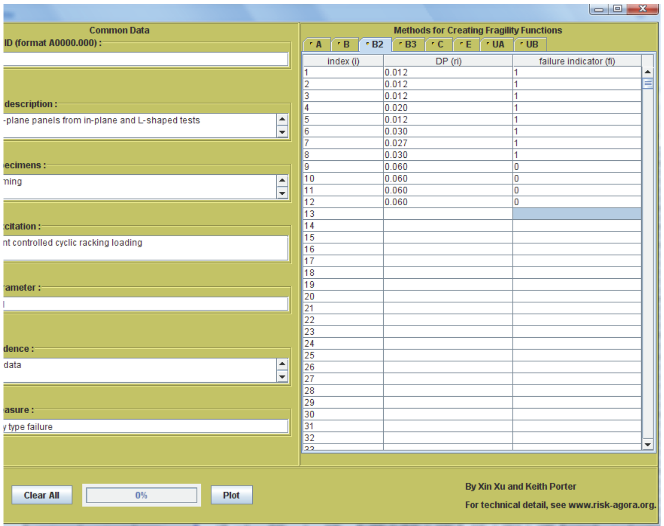

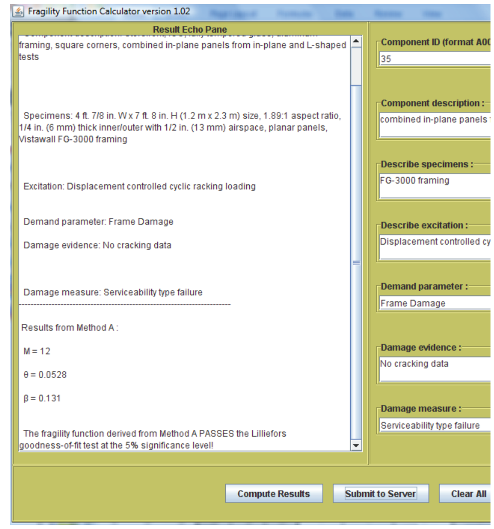

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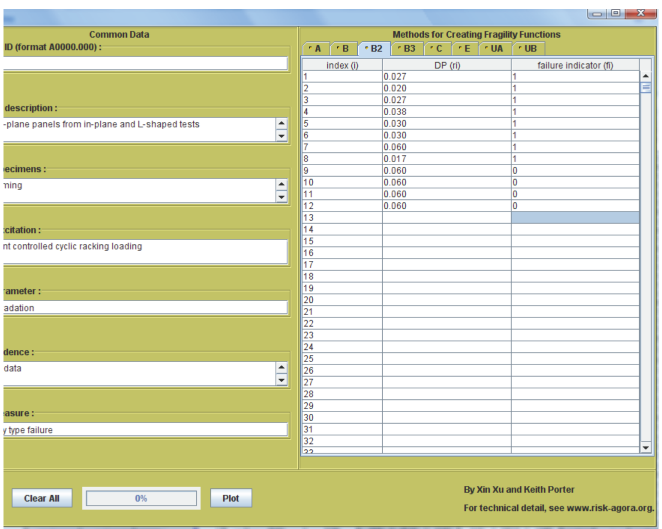

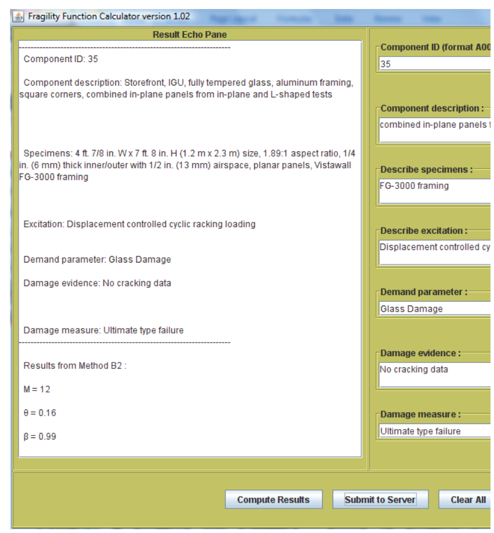

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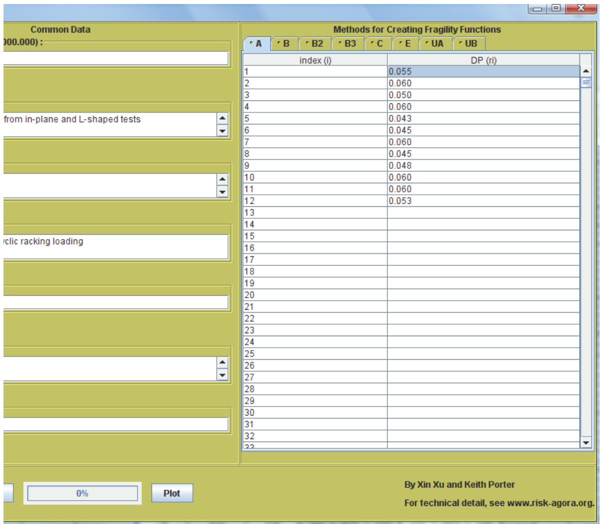

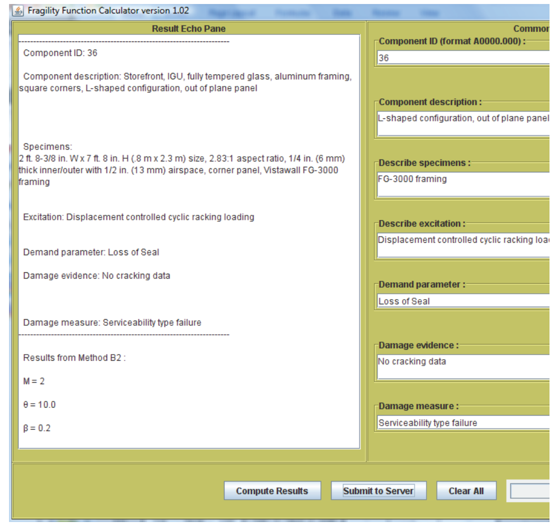

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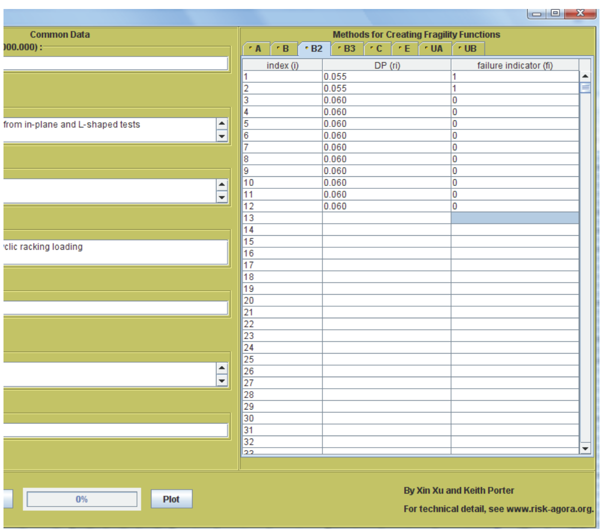

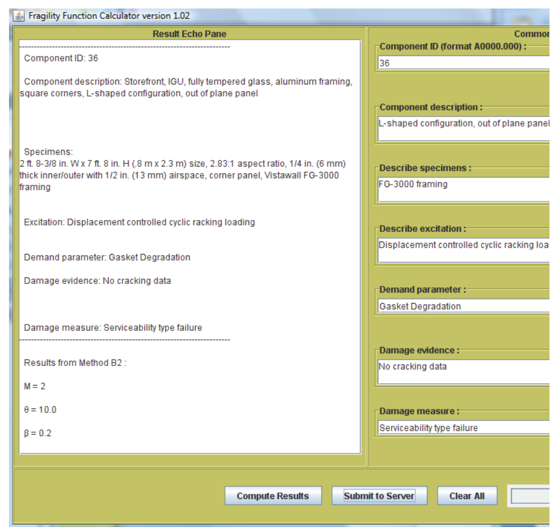

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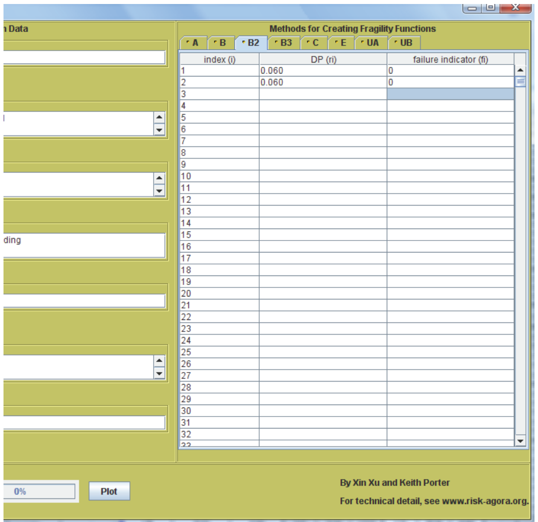

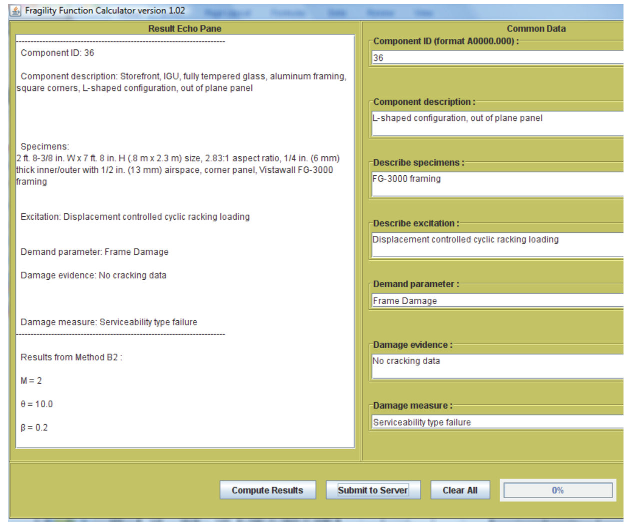

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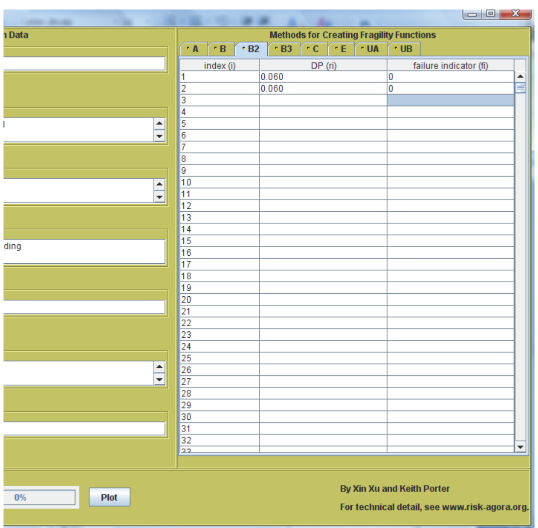
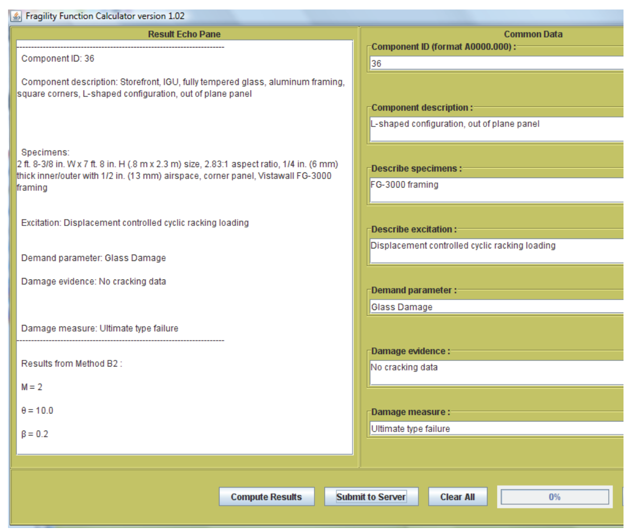
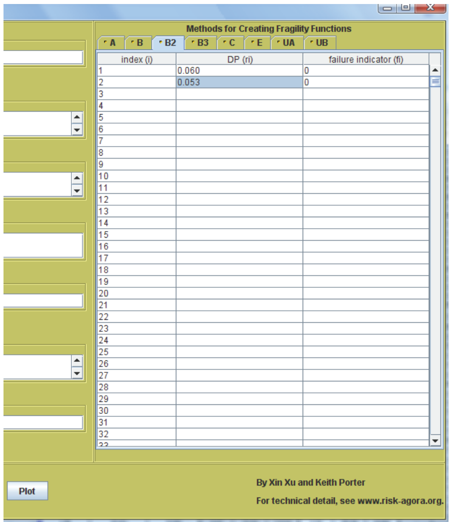
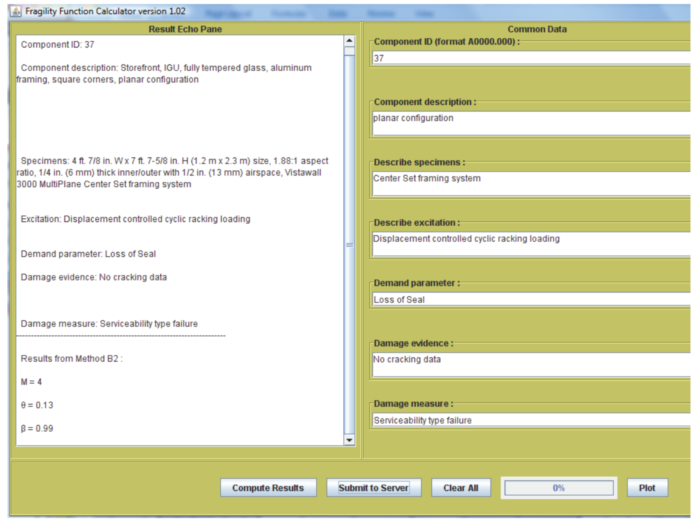




#37 LOSS OF SEAL





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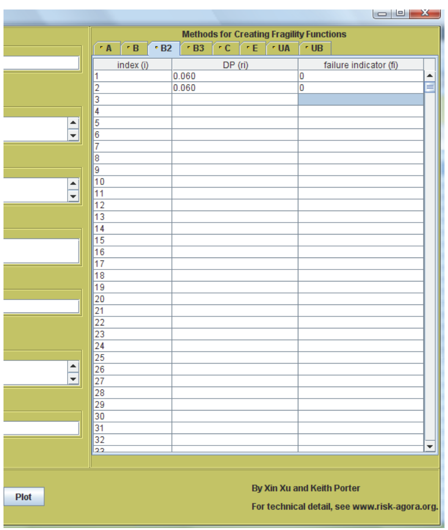

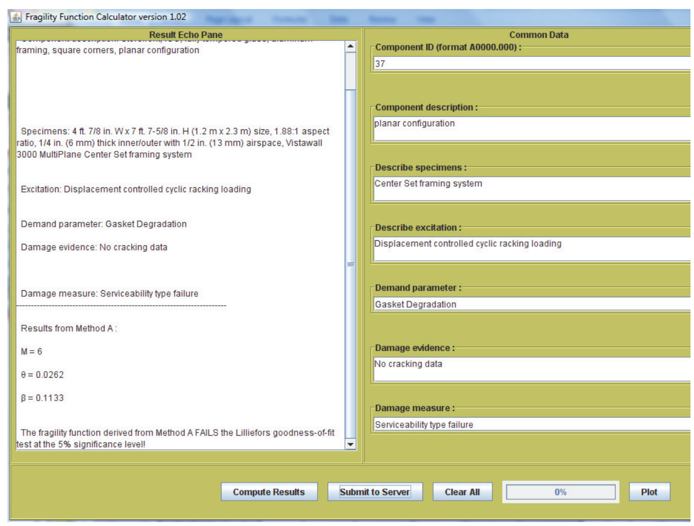

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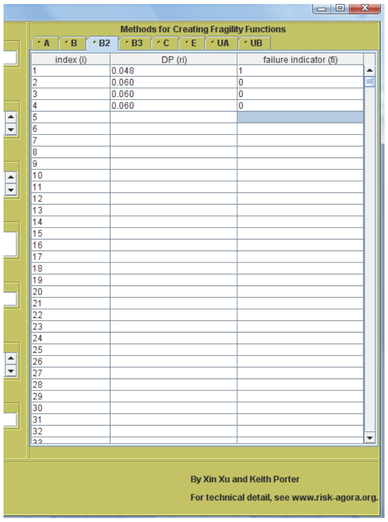

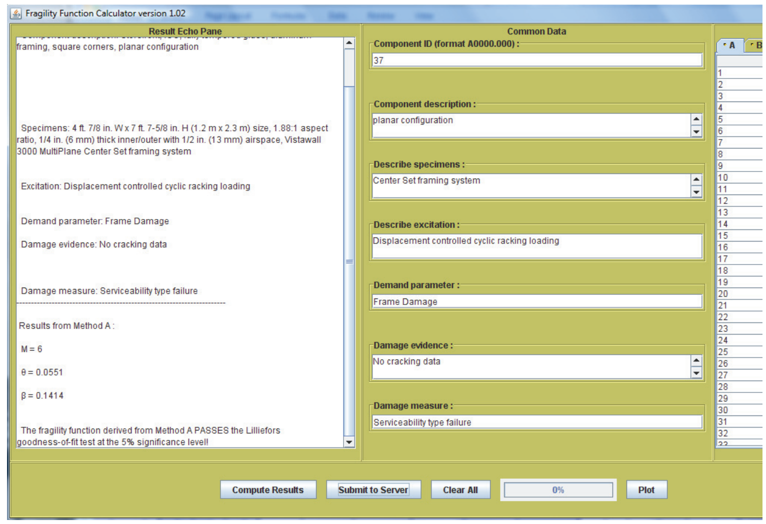

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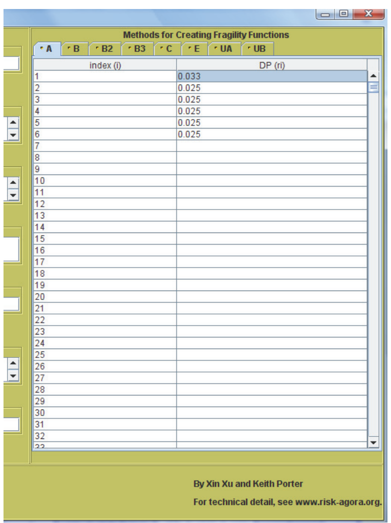

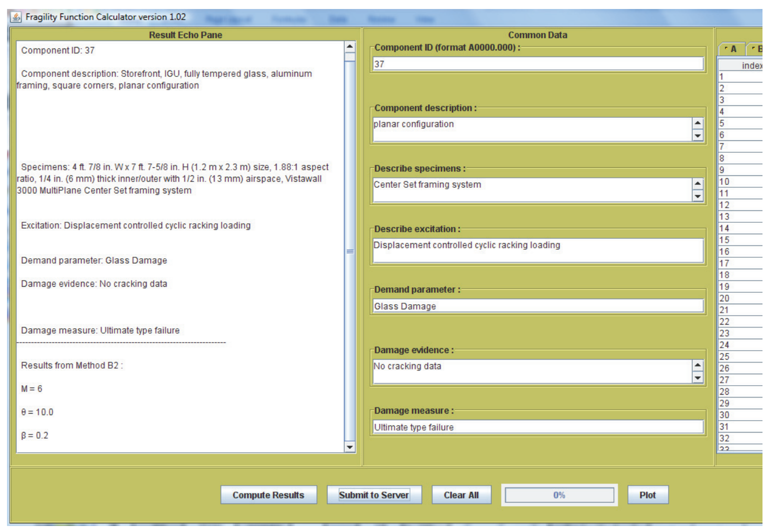

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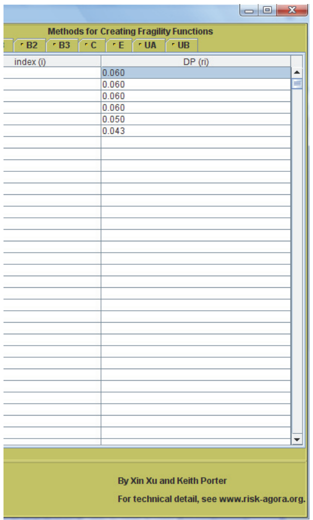

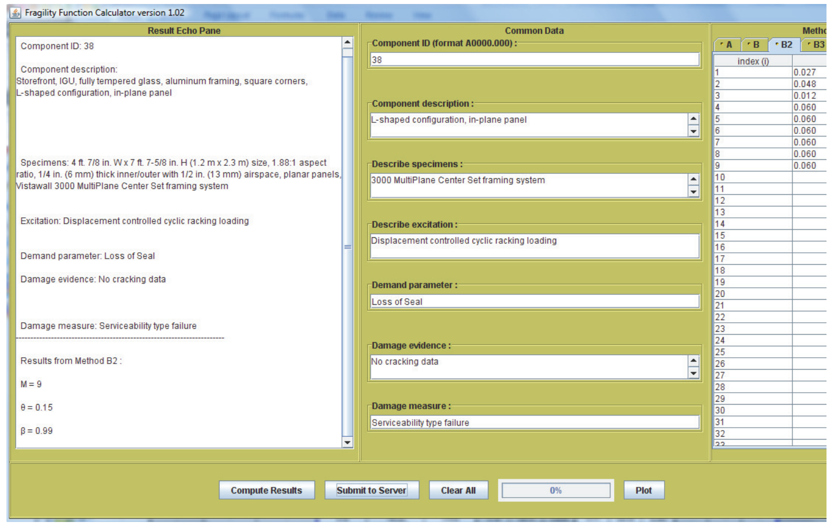

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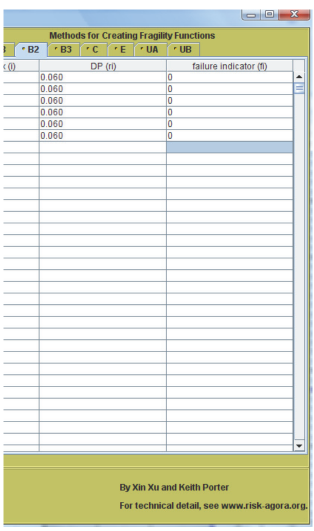

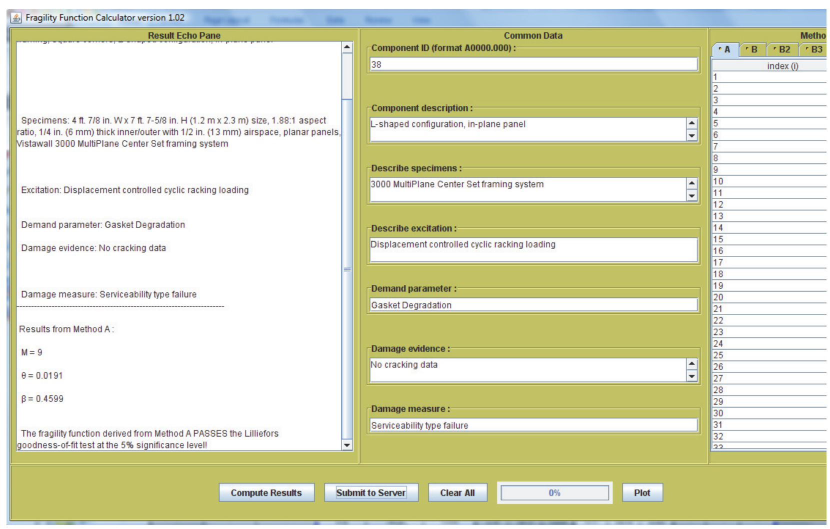

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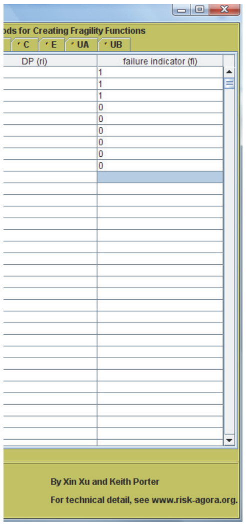
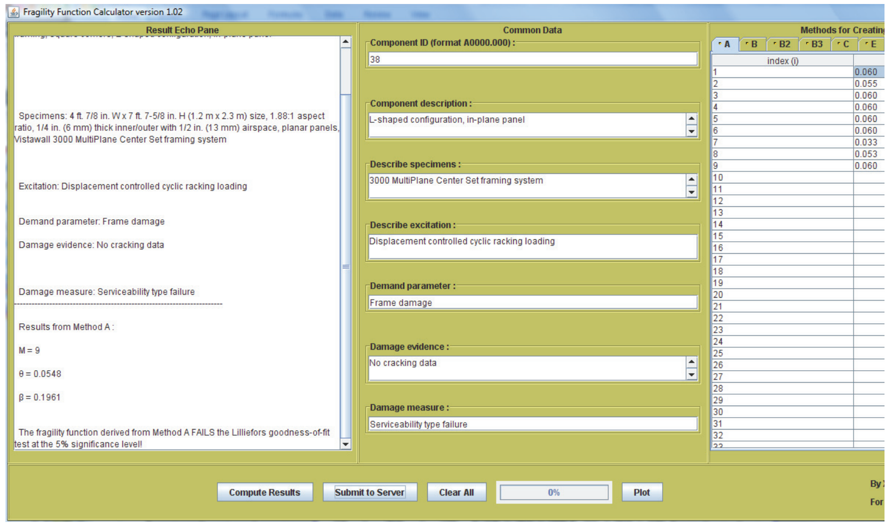
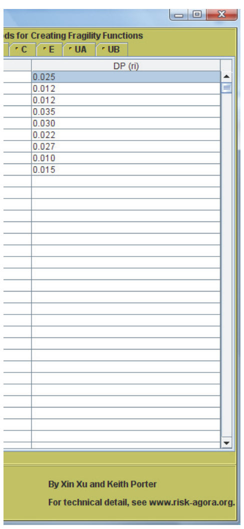
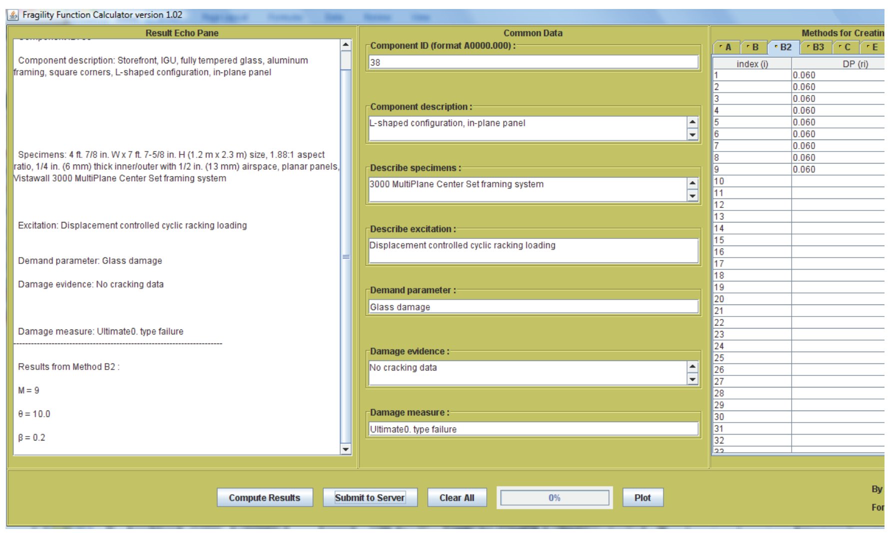


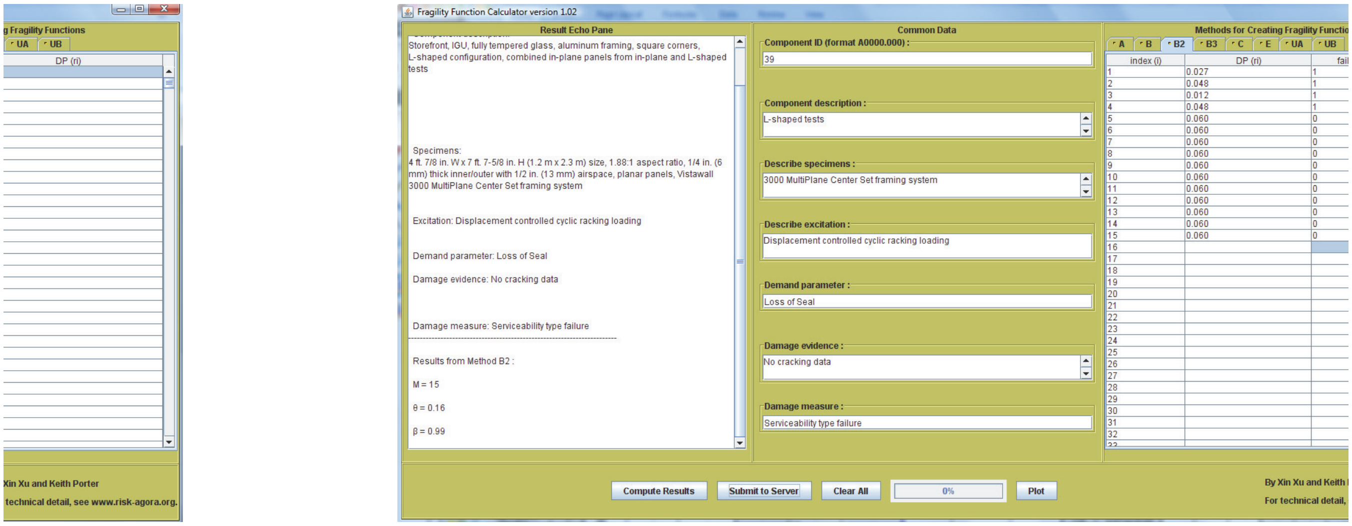


#38 GLASS CRACKING/FALLOUT

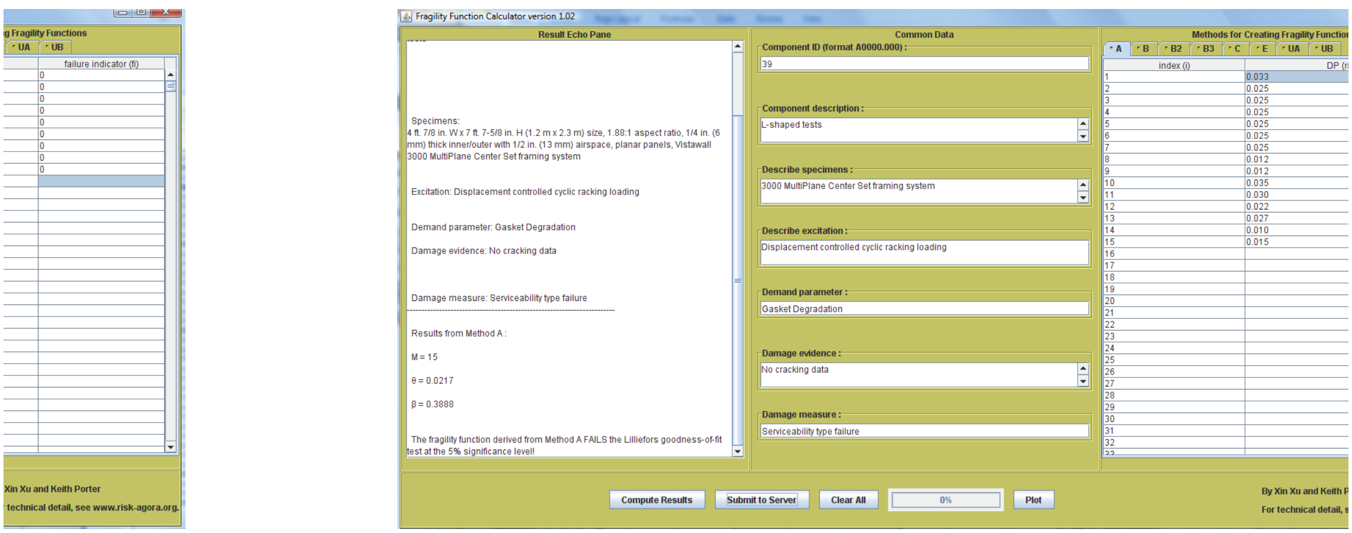




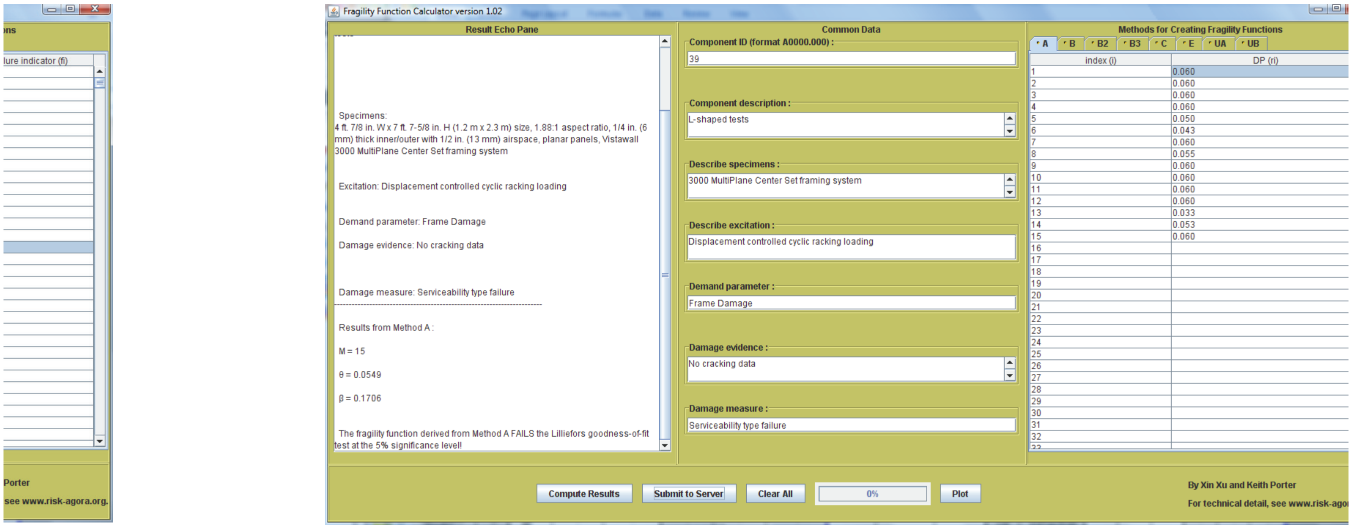
#39 LOSS OF SEAL



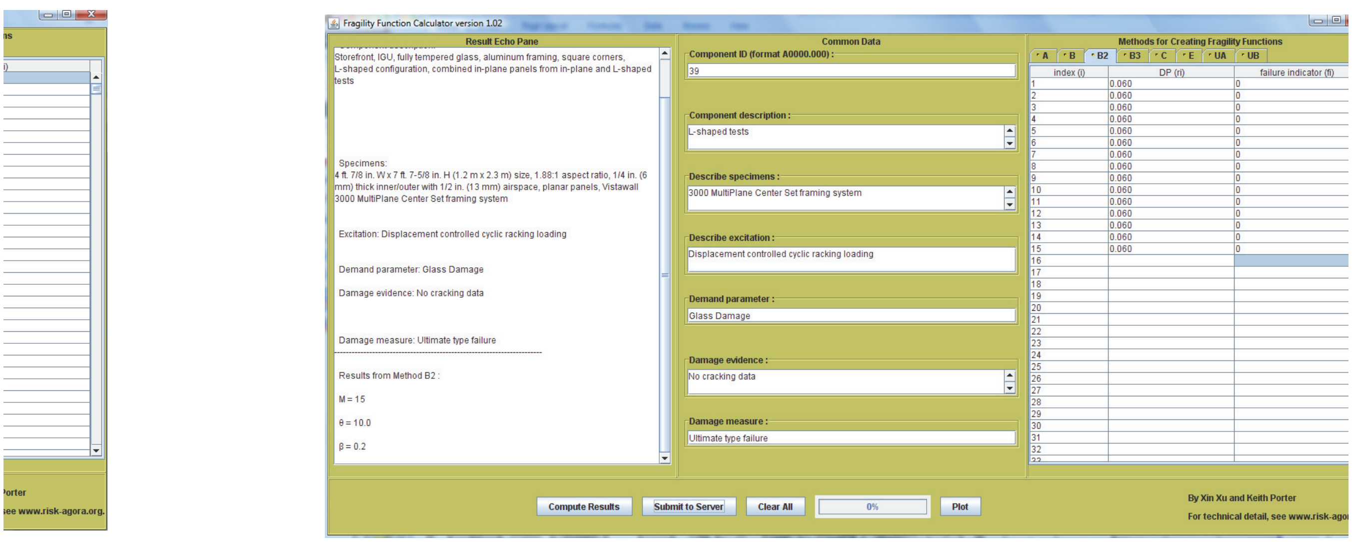
#39 GASKET DEGRADATION



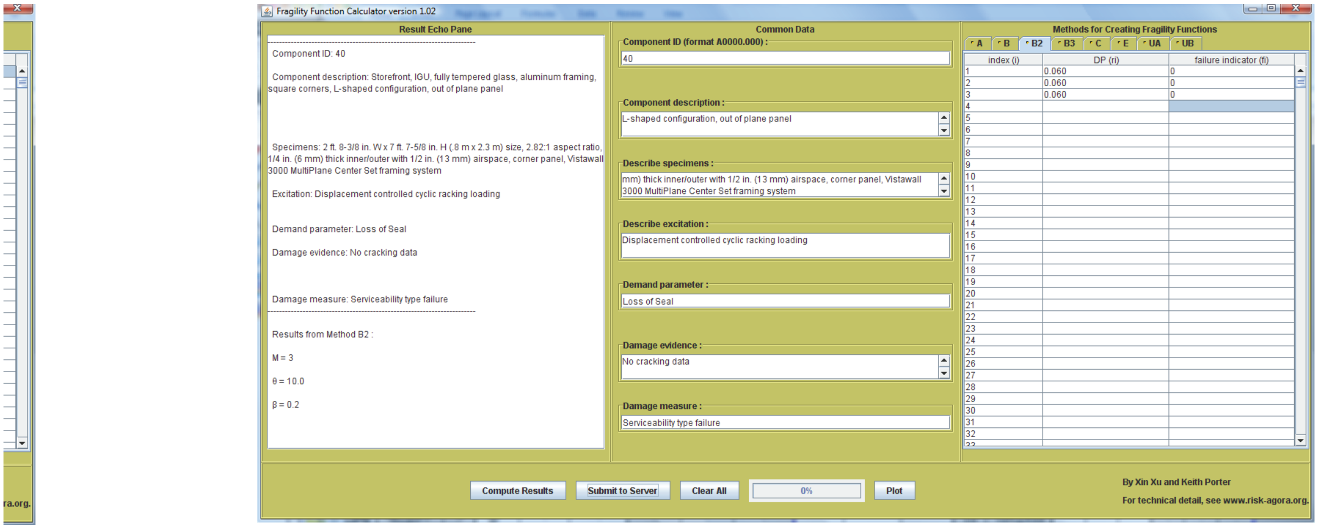
#39 FRAME DAMAGE



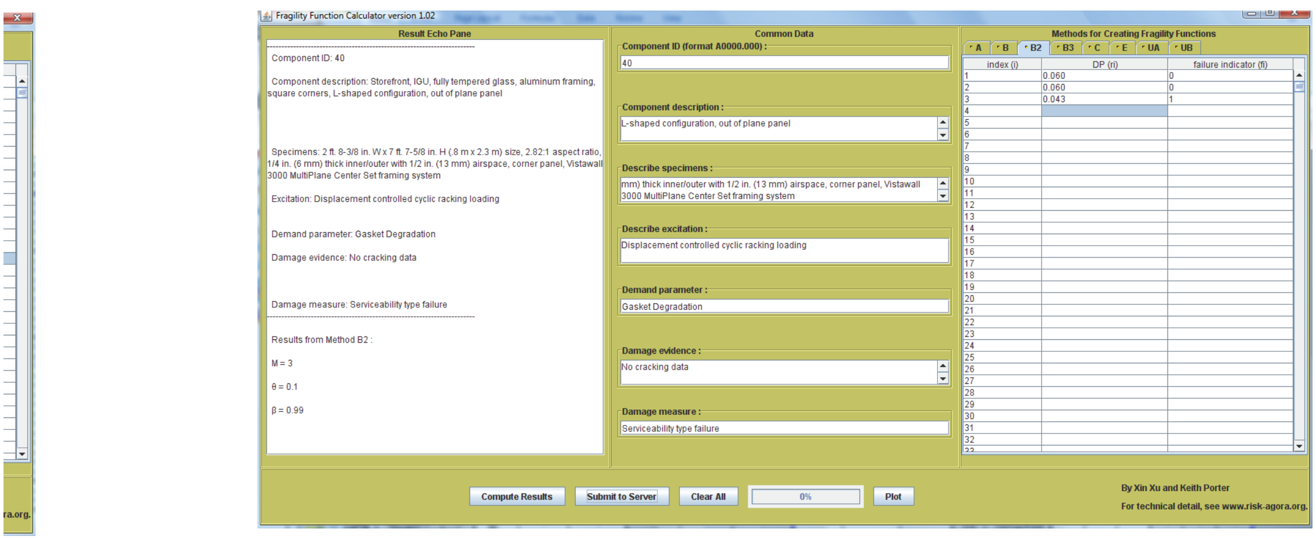
#39 GLASS CRACKING/FALLOUT



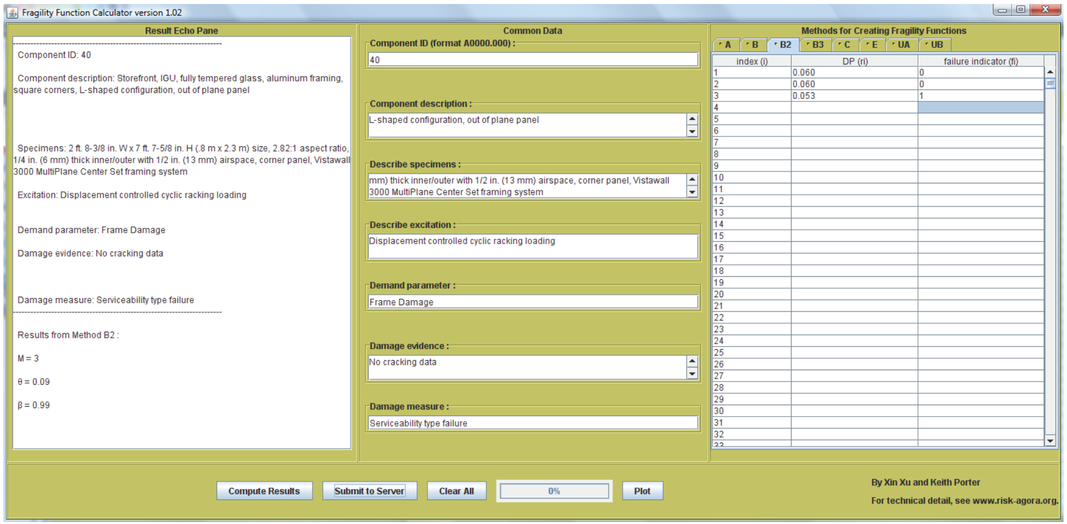
#40 LOSS OF SEAL



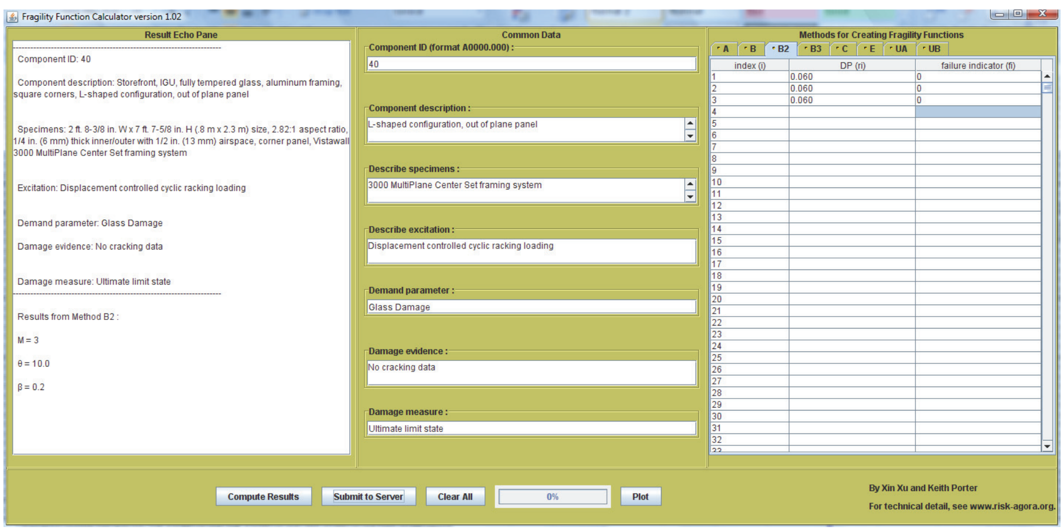
#40 GASKET DEGRADATION



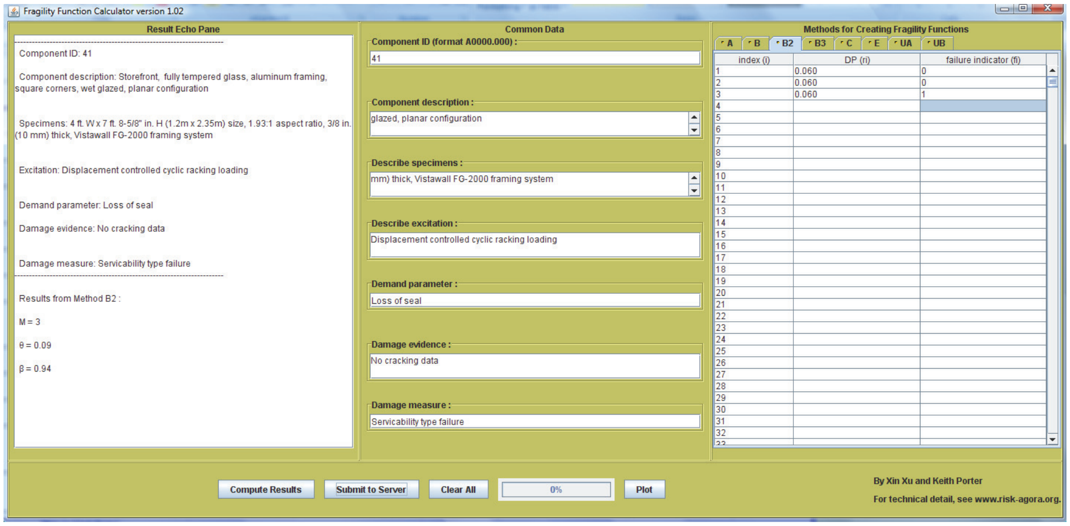
#40 FRAME DAMAGE



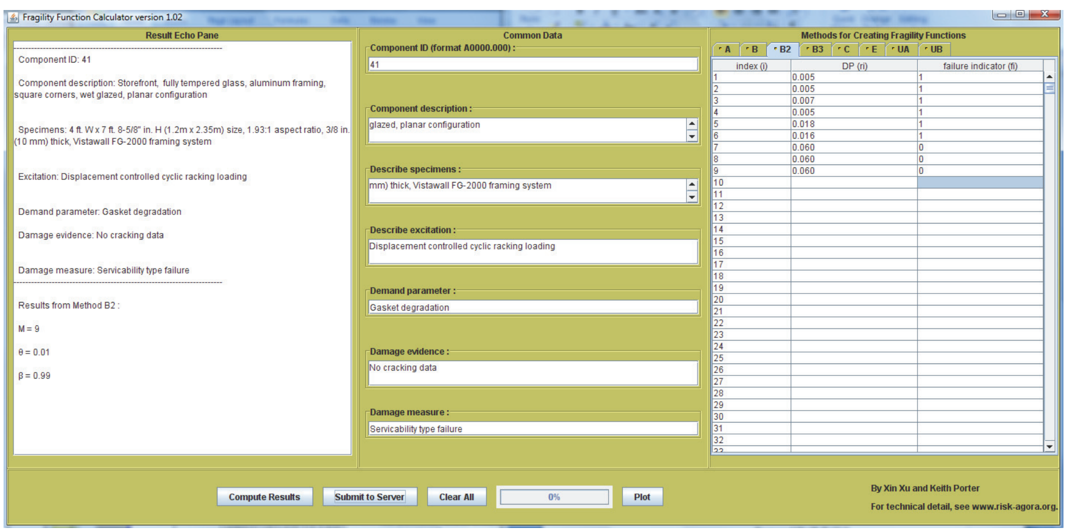
#40 GLASS CRACKING/FALLOUT



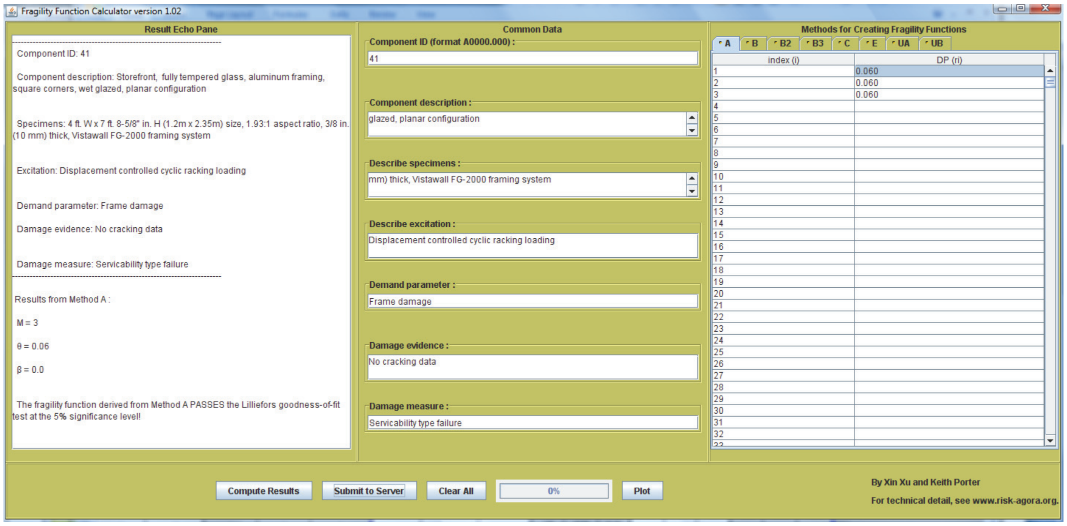
#41 LOSS OF SEAL



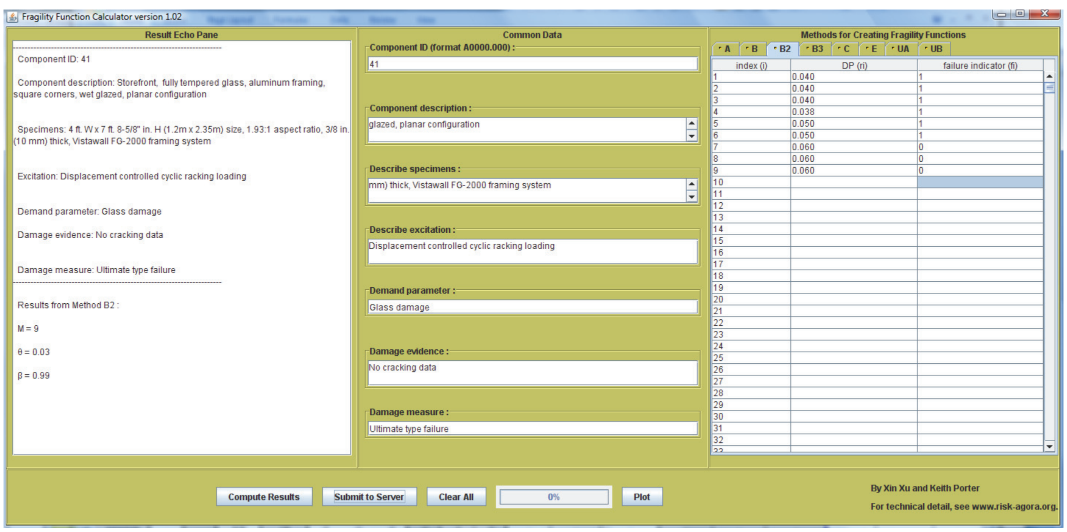
#41 GASKET DEGRADATION



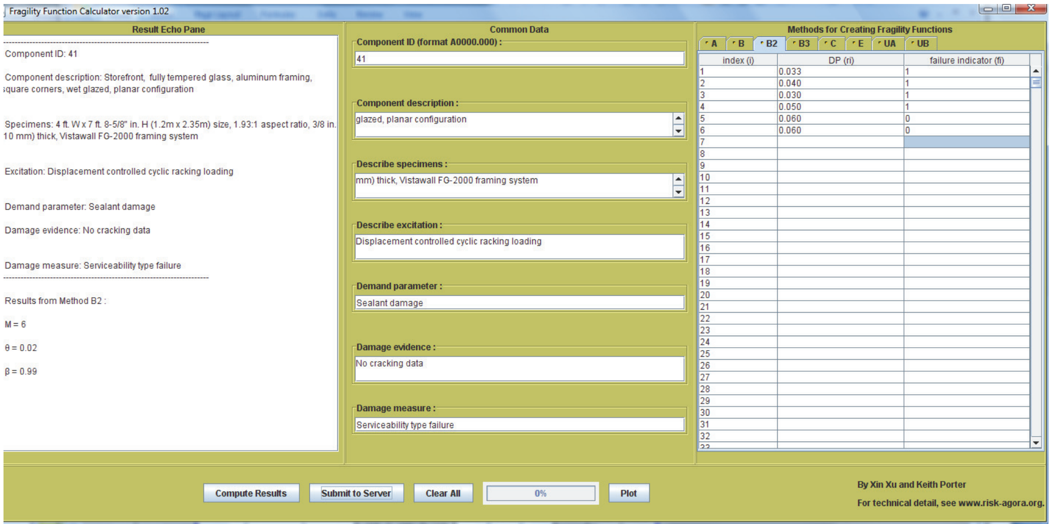
#41 FRAME DAMAGE **#41 SEALA**



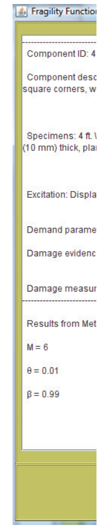
#41 GLASS CRACKING/FALLOUT **#42 LOSS (**



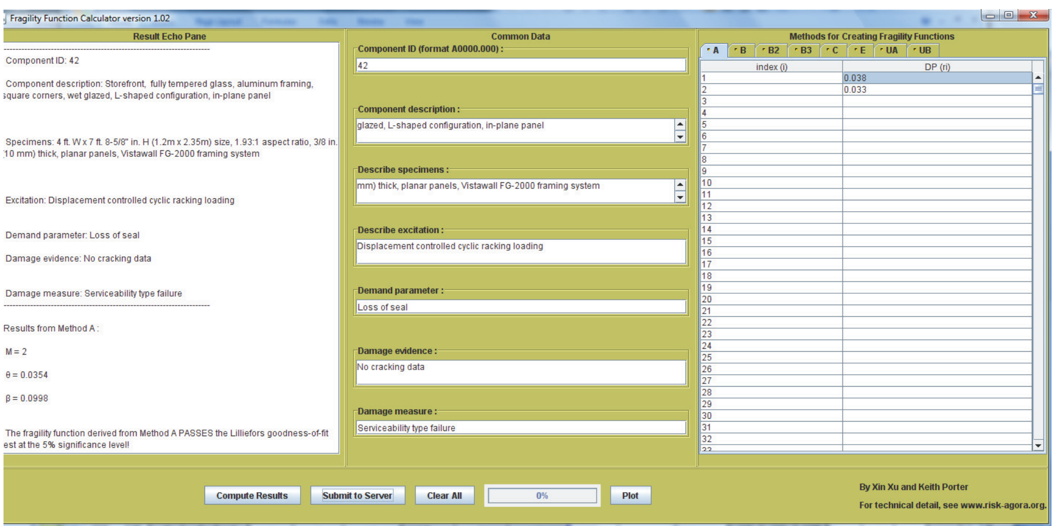
ANT DAMAGE



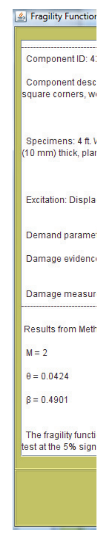
#42 GASKET DEGRA



OF SEAL

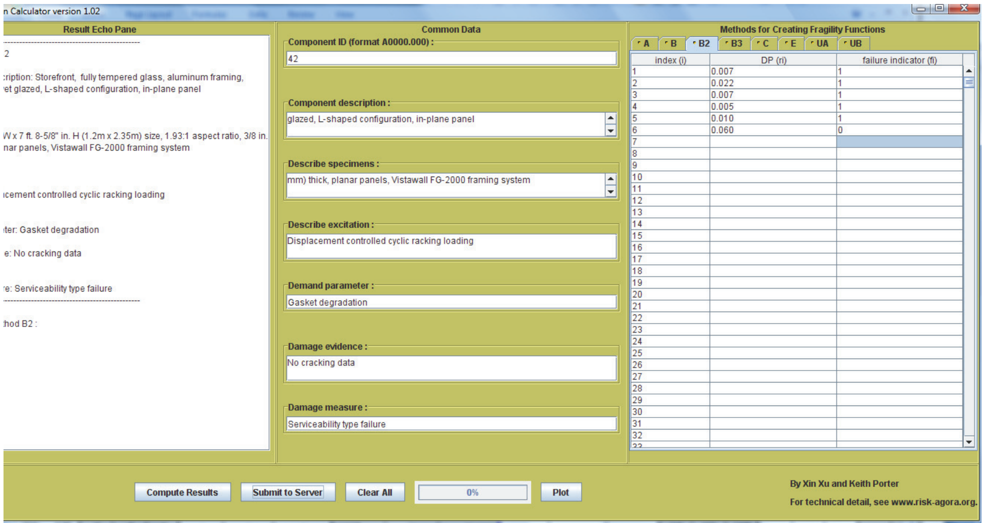


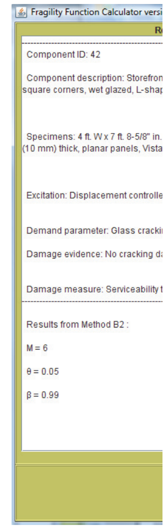
#42 FRAME DAMAGE



DATION

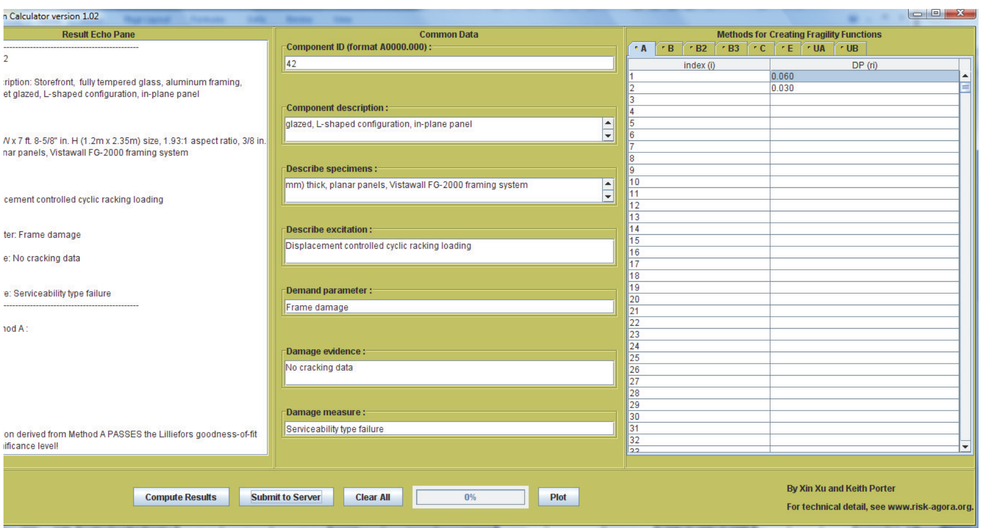
#42 GLASS CRACKING/FALLOU

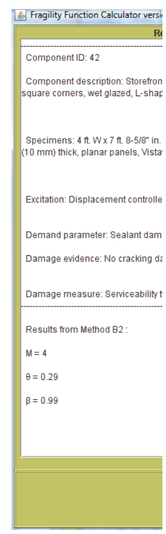




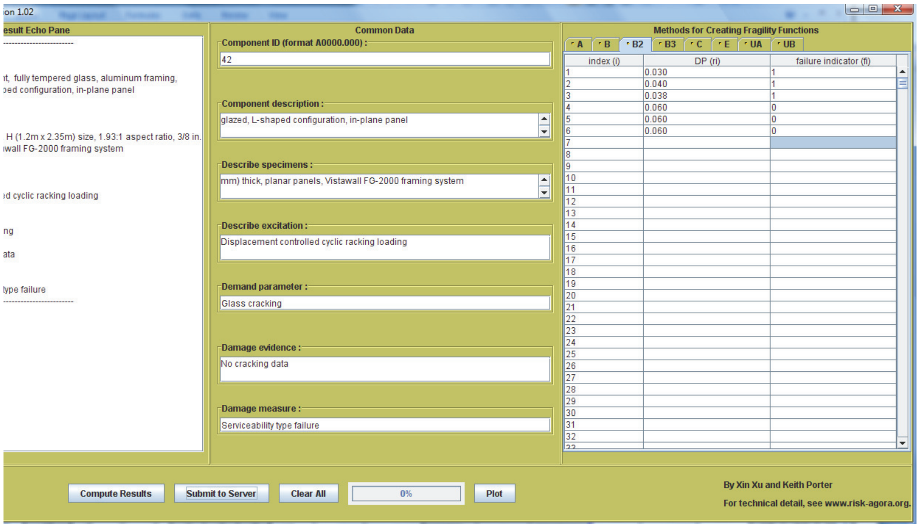
E

#42 SEALANT DAMAGE

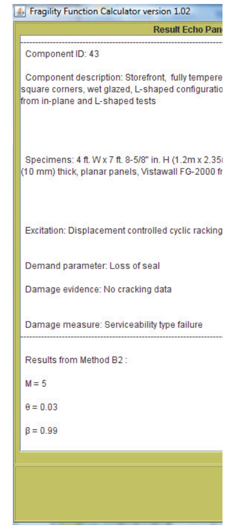


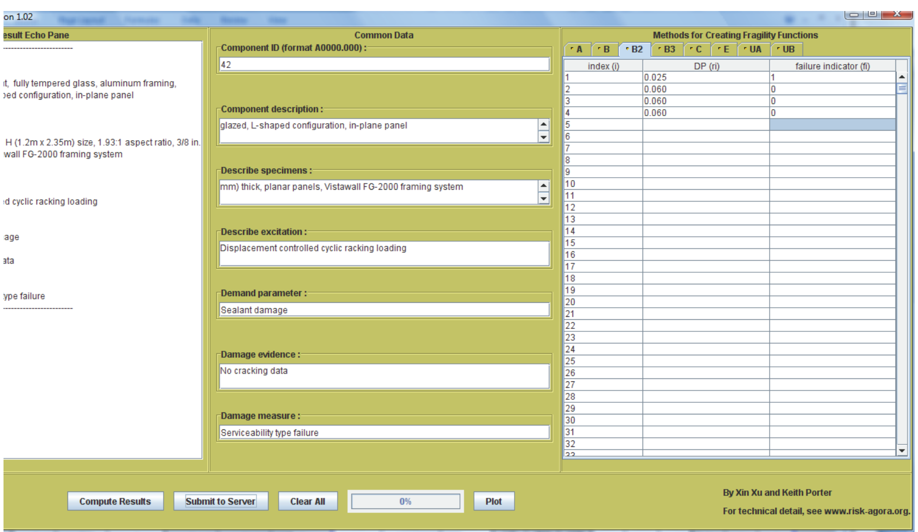


JT

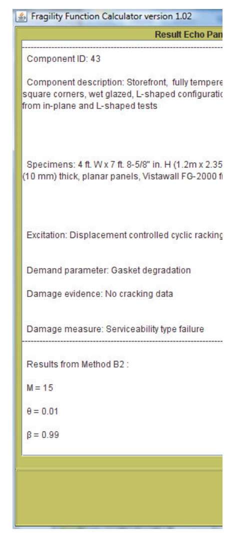


#43 LOSS OF SEAL

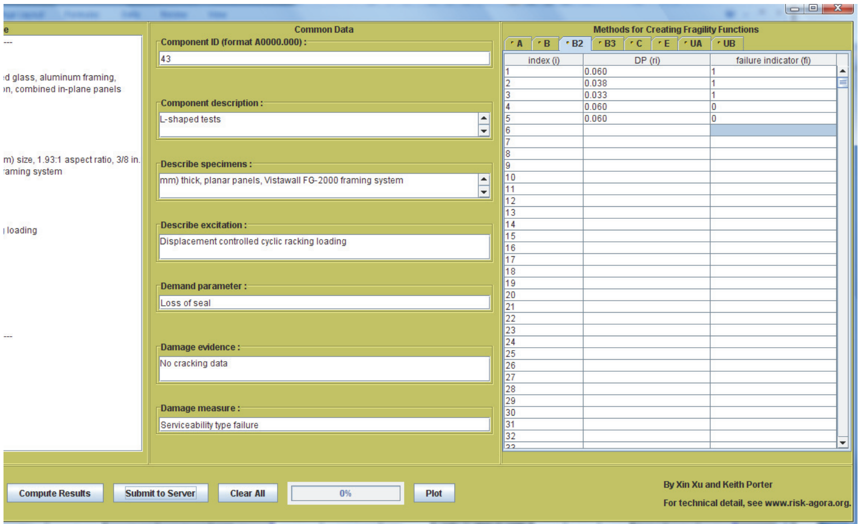


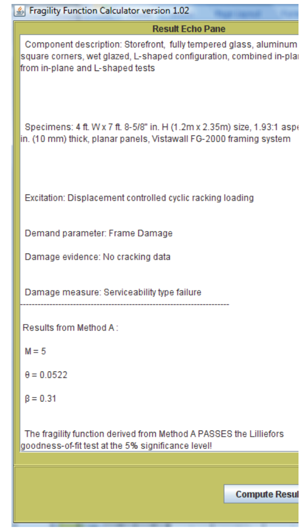


#43 GASKET DEGRADATION

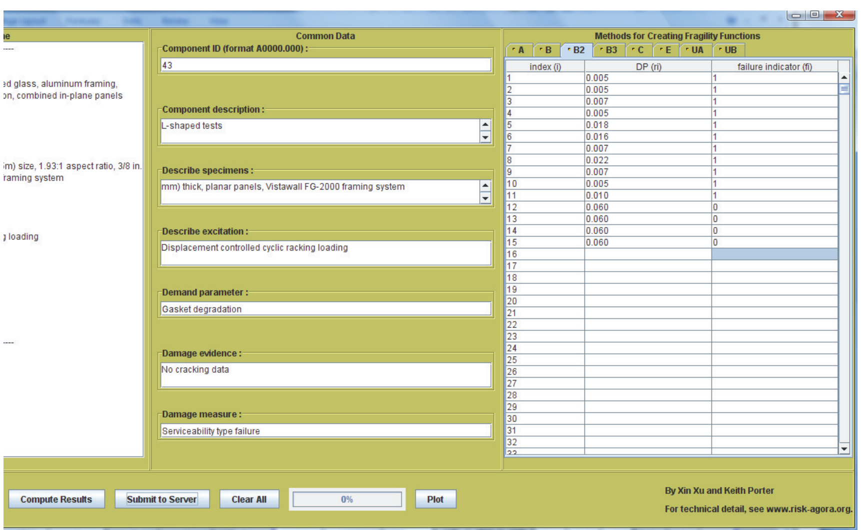


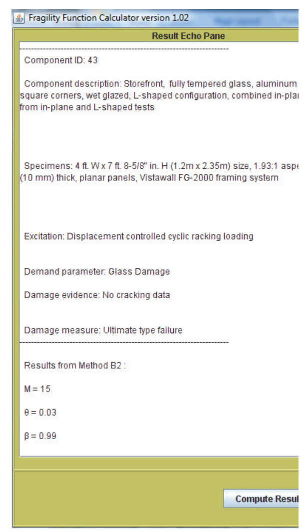
#43 FRAME DAMAGE



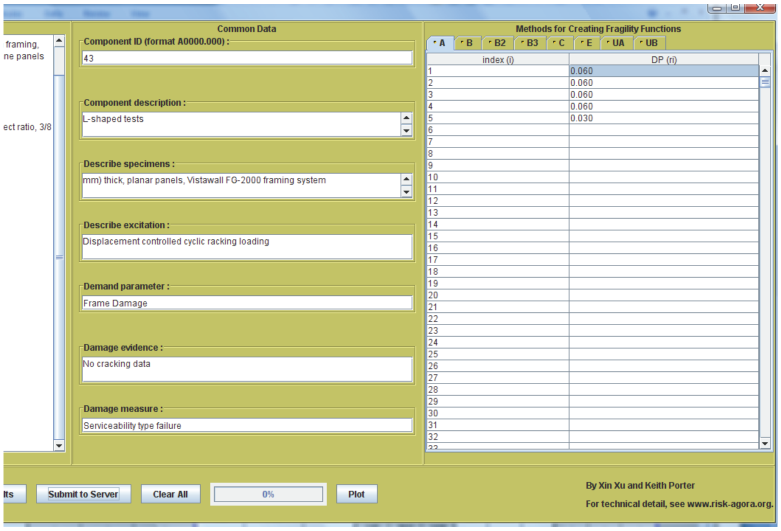


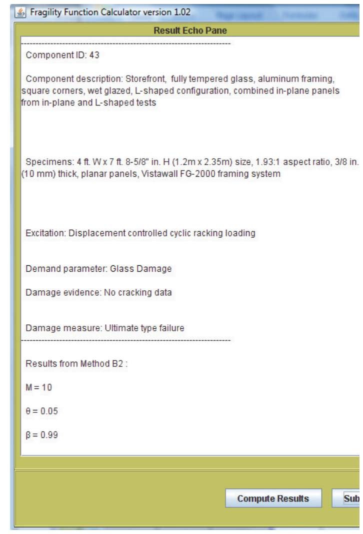
#43 GLASS CRACKING/FALLOUT



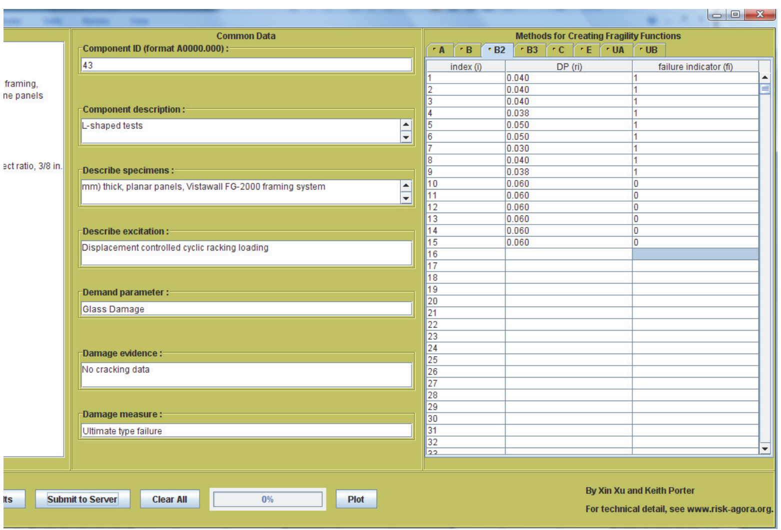


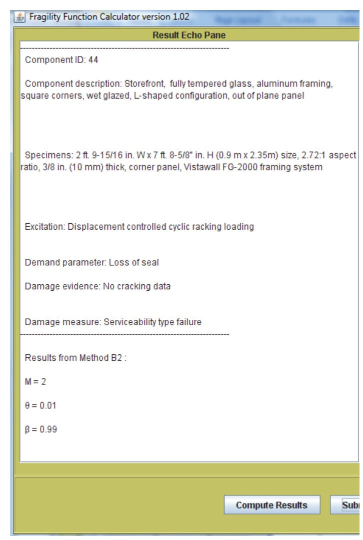
#43 SEALANT DAMAGE

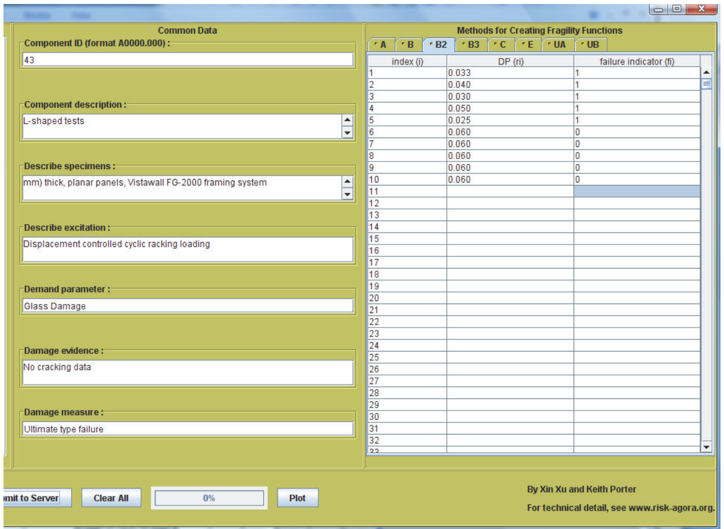




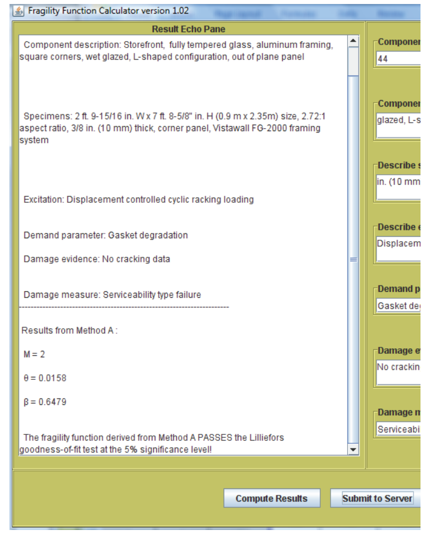
#44 LOSS OF SEAL

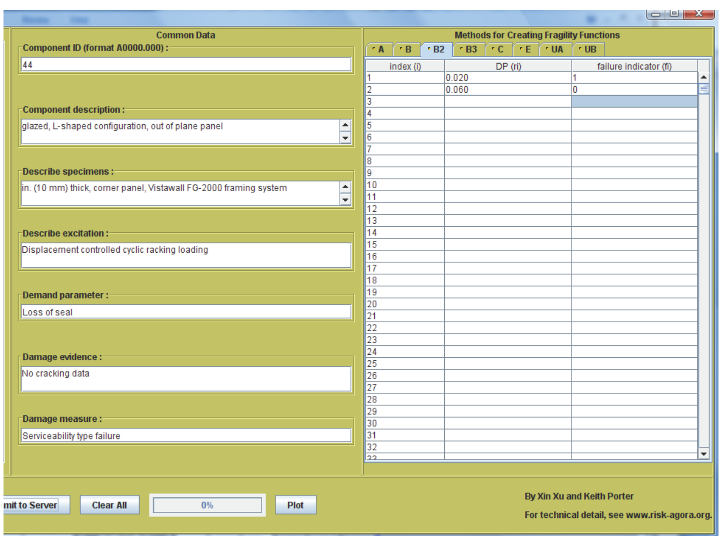




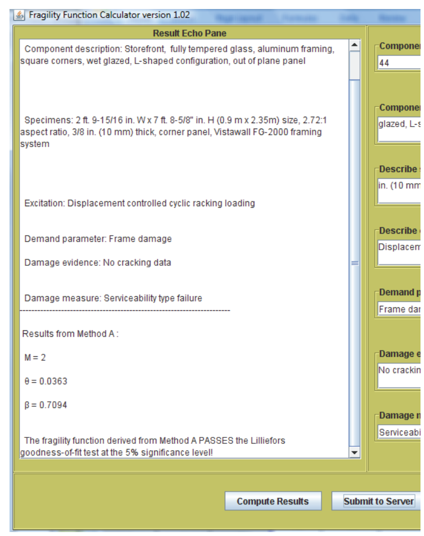


#44 GASKET DEGRADATION

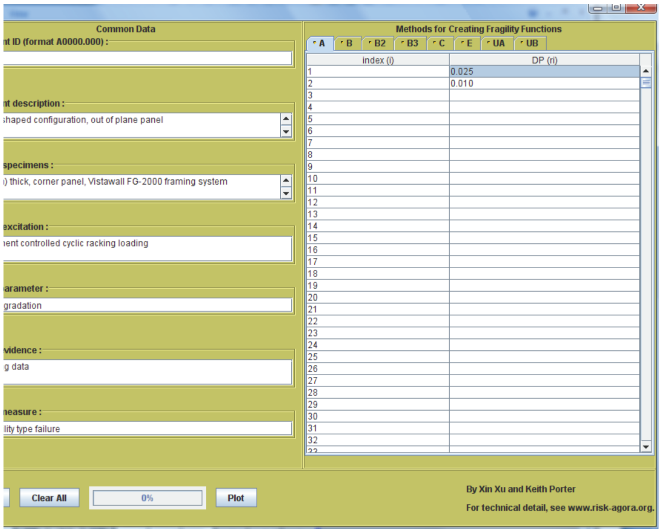


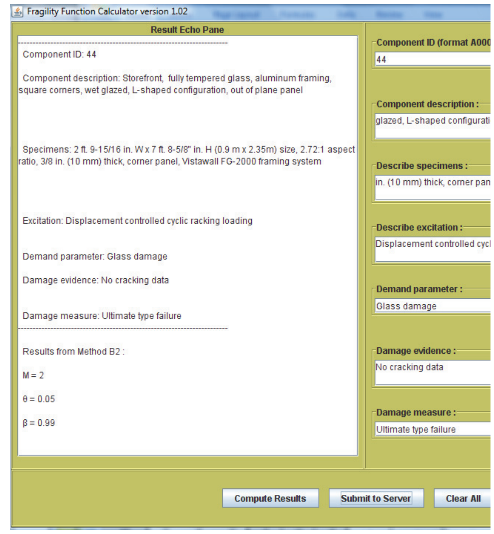


#44 FRAME DAMAGE

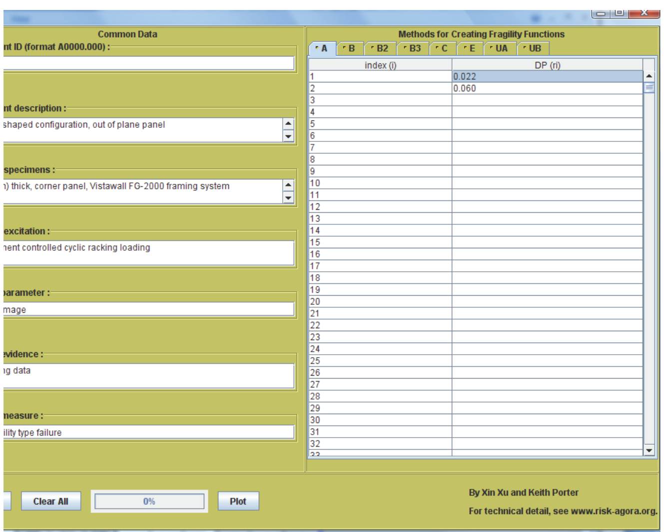


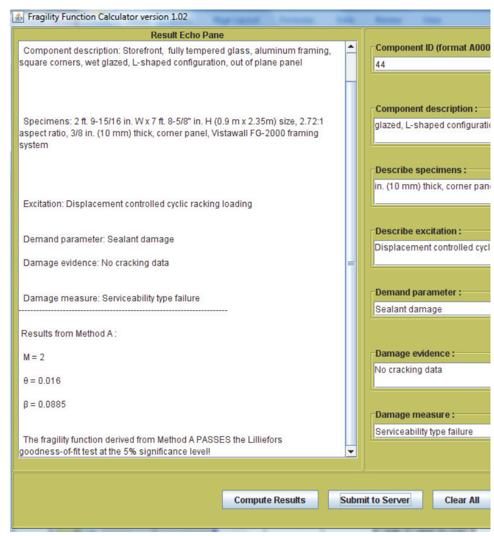
#44 GLASS CRACKING/FALLOUT

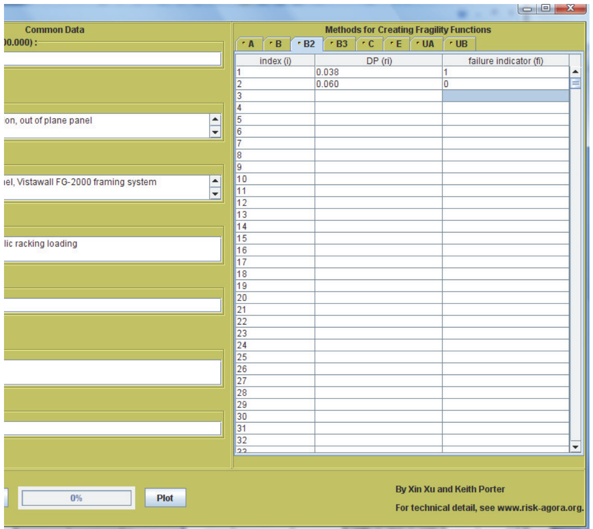


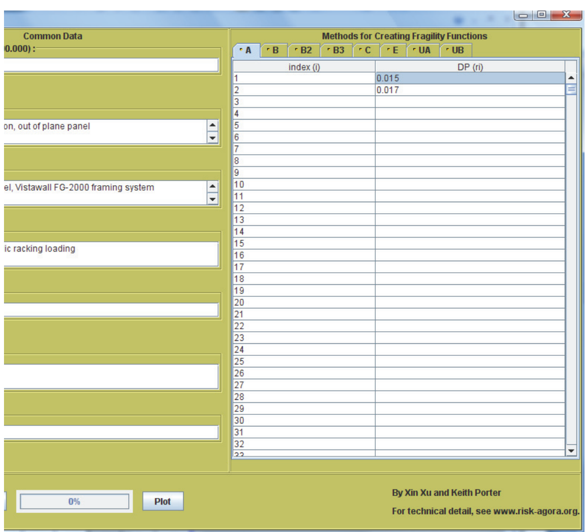


#44 SEALANT DAMAGE






Common Data
Methods for Creating Fragility Functions
A
B
B2
B3
C
E
UA
UB
index (i)
DP (ri)
failure indicator (fi)
0.038
0.060
on, out of plane panel
el, Vistawall FG-2000 framing system
lic racking loading
0%
Plot
By Xin Xu and Keith Porter
For technical detail, see www.risk-agora.org.


Common Data
Methods for Creating Fragility Functions
A
B
B2
B3
C
E
UA
UB
index (i)
DP (ri)
0.015
0.017
on, out of plane panel
el, Vistawall FG-2000 framing system
lic racking loading
0%
Plot
By Xin Xu and Keith Porter
For technical detail, see www.risk-agora.org.

Appendix D

Supplemental Fragility Development Tables

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 1** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed Monolithic, square corners, cut corner finish, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0138	0.0219
Beta(1):	0.262	0.315
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity	37.25	37.25
Min cost over upper qty	36.50	36.50
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	7
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ____
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0142	1	0.0232	1	n/a		
2	0.0115	1	0.0248	1	n/a		
3	0.0142	1	0.0272	1	n/a		
4	0.0142	1	0.0248	1	n/a		
5	0.0142	1	0.0168	1	n/a		
6	0.0142	1	0.0168	1	n/a		
7	0.0142	1	0.0221	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	N	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 2** **ANNEALED INSULATING GLASS UNIT**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed IGU, square corners, cut corner finish, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0234	0.0310
Beta(1):	0.300	0.295
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity	40.75	81.50
Min cost over upper qty	40	80
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	7
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ___
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0221	1	0.0381	1	n/a		
2	0.0301	1	0.0328	1	n/a		
3	0.0195	1	0.0275	1	n/a		
4	0.0195	1	0.0275	1	n/a		
5	0.0275	1	0.0381	1	n/a		
6	0.0248	1	0.0275	1	n/a		
7	0.0221	1	0.0275	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	N	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 3** **ASSYMETRIC (inner AN MONO/outer AN LAM.) INSULATING GLASS UNIT**			
Component category:	Exterior Glass Curtain Wall		
Basic composition:	Asymmetric IGU, 1/4 in. (6 mm) inner AN mono glass, 1/8 in. (3 mm) outer AN lam. (0.030 PVB) outer glass, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), square corners, cut corner finish, cut edge finish, avg. 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing		
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor		
Demand parameter (DP):	Peak Transient Interstory Drift Ratio		
Number of damage states:	3		
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous		
Author and date:	Memari et al. – March 2009		
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:	Glass Cracking	Glass Fallout	Gasket Seal Failure
Illustration:			
Median DP(1):	0.0276	0.0303	0.0270
Beta(1):	0.298	0.290	0.320
Probability(1):			
Correlation:	-	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime	Remove glass panel and replace damage gaskets
Possible consequences:			
Repair cost (Y/N/?):	Yes	Yes	Yes
Death or injury (Y/N/?):	No	Yes	No
Inoperative facility (Y/N/?):	No	Yes	No
Cost per unit(2)			
Max cost to lower quantity	47	87.75	11
Min cost over upper qty	46	86	11
Beta (cost)			
Lower quantity	4200	4200	
Upper quantity			
Repair duration per unit(2)			
Max duration to lower qty	6	6	2
Min duration over upper qty			
Beta (duration)			
Life-safety consequences(2)			
Comments:			

(1) If ordered damage states, leave “probability” blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in “probability.”

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	6
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0275	1	0.0301	1	0.0275	1	
2	0.0275	1	0.0301	1	0.0248	1	
3	0.0301	1	0.0328	1	0.0328	1	
4	0.0248	1	0.0275	1	0.0221	1	
5	0.0221	1	0.0248	1	0.0221	1	
6	0.0354	1	0.0381	1	0.0354	1	

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	Y
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 4** **ASSYMETRIC (inner AN MONO/outer AN LAM.) INSULATING GLASS UNIT**			
Component category:	Exterior Glass Curtain Wall		
Basic composition:	Asymmetric IGU, 1/4 in. (6 mm) inner AN mono glass, 1/8 in. (3 mm) outer AN lam. (0.060 PVB) outer glass, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), square corners, cut corner finish, cut edge finish, avg. 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing		
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor		
Demand parameter (DP):	Peak Transient Interstory Drift Ratio		
Number of damage states:	3		
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous		
Author and date:	Memari et al. – March 2009		
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:	Glass Cracking	Glass Fallout	Gasket Seal Failure
Illustration:			
Median DP(1):	0.0266	0.0299	0.0262
Beta(1):	0.322	0.346	0.317
Probability(1):	-	-	-
Correlation:			
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime	Remove glass panel and replace damage gaskets
Possible consequences:			
Repair cost (Y/N/?):	Yes	Yes	Yes
Death or injury (Y/N/?):	No	Yes	No
Inoperative facility (Y/N/?):	No	Yes	No
Cost per unit(2)			
Max cost to lower quantity	47	87.75	11
Min cost over upper qty	46	86	11
Beta (cost)			
Lower quantity	4200	4200	
Upper quantity			
Repair duration per unit(2)			
Max duration to lower qty	6	6	2
Min duration over upper qty			
Beta (duration)			
Life-safety consequences(2)			
Comments:			

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	6
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ____________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0328	1	0.0381	1	0.0328	1	
2	0.0301	1	0.0354	1	0.0275	1	
3	0.0275	1	0.0328	1	0.0275	1	
4	0.0221	1	0.0221	1	0.0221	1	
5	0.0195	1	0.0221	1	0.0195	1	
6	0.0301	1	0.0328	1	0.0301	1	

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	Y
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 5** **ASSYMETRIC (inner AN MONO/outer AN LAM.) INSULATING GLASS UNIT**			
Component category:	Exterior Glass Curtain Wall		
Basic composition:	Asymmetric IGU, 1/4 in. (6 mm) inner AN mono glass, 1/4 in. (6 mm) outer AN lam. (0.030 PVB) outer glass, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), square corners, cut corner finish, cut edge finish, avg. 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing		
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor		
Demand parameter (DP):	Peak Transient Interstory Drift Ratio		
Number of damage states:	3		
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous		
Author and date:	Memari et al. – March 2009		
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:	Glass Cracking	Glass Fallout	Gasket Seal Failure
Illustration:			
Median DP(1):	0.0268	0.0339	0.0260
Beta(1):	0.289	0.268	0.272
Probability(1):	-	-	-
Correlation:	-	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime	Remove glass panel and replace damage gaskets
Possible consequences:			
Repair cost (Y/N/?):	Yes	Yes	Yes
Death or injury (Y/N/?):	No	Yes	No
Inoperative facility (Y/N/?):	No	Yes	No
Cost per unit(2)			
Max cost to lower quantity	47	87.75	11
Min cost over upper qty	46	86	11
Beta (cost)			
Lower quantity	4200	4200	
Upper quantity			
Repair duration per unit(2)			
Max duration to lower qty	6	6	2
Min duration over upper qty			
Beta (duration)			
Life-safety consequences(2)			
Comments:			

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	6
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0221	1	0.0384	1	0.0221	1	
2	0.0328	1	0.0328	1	0.0275	1	
3	0.0275	1	0.0354	1	0.0275	1	
4	0.0248	1	0.0301	1	0.0248	1	
5	0.0248	1	0.0310	1	0.0248	1	
6	0.0301	1	0.0368	1	0.0301	1	

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	Y	Y
Discussion: see report			

Fragility, damage measures, and consequences for EXTERIOR GLASS CURTAIN WALL – TYPE 6 ANNEALED LAMINATED		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed Laminated, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass (0.030 PVB) square corners, cut corner finish, cut edge finish, 0.43 in. (11 mm) glass-to-frame clearance Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP[(1)]:	0.0156	0.0561
Beta[(1)]:	0.343	0.311
Probability[(1)]:	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	Yes	Yes
Death or injury (Y/N/?):	No	Yes
Inoperative facility (Y/N/?):	No	Yes
Cost per unit[(2)]		
Max cost to lower quantity	40.40	80.75
Min cost over upper qty	39.60	79.10
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit[(2)]		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences[(2)]		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	24
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	**DS1**		**DS2**		**DS3**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0142	1	0.0641	1	n/a		
2	0.0142	1	0.0548	1	n/a		
3	0.0168	1	0.0544	1	n/a		
4	0.0115	1	0.0431	1	n/a		
5	0.0115	1	0.0640	1	n/a		
6	0.0168	1	0.0610	1	n/a		
7	0.0115	1	0.0643	1	n/a		
8	0.0115	1	0.0344	1	n/a		
9	0.0142	1	0.0437	1	n/a		
10	0.0115	1	0.0419	1	n/a		
11	0.0142	1	0.0592	1	n/a		
12	0.0115	1	0.0614	1	n/a		
13	0.0221	1	0.0620	1	n/a		
14	0.0142	1	0.0381	1	n/a		
15	0.0168	1	0.0620	1	n/a		
16	0.0168	1	0.0620	1	n/a		
17	0.0142	1	0.0620	1	n/a		
18	0.0168	1	0.0620	1	n/a		
19	0.0221	1	0.0620	1	n/a		
20	0.0221	1	0.0620	1	n/a		
21	0.0195	1	0.0620	1	n/a		
22	0.0221	1	0.0620	1	n/a		
23	0.0195	1	0.0620	1	n/a		
24	0.0195	1	0.0620	1	n/a		

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	N	n/a

Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are $0.2 \le \beta \le 0.6$? If not discuss.	Y	Y	n/a
Discussion: *see report*			

Fragility, damage measures, and consequences for **EXTERIOR GLASS STOREFRONT – TYPE 7** **ANNEALED MONOLITHIC**			
Component category:	Exterior Glass Storefront		
Basic composition:	Annealed Monolithic, square corners, cut corner finish, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 0.41 in. (10 mm) avg. glass-to-frame clearance, Kawneer TriFab II 451 Storefront curtain wall framing		
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor		
Demand parameter (DP):	Peak Transient Interstory Drift Ratio		
Number of damage states:	3		
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous		
Author and date:	Memari et al. – March 2009		
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:	Glass Cracking	Glass Fallout	Gasket Seal Failure
Illustration:			
Median DP(1):	0.0413	0.0510	0.0303
Beta(1):	0.284	0.290	0.492
Probability(1):	-	-	-
Correlation:	-	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime	Remove glass panel and replace damage gaskets
Possible consequences:			
Repair cost (Y/N/?):	Yes	Yes	Yes
Death or injury (Y/N/?):	No	Yes	No
Inoperative facility (Y/N/?):	No	Yes	No
Cost per unit(2)			
Max cost to lower quantity	31.25	31.25	11
Min cost over upper qty	30.60	30.60	11
Beta (cost)			
Lower quantity	4200	4200	
Upper quantity			
Repair duration per unit(2)			
Max duration to lower qty	6	6	2
Min duration over upper qty			
Beta (duration)			
Life-safety consequences(2)			
Comments:			

(1) If ordered damage states, leave “probability” blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in “probability.”

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	12
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0340	1	0.0519	1	0.0247	1	
2	0.0401	1	0.0420	1	0.0417	1	
3	0.0525	1	0.0654	1	0.0448	1	
4	0.0401	1	0.0407	1	0.0386	1	
5	0.0432	1	0.0556	1	0.0278	1	
6	0.0525	1	0.0617	1	0.0309	1	
7	0.0370	1	0.0537	1	0.0309	1	
8	0.0401	1	0.0525	1	0.0093	1	
9	0.0432	1	0.0512	1	0.0401	1	
10	0.0370	1	0.0432	1	0.0278	1	
11	0.0432	1	0.0537	1	0.0432	1	
12	0.0370	1	0.0463	1	0.0278	1	

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	Y
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS STOREFRONT – TYPE 8** **ANNEALED INSULATING GLASS UNIT**			
Component category:	Exterior Glass Storefront		
Basic composition:	Annealed IGU, square corners, cut corner finish, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1 in. (25 mm) thick glass, 0.594 in. (15 mm) avg. glass-to-frame clearance, Kawneer TriFab II 451 Storefront curtain wall framing		
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor		
Demand parameter (DP):	Peak Transient Interstory Drift Ratio		
Number of damage states:	3		
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous		
Author and date:	Memari et al. – March 2009		
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:	Glass Cracking	Glass Fallout	Gasket Seal Failure
Illustration:			
Median DP(1):	0.0590	0.0665	0.0423
Beta(1):	0.258	0.253	0.303
Probability(1):	-	-	
Correlation:	-	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime	Remove glass panel and replace damage gaskets
Possible consequences:			
Repair cost (Y/N/?):	Yes	Yes	Yes
Death or injury (Y/N/?):	No	Yes	No
Inoperative facility (Y/N/?):	No	Yes	No
Cost per unit(2)			
Max cost to lower quantity	31.25	62.50	11
Min cost over upper qty	30.60	61.20	11
Beta (cost)			
Lower quantity	4200	4200	
Upper quantity			
Repair duration per unit(2)			
Max duration to lower qty	6	6	2
Min duration over upper qty			
Beta (duration)			
Life-safety consequences(2)			
Comments:			

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	12
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	**DS1**		**DS2**		**DS3**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0586	1	0.0685	1	0.0309	1	
2	0.0586	1	0.0648	1	0.0356	1	
3	0.0586	1	0.0611	1	0.0448	1	
4	0.0556	1	0.0710	1	0.0463	1	
5	0.0556	1	0.0679	1	0.0432	1	
6	0.0556	1	0.0667	1	0.0432	1	
7	0.0617	1	0.0648	1	0.0463	1	
8	0.0556	1	0.0648	1	0.0494	1	
9	0.0586	1	0.0648	1	0.0340	1	
10	0.0679	1	0.0679	1	0.0510	1	
11	0.0648	1	0.0679	1	0.0525	1	
12	0.0586	1	0.0679	1	0.0370	1	

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	N	Y	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	Y	Y
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS STOREFRONT – TYPE 9** **ANNEALED LAMINATED**			
Component category:	Exterior Glass Curtain Wall		
Basic composition:	Annealed Laminated, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass (0.030 PVB) square corners, cut corner finish, cut edge finish, 0.41 in. (10 mm) avg. glass-to-frame clearance, Kawneer TriFab II 451 Storefront curtain wall framing		
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor		
Demand parameter (DP):	Peak Transient Interstory Drift Ratio		
Number of damage states:	3		
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous		
Author and date:	Memari et al. – March 2009		
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:	Glass Cracking	Glass Fallout	Gasket Seal Failure
Illustration:			
Median DP(1):	0.0567	0.0800	0.0290
Beta(1):	0.289	0.9900	0.514
Probability(1):			
Correlation:			
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime	Remove glass panel and replace damage gaskets
Possible consequences:			
Repair cost (Y/N/?):	Yes	Yes	Yes
Death or injury (Y/N/?):	No	Yes	No
Inoperative facility (Y/N/?):	No	Yes	No
Cost per unit(2)			
Max cost to lower quantity	34.40	68.75	11
Min cost over upper qty	33.70	67.40	11
Beta (cost)			
Lower quantity	4200	4200	
Upper quantity			
Repair duration per unit(2)			
Max duration to lower qty	6	6	2
Min duration over upper qty			
Beta (duration)			
Life-safety consequences(2)			
Comments:			

(1) If ordered damage states, leave “probability” blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in “probability.”

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	12
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0648	1	0.0741	0	0.0325	1	Used bounded fragility
2	0.0617	1	0.0741	1	0.0340	1	Development for DS2
3	0.0463	1	0.0679	1	0.0386	1	
4	0.0494	1	0.0741	0	0.0093	1	
5	0.0525	1	0.0741	0	0.0370	1	
6	0.0525	1	0.0741	0	0.0340	1	
7	0.0679	1	0.0679	1	0.0401	1	
8	0.0525	1	0.0741	0	0.0278	1	
9	0.0679	1	0.0710	1	0.0263	1	
10	n/a	n/a	n/a	n/a	n/a	n/a	The test results are unusable
11	n/a	n/a	n/a	n/a	n/a	n/a	The test results are unusable
12	n/a	n/a	n/a	n/a	n/a	n/a	The test results are unusable

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	n/a	Y
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	n/a	Y
Discussion: DS2 used a Bounding Demand Data analysis.			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 10** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed Monolithic, square corners, cut corner finish, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 0 in. (0 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0088	0.0108
Beta(1):	0.252	0.251
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity	37.25	37.25
Min cost over upper qty	36.50	36.50
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0086	1	0.0106	1	n/a		
2	0.0090	1	0.0110	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 11** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed Monolithic, square corners, cut corner finish, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 1/8 in. (3 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0084	0.0107
Beta(1):	0.261	0.359
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity	37.25	37.25
Min cost over upper qty	36.50	36.50
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave “probability” blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in “probability.”
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report “Architectural Glass Seismic Behavior Fragility Curve Development”	
Number of specimens tested:	2
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ____________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0089	1	0.0089	1	n/a		
2	0.0080	1	0.0128	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for

EXTERIOR GLASS CURTAIN WALL – TYPE 12

ANNEALED MONOLITHIC

Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed Monolithic, square corners, cut corner finish, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 1/4 in. (6 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0147	0.0164
Beta(1):	0.252	0.262
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity	37.25	37.25
Min cost over upper qty	36.50	36.50
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	3
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0150	1	0.0150	1	n/a		
2	0.0142	1	0.0168	1	n/a		
3	0.0149	1	0.0175	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ β ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 13** **ANNEALED INSULATING GLASS UNIT**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed IGU, square corners, cut corner finish, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 1/4 in. (6 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0142	0.0221
Beta(1):	0.250	0.250
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity	40.75	81.50
Min cost over upper qty	40	80
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	1
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0142	1	0.0221	1	n/a		Only one specimen tested using this configuration – therefore the median DP was based on this one value

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 14** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed Monolithic, square corners, cut corner finish, cut edge finish, 4 ft W x 8 ft H (1.2 m x 2.4 m) size, 2:1 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0181	0.0212
Beta(1):	0.262	0.250
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity	37.25	37.25
Min cost over upper qty	36.50	36.50
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave “probability” blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in “probability.”
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0171	1	0.0212	1	n/a		
2	0.0191	1	0.0212	1	n/a		

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 15** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Annealed Monolithic, square corners, cut corner finish, cut edge finish, 8 ft W x 4 ft H (2.4 m x 1.2 m) size, 1:2 aspect ratio (H:W), 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – March 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0220	0.0257
Beta(1):	0.277	0.271
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity	37.25	37.25
Min cost over upper qty	36.50	36.50
Beta (cost)		
Lower quantity	4200	4200
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty	6	6
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	**DS1**		**DS2**		**DS3**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0202	1	0.0239	1	n/a		
2	0.0239	1	0.0277	1	n/a		

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ β ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 16** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, annealed glass, aluminum framing, square corners, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, two-sided SSG, Kawneer 1600 curtain wall framing, GE one part silicone (SCS 2000), center panel, .5 in. (12.7mm) mid-joint weather seal width, .25 in. (6.4 mm) edge weather seal width	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0288	0.04
Beta(1):	0.2580	1.0211
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ____________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0275	1	0.0328	1	n/a		
2	0.0301	1	0.0401	0	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	N	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 17** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, annealed glass, aluminum framing, square corners, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, two-sided SSG, Kawneer 1600 curtain wall framing, GE one part silicone (SCS 2000), outside panels, .5 in. (12.7mm) mid-joint weatherseal width, .25 in. (6.4 mm) edge weather seal width	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0273	0.0286
Beta(1):	0.2827	0.2773
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	4
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0248	1	0.0275	1	n/a		
2	0.0275	1	0.0301	1	n/a		
3	0.0248	1	0.0248	1	n/a		
4	0.0328	1	0.0328	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 18** **FULLY TEMPERED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, fully tempered glass, aluminum framing, square corners, seamed edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, two-sided SSG, Kawneer 1600 curtain wall framing, GE one part silicone (SCS 2000), center panel, .5 in. (12.7mm) mid-joint weatherseal width, .25 in. (6.4 mm) edge weather seal width	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0434	0.0434
Beta(1):	0.25	0.25
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave “probability” blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in “probability.”

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ____________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	**DS1**		**DS2**		**DS3**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0434	1	0.0434	1	n/a		
2	0.434	1	0.0434	1	n/a		

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 19** **FULLY TEMPERED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, fully tempered glass, aluminum framing, square corners, seamed edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, two-sided SSG, Kawneer 1600 curtain wall framing, GE one part silicone (SCS 2000), outside panels, .5 in. (12.7mm) mid-joint weatherseal width, .25 in. (6.4 mm) edge weather seal width	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0417	0.0417
Beta(1):	0.2978	0.2978
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	4
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	**DS1**		**DS2**		**DS3**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0460	1	0.0460	1	n/a		
2	0.0460	1	0.0460	1	n/a		
3	0.0328	1	0.0328	1	n/a		
4	0.0434	1	0.0434	1	n/a		

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

<u>**Fragility, damage measures, and consequences for**</u> **EXTERIOR GLASS CURTAIN WALL – TYPE 20** **ANNEALED LAMINATED**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Laminated, annealed glass, aluminum framing, square corners, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, two-sided SSG, Kawneer 1600 curtain wall framing, GE one part silicone (SCS 2000), center panel, .5 in. (12.7mm) mid-joint weatherseal width, .25 in. (6.4 mm) edge weather seal width	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0392	0.0434
Beta(1):	0.2886	0.25
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	**DS1**		**DS2**		**DS3**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0434	1	0.0434	1	n/a		
2	0.0354	1	0.0434	1	n/a		

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 21** **ANNEALED LAMINATED**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Laminated, annealed glass, aluminum framing, square corners, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, two-sided SSG, Kawneer 1600 curtain wall framing, GE one part silicone (SCS 2000), outside panels, .5 in. (12.7mm) mid-joint weatherseal width, .25 in. (6.4 mm) edge weather seal width	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0347	0.02
Beta(1):	0.2601	1.0211
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report “Architectural Glass Seismic Behavior Fragility Curve Development”	
Number of specimens tested:	4
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	*f*	*DP*	*f*	*DP*	*f*	
1	0.0328	1	0.0407	1	n/a		
2	0.0354	1	0.0434	1	n/a		
3	0.0328	1	0.0741	0	n/a		
4	0.0381	1	0.0434	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	N	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 22** **ANNEALED IGU**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Insulating glass unit, annealed glass, aluminum framing, square corners, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1 in. (25.4 mm) thick (.25 in. AN Mono, .5 in. air space, .25 in. AN Mono) glass, 0.43 in. (11 mm) glass-to-frame clearance, two-sided SSG, Kawneer 1600 curtain wall framing, GE one part silicone (SCS 2000), center panel, .5 in. (12.7mm) mid-joint weatherseal width, .5 in. (12.7 mm) edge weather seal width	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☒ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0514	0.054
Beta(1):	0.25	0.25
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report “Architectural Glass Seismic Behavior Fragility Curve Development”	
Number of specimens tested:	2
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	**DS1**		**DS2**		**DS3**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0514	1	0.0540	1	n/a		
2	0.0514	1	0.0540	1	n/a		

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 23** **ANNEALED IGU**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Insulating glass unit, annealed glass, aluminum framing, square corners, cut edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1 in. (25.4 mm) thick (.25 in. AN Mono, .5 in. air space, .25 in. AN Mono) glass, 0.43 in. (11 mm) glass-to-frame clearance, two-sided SSG, Kawneer 1600 curtain wall framing, GE one part silicone (SCS 2000), outside panels, .5 in. (12.7mm) mid-joint weatherseal width, .5 in. (12.7 mm) edge weather seal width	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0513	0.054
Beta(1):	0.2535	0.25
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	4
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ___
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0487	1	0.0540	1	n/a		
2	0.0540	1	0.0540	1	n/a		
3	0.0514	1	0.0540	1	n/a		
4	0.0514	1	0.0540	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 24** **HEAT STRENGTHENED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, heat strengthened glass, aluminum framing, square corners, seamed edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing, dry-glazed	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.024	0.025
Beta(1):	0.2856	0.2836
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	8
Construction quality:	☐ exceeds ▮ meets ☐ does not meet requirements of: ________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0301	1	0.0328	1	n/a		
2	0.0222	1	0.0222	1	n/a		
3	0.0222	1	0.0222	1	n/a		
4	0.0195	1	0.0248	1	n/a		
5	0.0248	1	0.0248	1	n/a		
6	0.0222	1	0.0222	1	n/a		
7	0.0275	1	0.0275	1	n/a		
8	0.0248	1	0.0248	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 25** **FULLY TEMPERED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, fully tempered glass, aluminum framing, square corners, seamed edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing, dry-glazed	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0285	0.0285
Beta(1):	0.2934	0.2934
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	6
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0301	1	0.0301	1	n/a		
2	0.0222	1	0.0222	1	n/a		
3	0.0275	1	0.0275	1	n/a		
4	0.0354	1	0.0354	1	n/a		
5	0.0275	1	0.0275	1	n/a		
6	0.0301	1	0.0301	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 26** **FULLY TEMPERED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, fully tempered glass, aluminum framing, square corners, polished edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing, dry-glazed	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0328	0.0328
Beta(1):	0.25	0.25
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report “Architectural Glass Seismic Behavior Fragility Curve Development”	
Number of specimens tested:	3
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0328	1	0.0328	1	n/a		
2	0.0328	1	0.0328	1	n/a		
3	0.0328	1	0.0328	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are $0.2 \le \beta \le 0.6$? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 27** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, annealed glass, aluminum framing, square corners, seamed edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing, dry-glazed	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0272	0.029
Beta(1):	0.2555	0.2566
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report “Architectural Glass Seismic Behavior Fragility Curve Development”	
Number of specimens tested:	5
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ___
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0278	1	0.0309	1	n/a		
2	0.0278	1	0.0278	1	n/a		
3	0.0278	1	0.0309	1	n/a		
4	0.0278	1	0.0278	1	n/a		
5	0.0247	1	0.0278	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 28** **ANNEALED MONOLITHIC**		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, annealed glass, aluminum framing, square corners, seamed edge finish, 4 ft W x 8 ft H (1.22 m x 1.44 m) size, 2:1 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing, dry-glazed	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0201	0.0232
Beta(1):	0.2607	0.2795
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ▮ meets ☐ does not meet requirements of: ______________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0212	1	0.0212	1	n/a		
2	0.0191	1	0.0253	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for EXTERIOR GLASS CURTAIN WALL – TYPE 29 ANNEALED MONOLITHIC		
Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Monolithic, annealed glass, aluminum framing, square corners, seamed edge finish, 8 ft W x 4 ft H (2.44 m x 1.22 m) size, 1:2 aspect ratio, 1/4 in. (6 mm) thick glass, 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing, dry-glazed	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0239	0.0274
Beta(1):	0.25	0.3172
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report “Architectural Glass Seismic Behavior Fragility Curve Development”	
Number of specimens tested:	2
Construction quality:	☐ exceeds ▮ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0239	1	0.0239	1	n/a		
2	0.0239	1	0.0315	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for

EXTERIOR GLASS CURTAIN WALL – TYPE 30

HEAT STRENGTHENED IGU

Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Insulating glass unit, heat strengthened glass, aluminum framing, square corners, seamed edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1 in. (25.4 mm) thick glass (.25 in. HS Mono, .5 in air space, .25 in. HS Mono), 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing, dry-glazed	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0263	0.0267
Beta(1):	0.2972	0.2962
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report “Architectural Glass Seismic Behavior Fragility Curve Development”	
Number of specimens tested:	6
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ____________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	DS1		DS2		DS3		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0222	1	0.0222	1	n/a		
2	0.0354	1	0.0354	1	n/a		
3	0.0248	1	0.0275	1	n/a		
4	0.0248	1	0.0248	1	n/a		
5	0.0275	1	0.0275	1	n/a		
6	0.0248	1	0.0248	1	n/a		

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for

EXTERIOR GLASS CURTAIN WALL – TYPE 31

ANNEALED MONOLITHIC

Component category:	Exterior Glass Curtain Wall	
Basic composition:	Curtain Wall, Insulating glass unit, fully tempered glass, aluminum framing, square corners, seamed edge finish, 5 ft W x 6 ft H (1.5 m x 1.8 m) size, 6:5 aspect ratio, 1 in. (25.4 mm) thick glass (.25 in. FT Mono, .5 in air space, .25 in. FT Mono), 0.43 in. (11 mm) glass-to-frame clearance, Kawneer 1600 curtain wall framing, dry-glazed	
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor	
Demand parameter (DP):	Peak Transient Interstory Drift Ratio	
Number of damage states:	2	
If multiple damage states:	■ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Memari et al. – February 2009	
Damage states, fragilities, and consequences		
	DS1	**DS2**
Description:	Glass Cracking	Glass Fallout
Illustration:		
Median DP(1):	0.0314	0.0314
Beta(1):	0.2549	0.2549
Probability(1):	-	-
Correlation:	-	-
Repairs required:	Replace cracked glass panels	Replace glass panels with glass fallout; cover exposure in meantime
Possible consequences:		
Repair cost (Y/N/?):	yes	yes
Death or injury (Y/N/?):	no	yes
Inoperative facility (Y/N/?):	no	yes
Cost per unit(2)		
Max cost to lower quantity		
Min cost over upper qty		
Beta (cost)		
Lower quantity		
Upper quantity		
Repair duration per unit(2)		
Max duration to lower qty		
Min duration over upper qty		
Beta (duration)		
Life-safety consequences(2)		
Comments:		

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report “Architectural Glass Seismic Behavior Fragility Curve Development”	
Number of specimens tested:	4
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Cracking and Fallout failure DS by visual observation accompanied by computer controlled drift values; Gasket failure DS by video analysis

Specimen	**DS1**		**DS2**		**DS3**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	
1	0.0328	1	0.0328	1	n/a		
2	0.0301	1	0.0301	1	n/a		
3	0.0328	1	0.0328	1	n/a		
4	0.0301	1	0.0301	1	n/a		

Quality test	**DS1**	**DS2**	**DS3**
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	n/a
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	Y	Y	n/a
Discussion: see report			

Fragility, damage measures, and consequences for **EXTERIOR GLASS CURTAIN WALL – TYPE 32** **Fully Tempered Insulating Glass Units**			
Component category:	Exterior Glass Unitized Curtain Wall		
Basic composition:	Unitized Curtain wall, IGU, fully tempered glass, aluminum framing, square corners; Inner/outer FT 1/4 in. (6mm) thick glass with 3/4 in. (18mm) airspace, En-Wall 7250 unitized wall system		
Normative quantity (unit):	Square feet of curtain wall oriented in a specific direction per floor		
Demand parameter (DP):	Peak Transient Interstory Drift Ratio		
Number of damage states:	3		
If multiple damage states:	☐ordered; ☐ mutually exclusive; ☐ simultaneous		
Author and date:	Memari et al. – January 2011		
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:	Vertical Joint Dislodging	Horizontal Joint Dislodging	Glass Damage
Illustration:			
Median DP(1):	0.53	0.0397	10.0
Beta(1):	1.0211	0.3067	0.3202
Probability(1):	-	-	-
Correlation:	-	-	-
Repairs required:	Realign Panels	Realign Panels	Replace Unitized Panel
Possible consequences:			
Repair cost (Y/N/?):	yes	yes	Yes
Death or injury (Y/N/?):	no	no	Yes
Inoperative facility (Y/N/?):	yes	yes	yes
Cost per unit(2)			
Max cost to lower quantity			
Min cost over upper qty			
Beta (cost)			
Lower quantity			
Upper quantity			
Repair duration per unit(2)			
Max duration to			

lower qty			
Min duration over upper qty			
Beta (duration)			
Life-safety consequences(2)			
Comments:			

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ▮ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Dislodging failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		Comment
	DP	*f*	*DP*	*f*	*DP*	*f*	
1	0.046	0	0.045	1	0.046	0	
2	0.010	1	0.035	1	0.046	0	

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	N	Y	Y
Discussion: see report			

Fragility, damage measures, and consequences for **3-PANEL PLANAR GLASS STOREFRONT SYSTEM – TYPE 33** **Fully Tempered Insulating Glass Units**				
Component category:	Glass Storefront system			
Basic composition:	Storefront, IGU, fully tempered glass, aluminum framing, square corners, planar configuration, 4 ft. 7/8 in. W x 7 ft. 8 in. H (1.2 m x 2.3 m) size, 1.89:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, Vistawall FG-3000 framing			
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor			
Demand parameter (DP):	Peak Transient Interstory Drift Ratio			
Number of damage states:	4			
If multiple damage states:	☐ordered; ☐ mutually exclusive; ☐ simultaneous			
Author and date:	Memari et al. – January 2011			
Damage states, fragilities, and consequences				
	DS1	**DS2**	**DS3**	**DS4**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage
Illustration:				
Median DP(1):	1.38	0.04	0.05	0.16
Beta(1):	1.0211	1.0211	0.2881	1.0211
Probability(1):	-	-	-	-
Correlation:	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.
Possible consequences:				
Repair cost (Y/N/?):	yes	yes	Yes	yes
Death or injury (Y/N/?):	no	no	No	yes
Inoperative facility (Y/N/?):	No	No	No	yes
Cost per unit(2)				
Max cost to lower quantity				
Min cost over upper qty				

Beta (cost)				
Lower quantity				
Upper quantity				
Repair duration per unit(2)				
Max duration to lower qty				
Min duration over upper qty				
Beta (duration)				
Life-safety consequences(2)				
Comments:				

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	6
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ____________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	**DS1**		**DS2**		**DS3**		**DS4**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.012	1	0.027	1	0.055	1	0.055	1	
2	0.012	1	0.020	1	0.060	1	0.060	0	
3	0.060	0	0.027	1	0.050	1	0.060	0	
4	0.060	0	0.060	0	0.060	1	0.060	0	
5	0.060	0	0.060	0	0.043	1	0.060	0	
6	0.060	0	0.060	0	0.045	1	0.060	0	

Quality test	**DS1**	**DS2**	**DS3**	**DS4**
Passes Lilliefors goodness of fit test?	Y	Y	Y	Y

(Type A only)				
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	N	N	Y	N
Discussion: see report				

Fragility, damage measures, and consequences for

4-PANEL REENTRANT CORNER GLASS STOREFRONT SYSTEM – TYPE 34

Fully Tempered Insulating Glass Units

Component category:	Glass Storefront system			
Basic composition:	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, in-plane panel, 4 ft. 7/8 in. W x 7 ft. 8 in. H (1.2 m x 2.3 m) size, 1.89:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, planar panels, Vistawall FG-3000 framing			
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor			
Demand parameter (DP):	Peak Transient Interstory Drift Ratio			
Number of damage states:	4			
If multiple damage states:	☐ordered; ☐ mutually exclusive; ☐ simultaneous			
Author and date:	Memari et al. – January 2011			
Damage states, fragilities, and consequences				
	DS1	**DS2**	**DS3**	**DS4**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage
Illustration:				
Median DP(1):	0.0203	0.01	0.054	0.16
Beta(1):	0.5004	0.3202	0.2805	1.0211
Probability(1):	-	-	-	-
Correlation:	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.
Possible consequences:				
Repair cost (Y/N/?):	yes	yes	Yes	yes
Death or injury (Y/N/?):	no	no	No	yes
Inoperative facility (Y/N/?):	No	No	No	yes
Cost per unit(2)				
Max cost to lower quantity				
Min cost over upper qty				

Beta (cost)				
Lower quantity				
Upper quantity				
Repair duration per unit(2)				
Max duration to lower qty				
Min duration over upper qty				
Beta (duration)				
Life-safety consequences(2)				
Comments:				

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	6
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	**DS1**		**DS2**		**DS3**		**DS4**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.012	1	0.038	1	0.060	1	0.060	0	
2	0.020	1	0.030	1	0.045	1	0.060	0	
3	0.012	1	0.030	1	0.048	1	0.055	1	
4	0.030	1	0.060	1	0.060	1	0.060	0	
5	0.027	1	0.017	1	0.060	1	0.060	0	
6	0.030	1	0.060	0	0.053	1	0.060	0	

Quality test	**DS1**	**DS2**	**DS3**	**DS4**
Passes Lilliefors goodness of fit test?	Y	Y	Y	Y

(Type A only)				
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	Y	Y	N
Discussion: see report				

Fragility, damage measures, and consequences for **IN-PLANE PANELS OF COMBINED GLASS STOREFRONT SYSTEMS – TYPE 35** **Fully Tempered Insulating Glass Units**				
Component category:	Glass Storefront system			
Basic composition:	Storefront, IGU, fully tempered glass, aluminum framing, square corners, combined in-plane panels from in-plane and L-shaped tests, 4 ft. 7/8 in. W x 7 ft. 8 in. H (1.2 m x 2.3 m) size, 1.89:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, planar panels, Vistawall FG-3000 framing			
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor			
Demand parameter (DP):	Peak Transient Interstory Drift Ratio			
Number of damage states:	4			
If multiple damage states:	☐ordered; ■ mutually exclusive; ☐ simultaneous			
Author and date:	Memari et al. – January 2011			
Damage states, fragilities, and consequences				
	DS1	**DS2**	**DS3**	**DS4**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage
Illustration:				
Median DP[(1)]:	0.01	0.01	0.0528	0.16
Beta[(1)]:	0.3202	1.0211	0.2822	1.0211
Probability[(1)]:	-	-	-	-
Correlation:	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.
Possible consequences:				
Repair cost (Y/N/?):	yes	yes	Yes	yes
Death or injury (Y/N/?):	no	no	No	yes
Inoperative facility (Y/N/?):	No	No	No	yes
Cost per unit[(2)]				
Max cost to lower quantity				
Min cost over upper qty				

Beta (cost)				
Lower quantity				
Upper quantity				
Repair duration per unit(2)				
Max duration to lower qty				
Min duration over upper qty				
Beta (duration)				
Life-safety consequences(2)				
Comments:				

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	12
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ____________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		DS4		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.012	1	0.027	1	0.055	1	0.055	1	
2	0.012	1	0.020	1	0.060	1	0.060	0	
3	0.060	0	0.027	1	0.050	1	0.060	0	
4	0.060	0	0.060	0	0.060	1	0.060	0	
5	0.060	0	0.060	0	0.043	1	0.060	0	
6	0.060	0	0.060	0	0.045	1	0.060	0	
7	0.012	1	0.038	1	0.060	1	0.060	0	
8	0.020	1	0.030	1	0.045	1	0.060	0	
9	0.012	1	0.030	1	0.048	1	0.055	1	
10	0.030	1	0.060	1	0.060	1	0.060	0	
11	0.027	1	0.017	1	0.060	1	0.060	0	
12	0.030	1	0.060	0	0.053	1	0.060	0	

Quality test	DS1	DS2	DS3	DS4
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	N	Y	N
Discussion: see report				

Fragility, damage measures, and consequences for **OUT-OF-PLANE PANEL OF REENTRANT CORNER GLASS STOREFRONT SYSTEM – TYPE 36** **Fully Tempered Insulating Glass Units**				
Component category:	Glass Storefront system			
Basic composition:	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, out of plane panel, 2 ft. 8-3/8 in. W x 7 ft. 8 in. H (.8 m x 2.3 m) size, 2.83:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, corner panel, Vistawall FG-3000 framing			
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor			
Demand parameter (DP):	Peak Transient Interstory Drift Ratio			
Number of damage states:	4			
If multiple damage states:	☐ordered; ☐ mutually exclusive; ☐ simultaneous			
Author and date:	Memari et al. – January 2011			
Damage states, fragilities, and consequences				
	DS1	**DS2**	**DS3**	**DS4**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage
Illustration:				
Median DP(1):	10.0	10.0	10.0	10.0
Beta(1):	0.3202	0.3202	0.3202	0.3202
Probability(1):	-	-	-	-
Correlation:	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.
Possible consequences:				
Repair cost (Y/N/?):	yes	yes	Yes	yes
Death or injury (Y/N/?):	no	no	No	yes
Inoperative facility (Y/N/?):	No	No	No	yes
Cost per unit(2)				
Max cost to lower quantity				
Min cost over				

upper qty				
Beta (cost)				
Lower quantity				
Upper quantity				
Repair duration per unit(2)				
Max duration to lower qty				
Min duration over upper qty				
Beta (duration)				
Life-safety consequences(2)				
Comments:				

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	**DS1**		**DS2**		**DS3**		**DS4**		**Comment**
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.060	0	0.060	0	0.060	0	0.060	0	
2	0.060	0	0.060	0	0.053	1	0.060	0	

Quality test	**DS1**	**DS2**	**DS3**	**DS4**
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a

Are 0.2 ≤ β ≤ 0.6? If not discuss.	Y	Y	Y	Y
Discussion: see report				

Fragility, damage measures, and consequences for

3-PANEL PLANAR GLASS STOREFRONT SYSTEM – TYPE 37

Fully Tempered Insulating Glass Units

Component category:	Glass Storefront system
Basic composition:	Storefront, IGU, fully tempered glass, aluminum framing, square corners, planar configuration, 4 ft. 7/8 in. W x 7 ft. 7-5/8 in. H (1.2 m x 2.3 m) size, 1.88:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, Vistawall 3000 MultiPlane Center Set framing system
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor
Demand parameter (DP):	Peak Transient Interstory Drift Ratio
Number of damage states:	4
If multiple damage states:	□ordered; ■ mutually exclusive; □ simultaneous
Author and date:	Memari et al. – January 2011

Damage states, fragilities, and consequences

	DS1	DS2	DS3	DS4
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage
Illustration:				
Median DP[1]:	0.13	0.0262	0.0551	10.0
Beta[1]:	1.0211	0.2745	0.2872	0.3202
Probability[1]:	-	-	-	-
Correlation:	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.
Possible consequences:				
Repair cost (Y/N/?):	yes	yes	Yes	yes
Death or injury (Y/N/?):	no	no	No	yes
Inoperative facility (Y/N/?):	No	No	No	yes
Cost per unit[2]				
Max cost to lower quantity				
Min cost over upper qty				

Beta (cost)				
Lower quantity				
Upper quantity				
Repair duration per unit(2)				
Max duration to lower qty				
Min duration over upper qty				
Beta (duration)				
Life-safety consequences(2)				
Comments:				

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	6
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		DS4		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.060	0	0.033	1	0.060	1	0.060	0	
2	0.060	0	0.025	1	0.060	1	0.060	0	
3	0.048	1	0.025	1	0.060	1	0.060	0	
4	0.060	0	0.025	1	0.060	1	0.060	0	
5	0.060	0	0.025	1	0.050	1	0.060	0	
6	0.060	0	0.025	1	0.043	1	0.060	0	

Quality test	DS1	DS2	DS3	DS4
Passes Lilliefors goodness of fit test?	Y	N	Y	Y

(Type A only)				
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	N	Y	Y	Y
Discussion: see report				

Fragility, damage measures, and consequences for

4-PANEL REENTRANT CORNER GLASS STOREFRONT SYSTEM – TYPE 38

Fully Tempered Insulating Glass Units

Component category:	Glass Storefront system
Basic composition:	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, in-plane panel, 4 ft. 7/8 in. W x 7 ft. 7-5/8 in. H (1.2 m x 2.3 m) size, 1.88:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, planar panels, Vistawall 3000 MultiPlane Center Set framing system
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor
Demand parameter (DP):	Peak Transient Interstory Drift Ratio
Number of damage states:	4
If multiple damage states:	☐ordered; ☒ mutually exclusive; ☐ simultaneous
Author and date:	Memari et al. – January 2011

Damage states, fragilities, and consequences

	DS1	DS2	DS3	DS4
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage
Illustration:				
Median DP(1):	0.15	0.0191	0.0548	10.0
Beta(1):	1.0211	0.5235	0.3177	0.3202
Probability(1):	-	-	-	-
Correlation:	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.
Possible consequences:				
Repair cost (Y/N/?):	yes	yes	Yes	yes
Death or injury (Y/N/?):	no	no	No	yes
Inoperative facility (Y/N/?):	No	No	No	yes
Cost per unit(2)				
Max cost to lower quantity				
Min cost over upper qty				

Beta (cost)				
Lower quantity				
Upper quantity				
Repair duration per unit(2)				
Max duration to lower qty				
Min duration over upper qty				
Beta (duration)				
Life-safety consequences(2)				
Comments:				

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	9
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		DS4		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.060	0	0.025	1	0.060	1	0.060	0	
2	0.060	0	0.012	1	0.055	1	0.060	0	
3	0.012	1	0.012	1	0.060	1	0.060	0	
4	0.060	0	0.035	1	0.060	1	0.060	0	
5	0.060	0	0.030	1	0.060	1	0.060	0	
6	0.027	1	0.022	1	0.060	1	0.060	0	
7	0.048	1	0.027	1	0.033	1	0.060	0	
8	0.060	0	0.010	1	0.053	1	0.060	0	
9	0.060	0	0.015	1	0.060	1	0.060	0	

Quality test	DS1	DS2	DS3	DS4
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	N	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	N	Y	Y	Y
Discussion: see report				

Fragility, damage measures, and consequences for **IN-PLANE PANELS OF COMBINED GLASS STOREFRONT SYSTEMS – TYPE 39** **Fully Tempered Insulating Glass Units**				
Component category:	Glass Storefront system			
Basic composition:	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, combined in-plane panels from in-plane and L-shaped tests, 4 ft. 7/8 in. W x 7 ft. 7-5/8 in. H (1.2 m x 2.3 m) size, 1.88:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, planar panels, Vistawall 3000 MultiPlane Center Set framing system			
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor			
Demand parameter (DP):	Peak Transient Interstory Drift Ratio			
Number of damage states:	4			
If multiple damage states:	☐ordered; ■ mutually exclusive; ☐ simultaneous			
Author and date:	Memari et al. – January 2011			
Damage states, fragilities, and consequences				
	DS1	**DS2**	**DS3**	**DS4**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage
Illustration:				
Median DP(1):	0.16	0.0217	0.0549	10.0
Beta(1):	1.0211	0.4622	0.3027	0.3202
Probability(1):	-	-	-	-
Correlation:	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.
Possible consequences:				
Repair cost (Y/N/?):	yes	yes	Yes	yes
Death or injury (Y/N/?):	no	no	No	yes
Inoperative facility (Y/N/?):	No	No	No	yes
Cost per unit(2)				
Max cost to lower quantity				
Min cost over upper qty				

Beta (cost)				
Lower quantity				
Upper quantity				
Repair duration per unit(2)				
Max duration to lower qty				
Min duration over upper qty				
Beta (duration)				
Life-safety consequences(2)				
Comments:				

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	15
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ____________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		DS4		Comment
	DP	*f*	*DP*	*f*	*DP*	*f*	*DP*	*f*	
1	0.060	0	0.033	1	0.060	1	0.060	0	
2	0.060	0	0.025	1	0.060	1	0.060	0	
3	0.048	1	0.025	1	0.060	1	0.060	0	
4	0.060	0	0.025	1	0.060	1	0.060	0	
5	0.060	0	0.025	1	0.050	1	0.060	0	
6	0.060	0	0.025	1	0.043	1	0.060	0	
7	0.060	0	0.025	1	0.060	1	0.060	0	
8	0.060	0	0.012	1	0.055	1	0.060	0	
9	0.012	1	0.012	1	0.060	1	0.060	0	
10	0.060	0	0.035	1	0.060	1	0.060	0	
11	0.060	0	0.030	1	0.060	1	0.060	0	
12	0.027	1	0.022	1	0.060	1	0.060	0	
13	0.048	1	0.027	1	0.033	1	0.060	0	
14	0.060	0	0.010	1	0.053	1	0.060	0	
15	0.060	0	0.015	1	0.060	1	0.060	0	

Quality test	DS1	DS2	DS3	DS4
Passes Lilliefors goodness of fit test? (Type A only)	Y	N	N	Y
Are θ and *β* within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a
Are 0.2 ≤ *β* ≤ 0.6? If not discuss.	N	Y	Y	Y
Discussion: see report				

Fragility, damage measures, and consequences for **OUT-OF-PLANE PANELS OF REENTRANT CORNER GLASS STOREFRONT SYSTEM – TYPE 40** **Fully Tempered Insulating Glass Units**				
Component category:	Glass Storefront system			
Basic composition:	Storefront, IGU, fully tempered glass, aluminum framing, square corners, L-shaped configuration, out of plane panel, 2 ft. 8-3/8 in. W x 7 ft. 7-5/8 in. H (.8 m x 2.3 m) size, 2.82:1 aspect ratio, 1/4 in. (6 mm) thick inner/outer with 1/2 in. (13 mm) airspace, corner panel, Vistawall 3000 MultiPlane Center Set framing system			
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor			
Demand parameter (DP):	Peak Transient Interstory Drift Ratio			
Number of damage states:	4			
If multiple damage states:	☐ordered; ☐ mutually exclusive; ☐ simultaneous			
Author and date:	Memari et al. – January 2011			
Damage states, fragilities, and consequences				
	DS1	**DS2**	**DS3**	**DS4**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage
Illustration:				
Median DP(1):	10.0	0.1	0.09	10.0
Beta(1):	0.3202	1.0211	1.0211	0.3202
Probability(1):	-	-	-	-
Correlation:	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.
Possible consequences:				
Repair cost (Y/N/?):	yes	yes	Yes	yes
Death or injury (Y/N/?):	no	no	No	yes
Inoperative facility (Y/N/?):	No	No	No	yes
Cost per unit(2)				
Max cost to lower quantity				
Min cost over upper qty				

Beta (cost)				
Lower quantity				
Upper quantity				
Repair duration per unit(2)				
Max duration to lower qty				
Min duration over upper qty				
Beta (duration)				
Life-safety consequences(2)				
Comments:				

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	3
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		DS4		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.060	0	0.060	0	0.060	0	0.060	0	
2	0.060	0	0.060	0	0.060	0	0.060	0	
3	0.060	0	0.043	1	0.053	1	0.060	0	

Quality test	DS1	DS2	DS3	DS4
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a

Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	N	Y	N
Discussion: see report				

<u>Fragility, damage measures, and consequences for</u>

3-PANEL PLANAR GLASS STOREFRONT SYSTEM – TYPE 41

Fully Tempered Insulating Glass Units

Component category:	Glass Storefront system				
Basic composition:	Storefront, fully tempered glass, aluminum framing, square corners, wet glazed, planar configuration, 4 ft. W x 7 ft. 8-5/8" in. H (1.2m x 2.35m) size, 1.93:1 aspect ratio, 3/8 in. (10 mm) thick, Vistawall FG-2000 framing system				
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor				
Demand parameter (DP):	Peak Transient Interstory Drift Ratio				
Number of damage states:	5				
If multiple damage states:	☐ordered; ☒ mutually exclusive; ☐ simultaneous				
Author and date:	Memari et al. – January 2011				
Damage states, fragilities, and consequences					
	DS1	**DS2**	**DS3**	**DS4**	**DS5**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage	Sealant Damage
Illustration:					
Median DP[(1)]:	0.09	0.01	0.06	0.03	0.02
Beta[(1)]:	0.9727	1.0211	0.25	1.0211	1.0211
Probability[(1)]:	-	-	-	-	-
Correlation:	-	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.	Remove and replace sealant
Possible consequences:					
Repair cost (Y/N/?):	yes	yes	yes	yes	yes
Death or injury (Y/N/?):	no	no	no	yes	no
Inoperative facility (Y/N/?):	no	no	no	yes	no
Cost per unit[(2)]					
Max cost to lower quantity					
Min cost over upper qty					

Beta (cost)					
Lower quantity					
Upper quantity					
Repair duration per unit(2)					
Max duration to lower qty					
Min duration over upper qty					
Beta (duration)					
Life-safety consequences(2)					
Comments:					

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	9
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		DS4		DS5		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1			0.060	0			0.040	1	0.033	1	
2	0.060	0	0.005	1	0.060	1	0.040	1	0.040	1	
3			0.005	1			0.040	1	-	-	
4			0.007	1			0.060	0	0.060	0	
5	0.060	1	0.060	0	0.060	1	0.060	0	0.060	0	
6			0.005	1			0.060	0	-	-	
7			0.018	1			0.038	1	0.030	1	
8	0.060	0	0.060	0	0.060	1	0.050	1	0.050	1	
9			0.016	1			0.050	1	-	-	

Quality test	DS1	DS2	DS3	DS4	DS5
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y	Y	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a	n/a
Are $0.2 \le \beta \le 0.6$? If not discuss.	N	N	Y	N	N
Discussion: see report					

Fragility, damage measures, and consequences for

4-PANEL REENTRANT CORNER GLASS STOREFRONT SYSTEM – TYPE 42

Fully Tempered Insulating Glass Units

Component category:	Glass Storefront system
Basic composition:	Storefront, fully tempered glass, aluminum framing, square corners, wet glazed, L-shaped configuration, in-plane panel, 4 ft. W x 7 ft. 8-5/8" in. H (1.2m x 2.35m) size, 1.93:1 aspect ratio, 3/8 in. (10 mm) thick, planar panels, Vistawall FG-2000 framing system
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor
Demand parameter (DP):	Peak Transient Interstory Drift Ratio
Number of damage states:	5
If multiple damage states:	☐ordered; ☐ mutually exclusive; ☐ simultaneous
Author and date:	Memari et al. – January 2011

Damage states, fragilities, and consequences

	DS1	DS2	DS3	DS4	DS5
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage	Sealant Damage
Illustration:					
Median DP[1]:	0.0354	0.01	0.0424	0.05	0.29
Beta[1]:	0.2692	1.0211	0.5502	1.0211	1.0211
Probability[1]:	-	-	-	-	-
Correlation:	-	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.	Remove and replace sealant
Possible consequences:					
Repair cost (Y/N/?):	yes	yes	yes	yes	yes
Death or injury (Y/N/?):	no	no	no	yes	no
Inoperative facility (Y/N/?):	no	no	no	yes	no
Cost per unit[2]					
Max cost to					

lower quantity					
Min cost over upper qty					
Beta (cost)					
Lower quantity					
Upper quantity					
Repair duration per unit(2)					
Max duration to lower qty					
Min duration over upper qty					
Beta (duration)					
Life-safety consequences(2)					
Comments:					

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	6
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ____________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		DS4		DS5		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.038	1	0.007	1	0.060	1	0.030	1	0.025	1	
2			0.022	1			0.060	0	0.060	0	
3			0.007	1			0060	0	-	-	
4	0.033	1	0.005	1	0.030	1	0.040	1	0.060	0	
5			0.060	0			0.038	1	0.060	0	
6			0.010	1			0.060	0	-	-	

Quality test	DS1	DS2	DS3	DS4	DS5
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y	Y	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	N	Y	N	N
Discussion: see report					

Fragility, damage measures, and consequences for **PLANE PANELS OF COMBINED GLASS STOREFRONT SYSTEMS – TYPE 43** **Fully Tempered Insulating Glass Units**					
Component category:	Glass Storefront system				
Basic composition:	Storefront, fully tempered glass, aluminum framing, square corners, wet glazed, L-shaped configuration, combined in-plane panels from in-plane and L-shaped tests, 4 ft. W x 7 ft. 8-5/8" in. H (1.2m x 2.35m) size, 1.93:1 aspect ratio, 3/8 in. (10 mm) thick, planar panels, Vistawall FG-2000 framing system				
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor				
Demand parameter (DP):	Peak Transient Interstory Drift Ratio				
Number of damage states:	5				
If multiple damage states:	☐ordered; ■ mutually exclusive; ☐ simultaneous				
Author and date:	Memari et al. – January 2011				
Damage states, fragilities, and consequences					
	DS1	**DS2**	**DS3**	**DS4**	**DS5**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage	Sealant Damage
Illustration:					
Median DP(1):	0.03	0.01	0.0522	0.03	0.05
Beta(1):	1.0211	1.0211	0.3982	1.0211	1.0211
Probability(1):	-	-	-	-	-
Correlation:	-	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.	Remove and replace sealant
Possible consequences:					
Repair cost (Y/N/?):	yes	yes	yes	yes	yes
Death or injury (Y/N/?):	no	no	no	yes	no
Inoperative facility (Y/N/?):	no	no	no	yes	no
Cost per unit(2)					
Max cost to lower quantity					

Min cost over upper qty					
Beta (cost)					
Lower quantity					
Upper quantity					
Repair duration per unit(2)					
Max duration to lower qty					
Min duration over upper qty					
Beta (duration)					
Life-safety consequences(2)					
Comments:					

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	15
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ____________________
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

Specimen	DS1		DS2		DS3		DS4		DS5		Comment
	DP	*f*	*DP*	*f*	*DP*	*f*	*DP*	*f*	*DP*	*f*	
1	0.060	0	0.060	0	0.060	1	0.040	1	0.033	1	
2			0.005	1			0.040	1	0.040	1	
3			0.005	1			0.040	1	-	-	
4	0.060	1	0.007	1	0.060	1	0.060	0	0.060	0	
5			0.060	0			0.060	0	0.060	0	
6			0.005	1			0.060	0	-	-	
7	0.060	0	0.018	1	0.060	1	0.038	1	0.030	1	
8			0.060	0			0.050	1	0.050	1	
9			0.016	1			0.050	1	-	-	
10	0.038	1	0.007	1	0.060	1	0.030	1	0.025	1	
11			0.022	1			0.060	0	0.060	0	
12			0.007	1			0.060	0	-	-	
13	0.033	1	0.005	1	0.060	1	0.040	1	0.060	0	
14			0.060	0			0.038	1	0.060	0	
15			0.010	1			0.060	0	-	-	

Quality test	DS1	DS2	DS3	DS4	DS5
Passes Lilliefors goodness of fit test? (Type A only)	Y	Y	Y	Y	Y
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	N	N	Y	N	N
Discussion: see report					

Fragility, damage measures, and consequences for **OUT-OF-PLANE PANELS OF REENTRANT CORNER GLASS STOREFRONT SYSTEM – TYPE 44** **Fully Tempered Insulating Glass Units**					
Component category:	Glass Storefront system				
Basic composition:	Storefront, fully tempered glass, aluminum framing, square corners, wet glazed, L-shaped configuration, out of plane panel, 2 ft. 9-15/16 in. W x 7 ft. 8-5/8" in. H (0.9 m x 2.35m) size, 2.72:1 aspect ratio, 3/8 in. (10 mm) thick, corner panel, Vistawall FG-2000 framing system				
Normative quantity (unit):	Square feet of storefront oriented in a specific direction per floor				
Demand parameter (DP):	Peak Transient Interstory Drift Ratio				
Number of damage states:	5				
If multiple damage states:	☐ordered; ■ mutually exclusive; ☐ simultaneous				
Author and date:	Memari et al. – January 2011				
Damage states, fragilities, and consequences					
	DS1	**DS2**	**DS3**	**DS4**	**DS5**
Description:	Loss of Seal	Gasket Degradation	Frame Damage	Glass Damage	Sealant Damage
Illustration:					
Median DP[(1)]:	0.01	0.0158	0.0363	0.05	0.016
Beta[(1)]:	1.0211	0.6945	0.7522	1.0211	0.2652
Probability[(1)]:	-	-	-	-	-
Correlation:	-	-	-	-	-
Repairs required:	Reposition glass and reseal glass perimeter	Remove and replace gaskets	Remove glass panel and replace framing member. Reinstall glass panel	Remove and replace glass panel.	Remove and replace sealant
Possible consequences:					
Repair cost (Y/N/?):	yes	yes	yes	yes	yes
Death or injury (Y/N/?):	no	no	no	yes	no
Inoperative facility (Y/N/?):	no	no	no	yes	no
Cost per unit[(2)]					

Max cost to lower quantity					
Min cost over upper qty					
Beta (cost)					
Lower quantity					
Upper quantity					
Repair duration per unit(2)					
Max duration to lower qty					
Min duration over upper qty					
Beta (duration)					
Life-safety consequences(2)					
Comments:					

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."
(2) Leave cost per unit, repair duration per unit, and life-safety consequence fields blank unless the data are provided consistent with Consequence Specification [to be written].

Literature summary: refer to report "Architectural Glass Seismic Behavior Fragility Curve Development"	
Number of specimens tested:	2
Construction quality:	☐ exceeds ■ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	New or uncompromised parts if used in a previous test
Loading protocols applied:	Displacement controlled cyclic racking loading
Method for observing damage:	Observed failures by visual observation accompanied by computer controlled drift values;

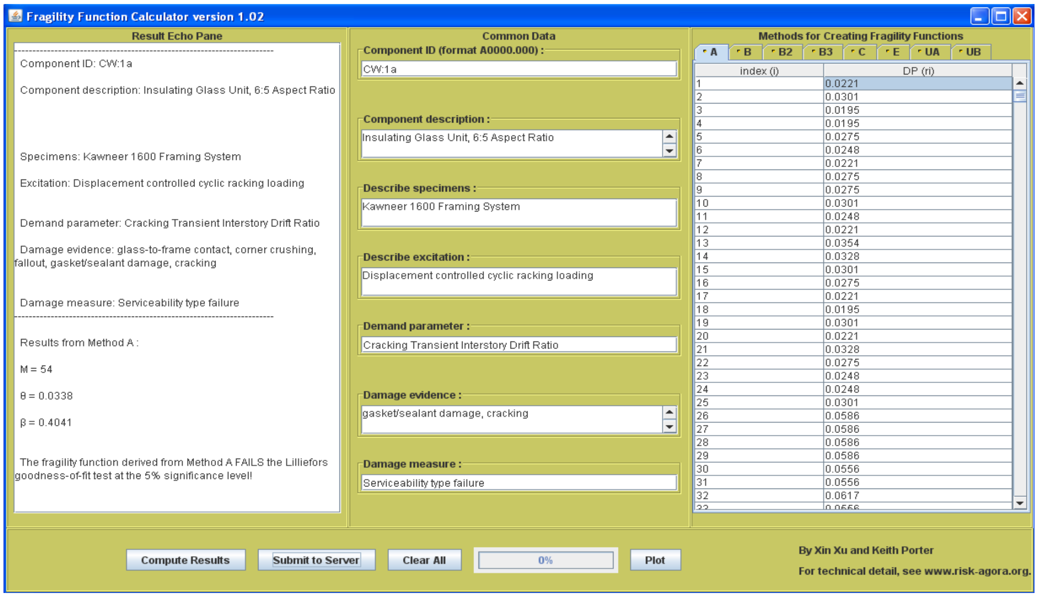
Specimen	DS1		DS2		DS3		DS4		DS5		Comment
	DP	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	***DP***	***f***	
1	0.060	0	0.025	1	0.022	1	0.060	0	0.015	1	
2	0.020	1	0.010	1	0.060	1	0.038	1	0.017	1	

Quality test	DS1	DS2	DS3	DS4	DS5
Passes Lilliefors goodness of fit test? (Type A	Y	Y	Y	Y	Y

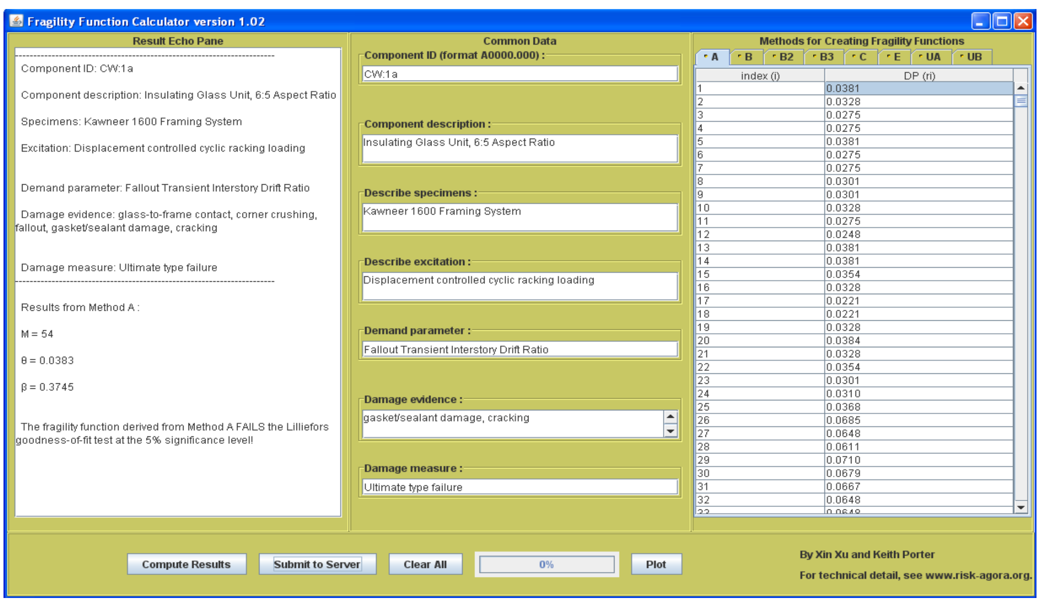
only)					
Are θ and β within 20% of past results? If not discuss.	n/a	n/a	n/a	n/a	n/a
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	N	N	N	N	Y
Discussion: see report					

Appendix F
Software Output: Data Groupings

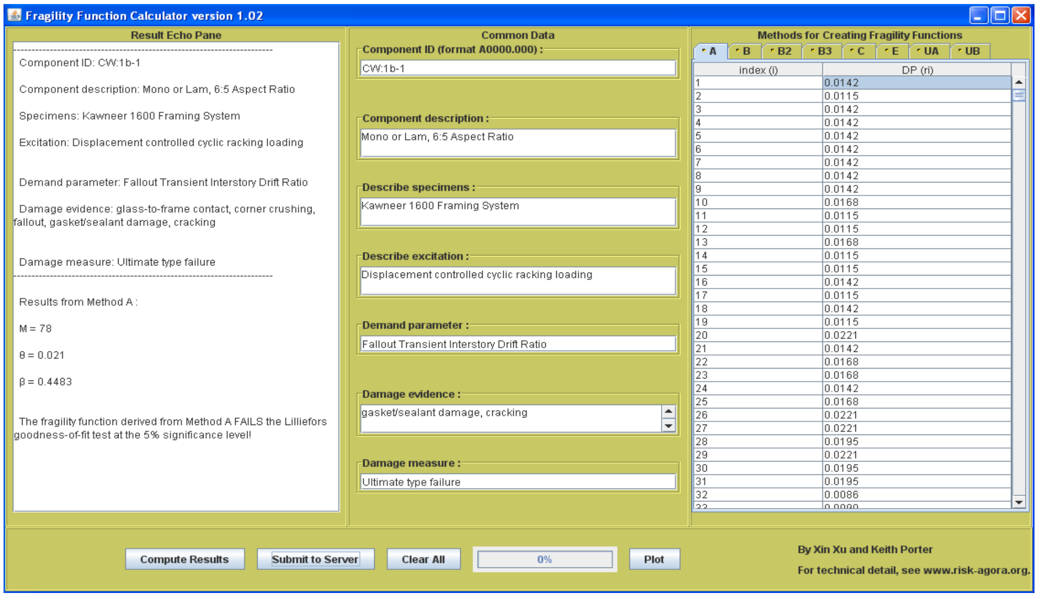
LEVEL CW:1a Cracking



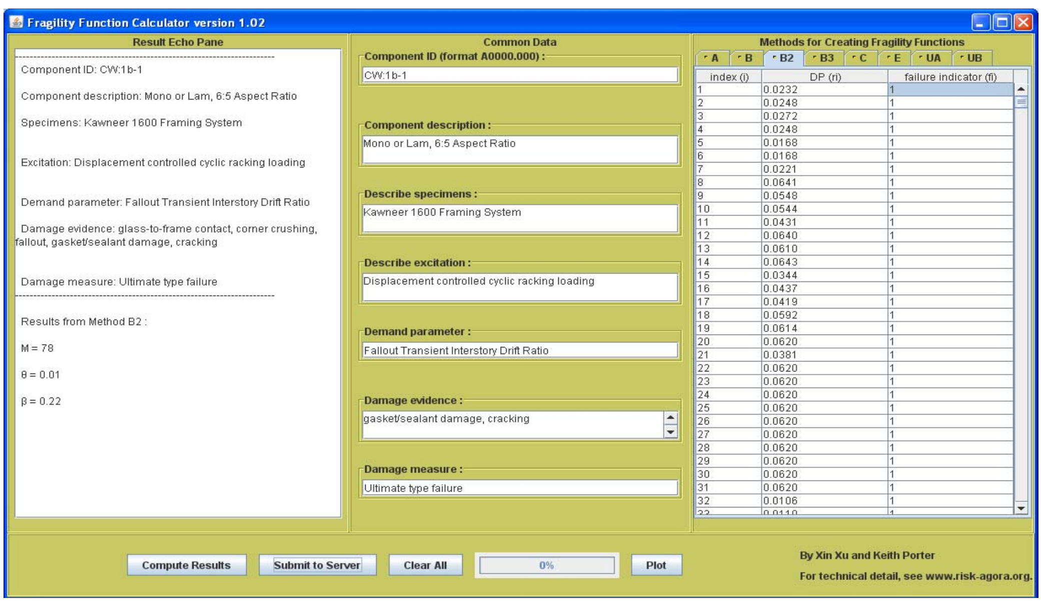
LEVEL CW:1a Fallout



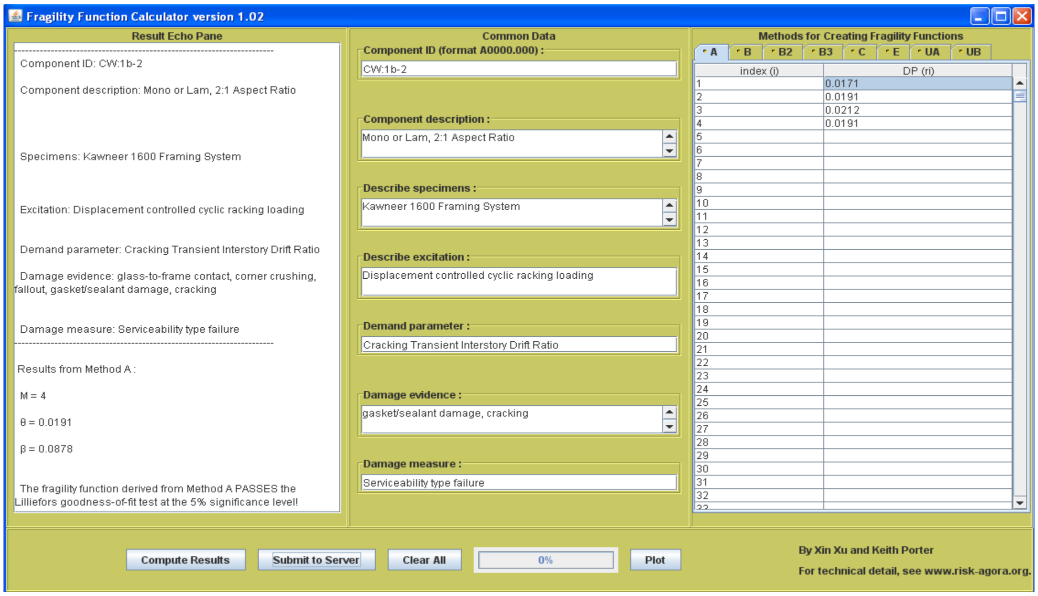
LEVEL CW:1b-1 Cracking



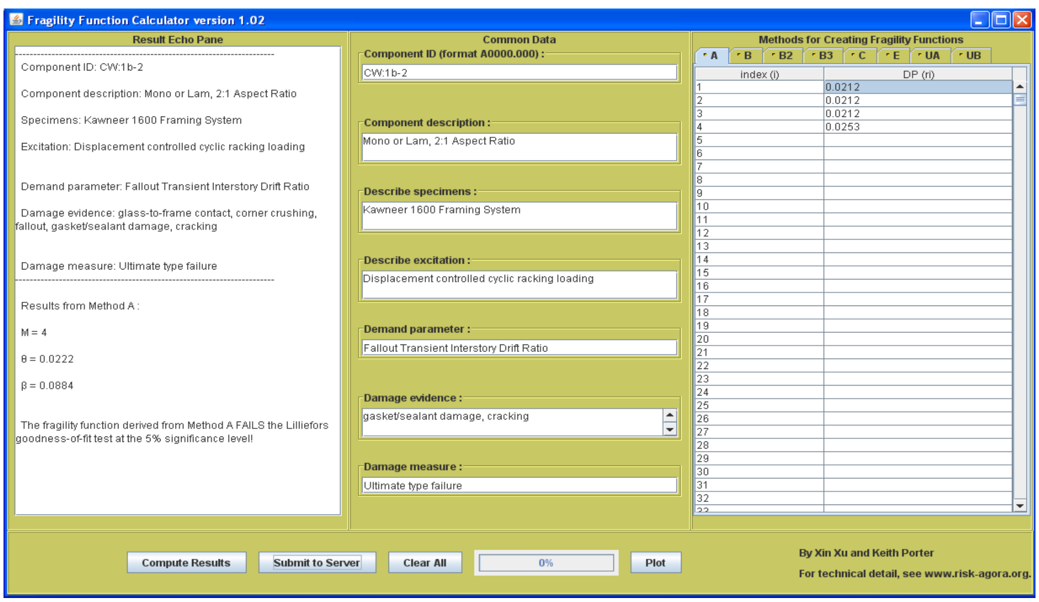
LEVEL CW:1b-1 Fallout



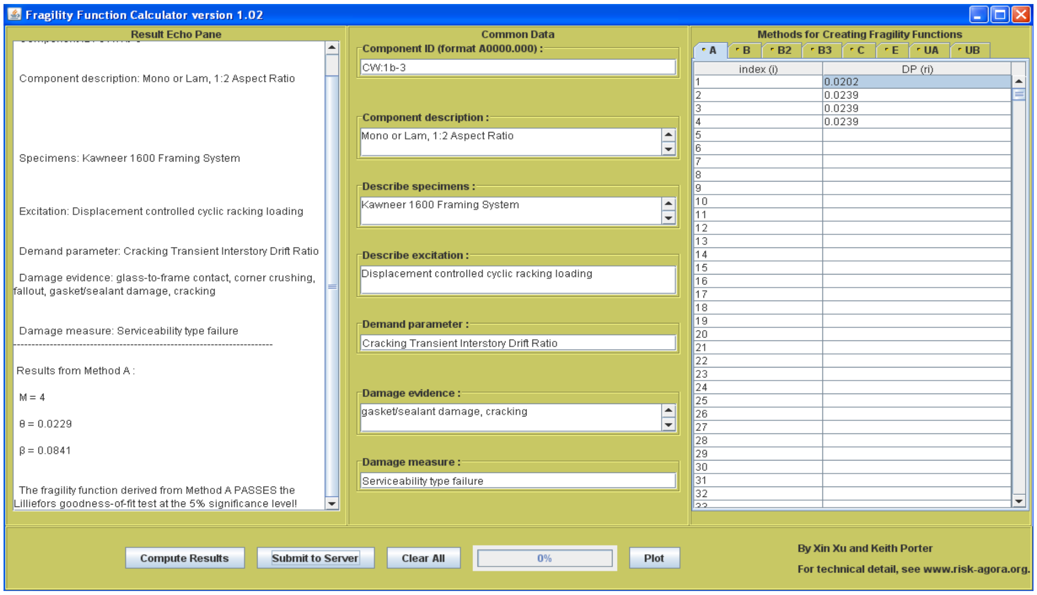
LEVEL CW:1b-2 Cracking



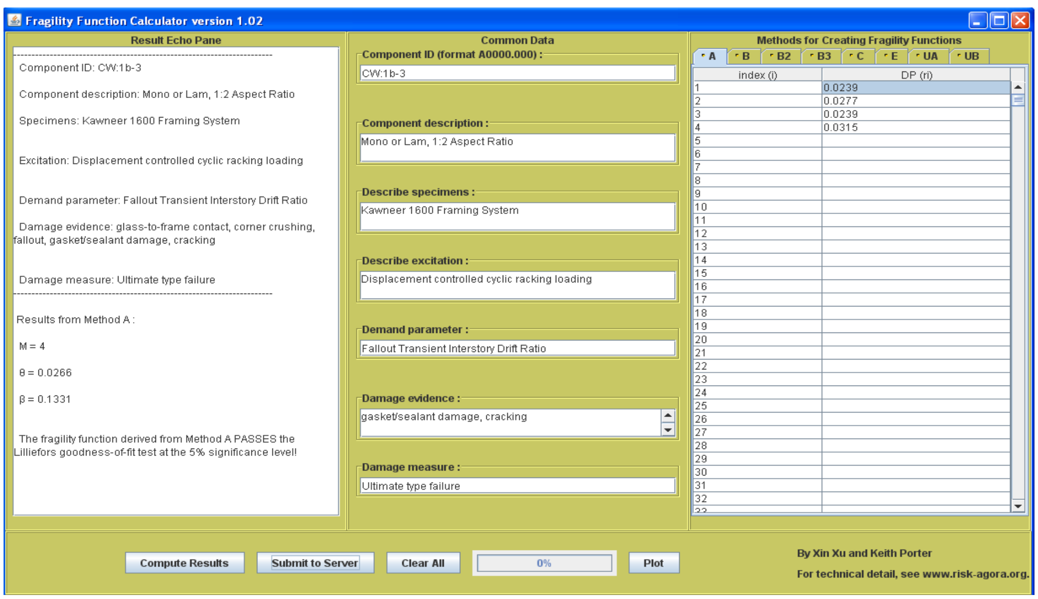
LEVEL CW:1b-2 Fallout



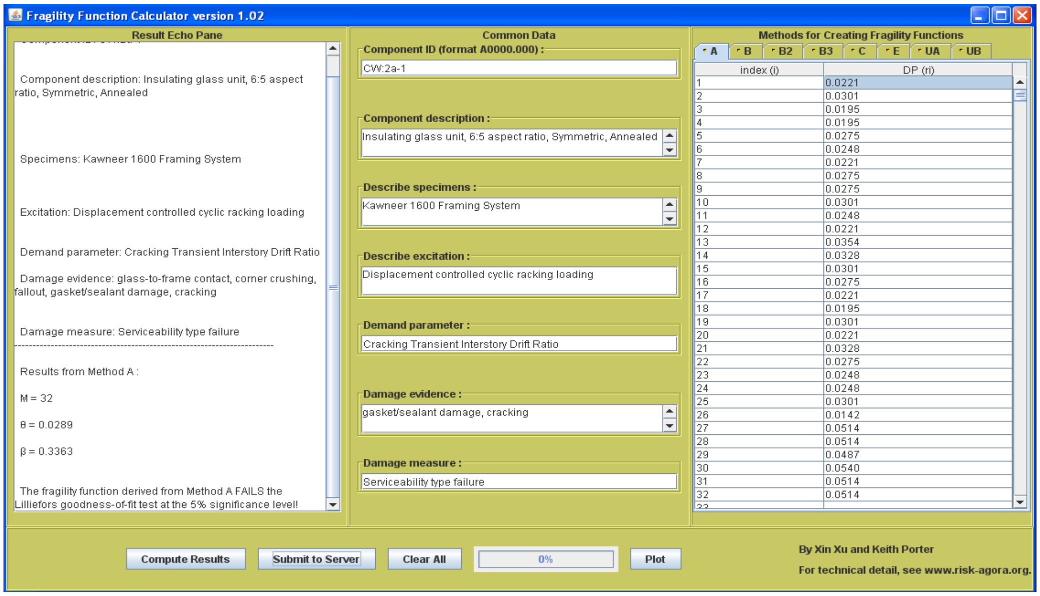
LEVEL CW:1b-3 Cracking



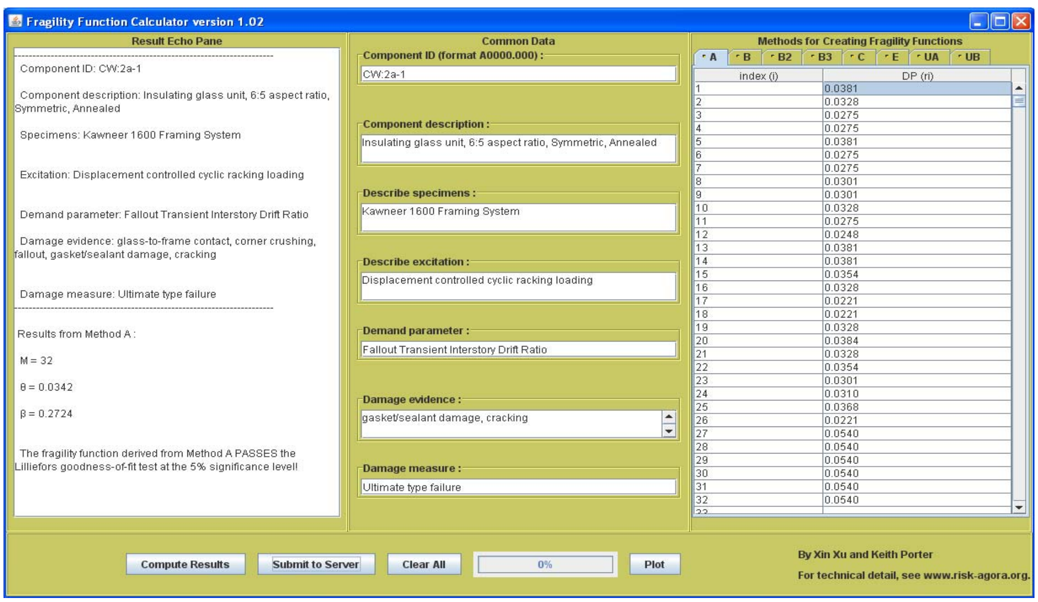
LEVEL CW:1b-3 Fallout



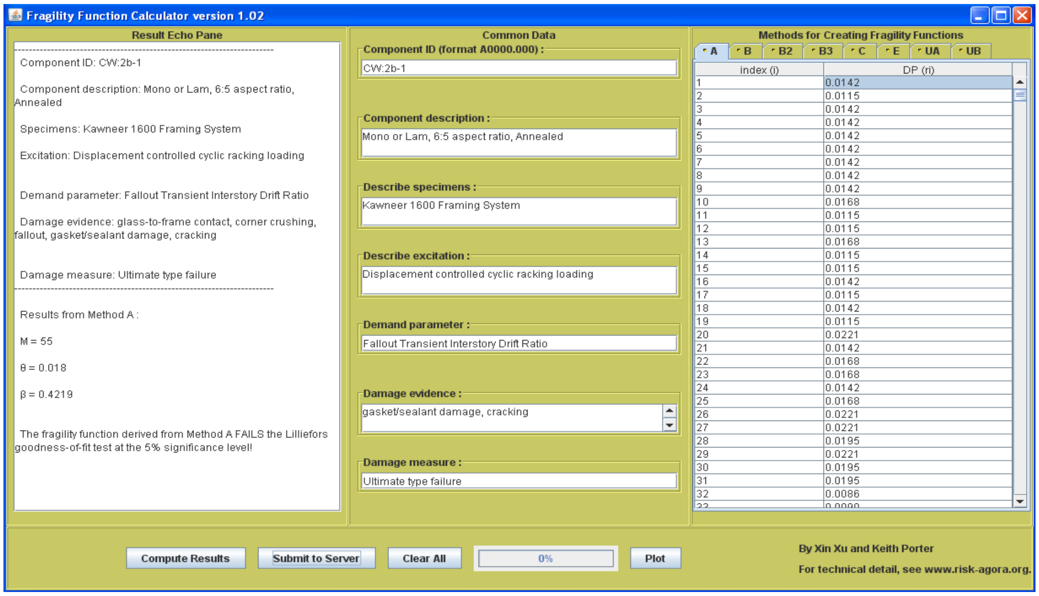
LEVEL CW:2a-1 Cracking



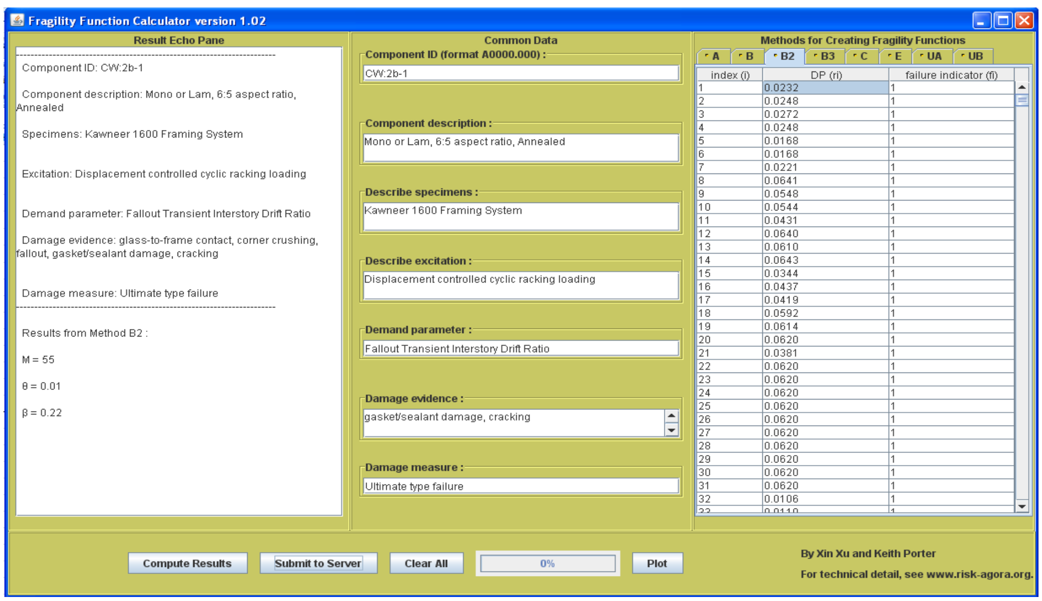
LEVEL CW:2a-1 Fallout



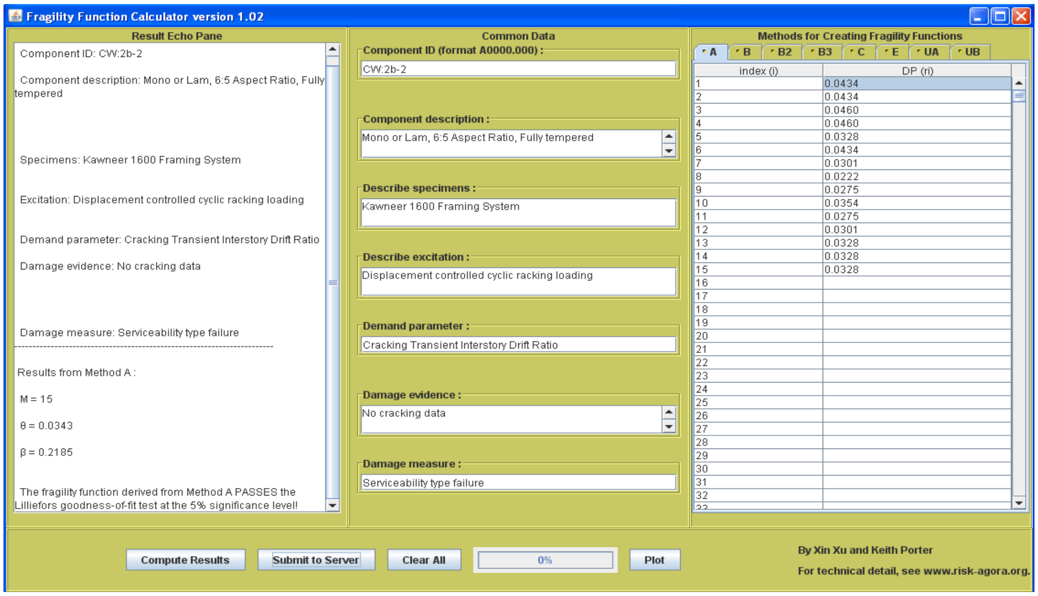
LEVEL CW:2b-1 Cracking



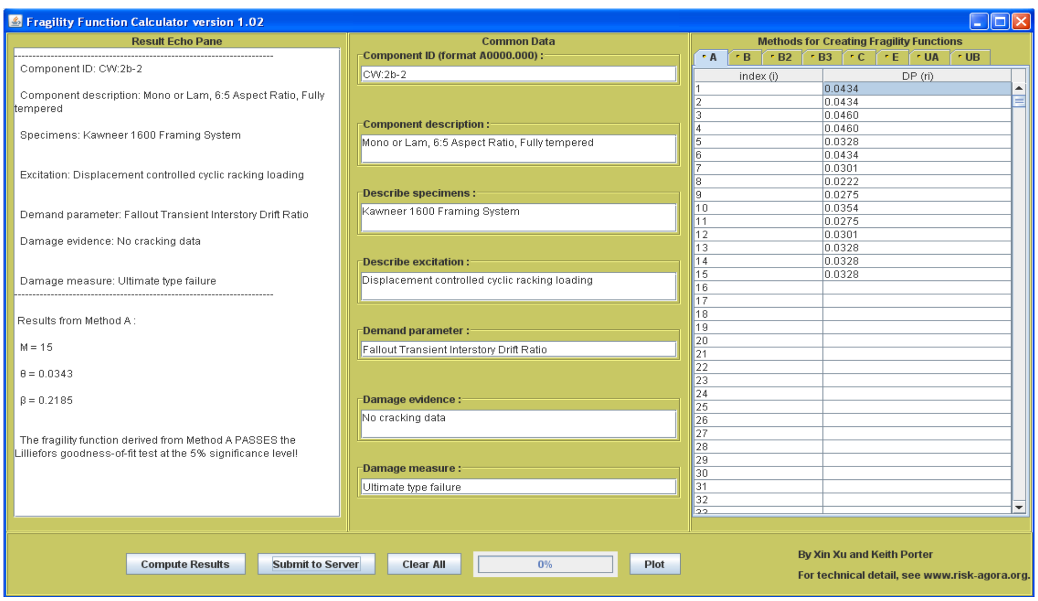
LEVEL CW:2b-1 Fallout



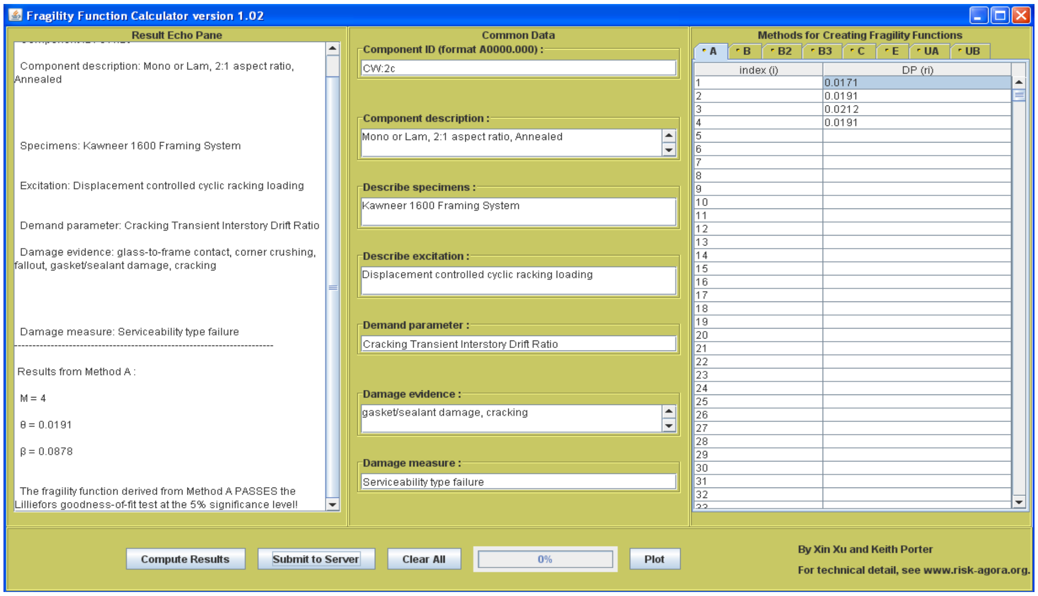
LEVEL CW:2b-2 Cracking



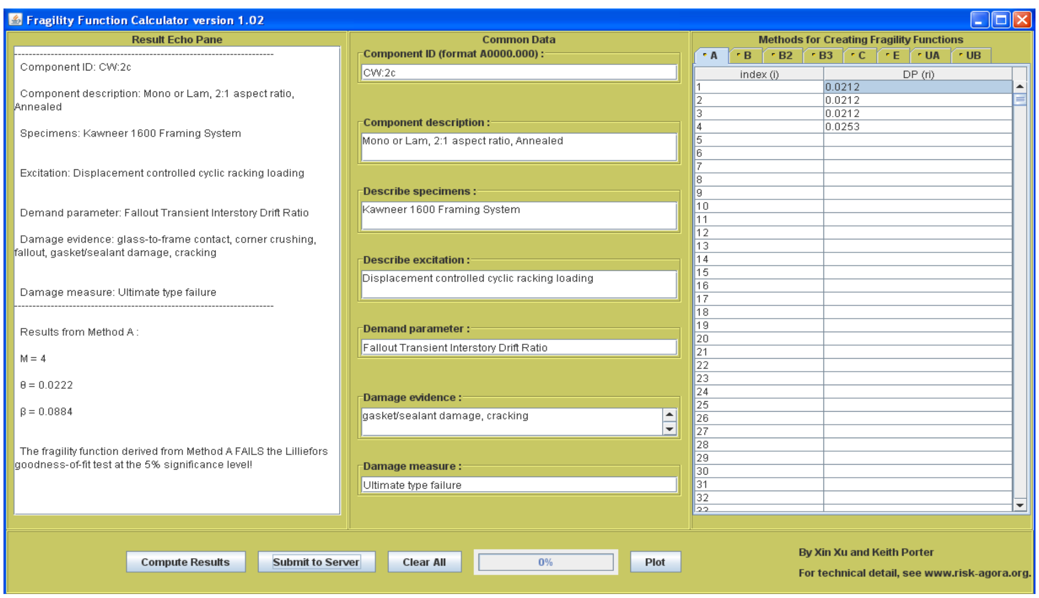
LEVEL CW:2b-2 Fallout



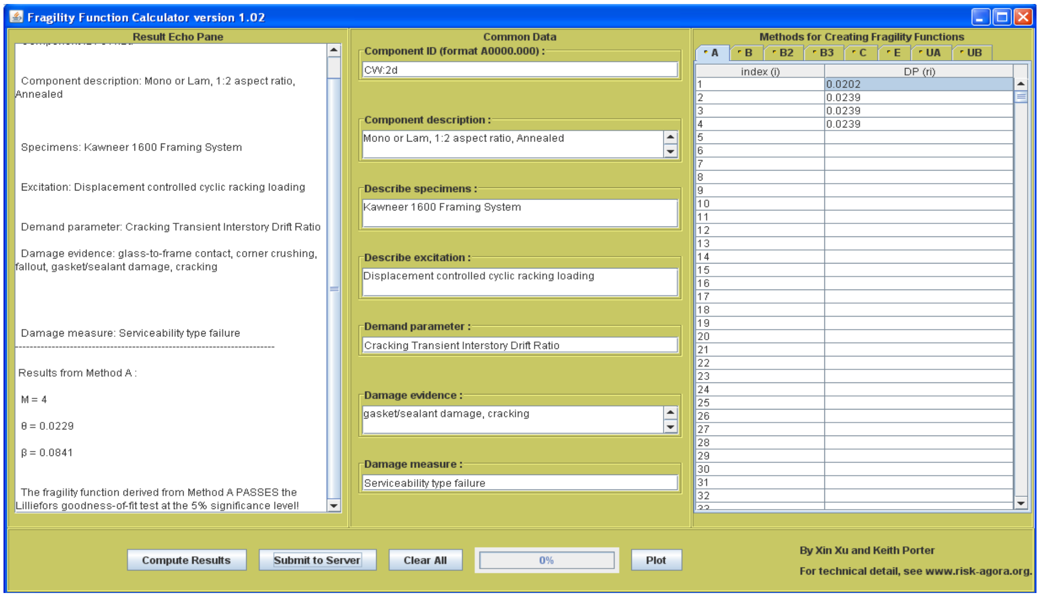
LEVEL CW:2c Cracking



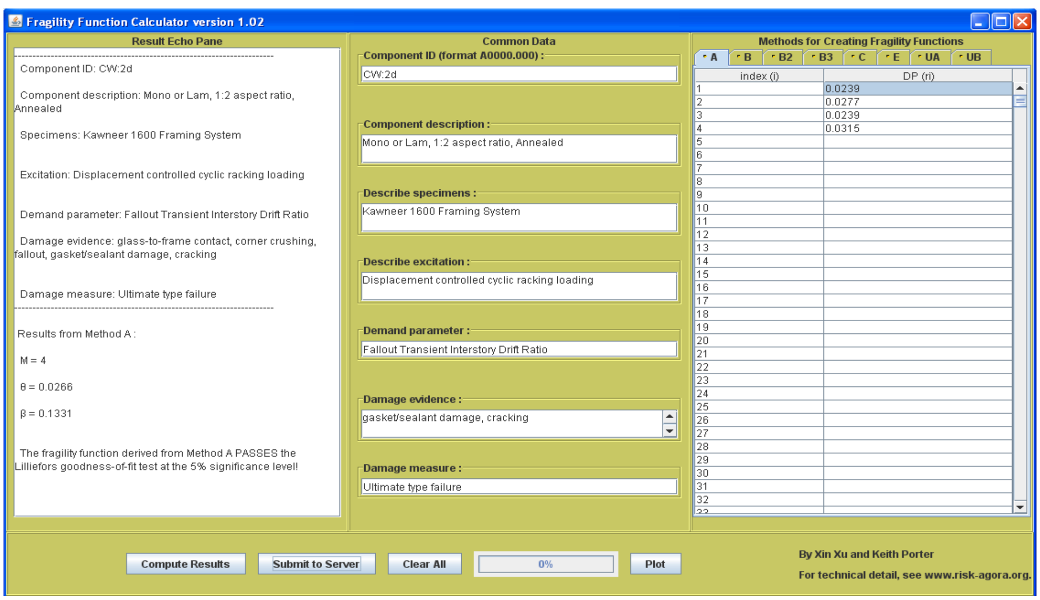
LEVEL CW:2c Fallout



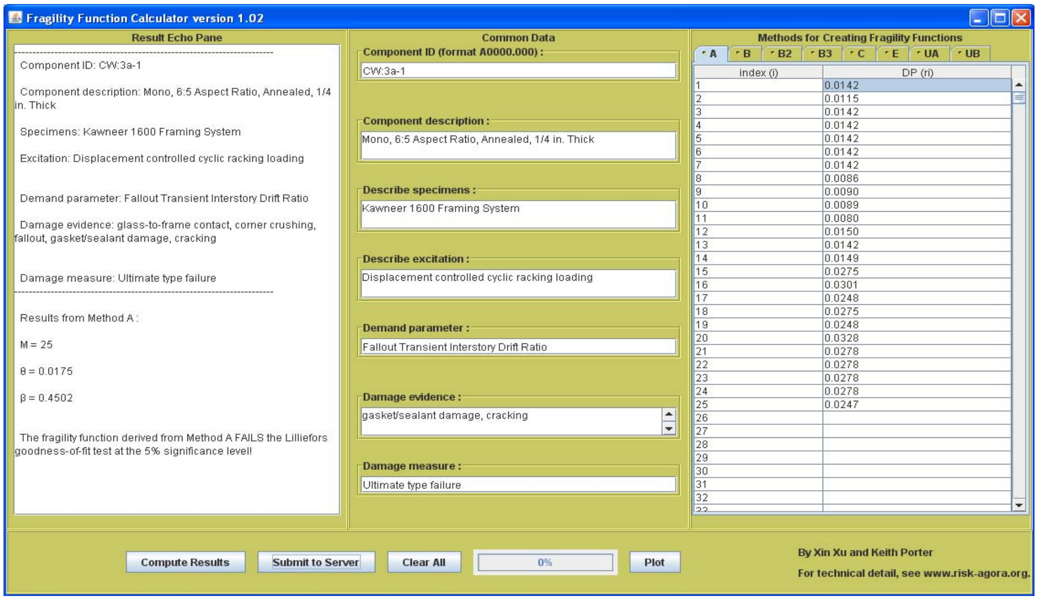
LEVEL CW:2d Cracking



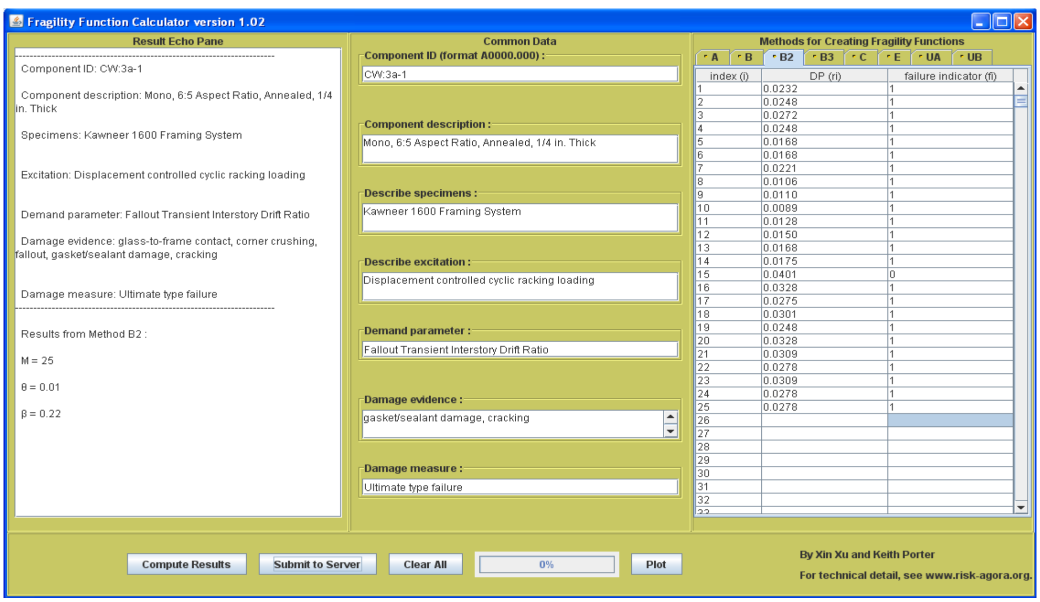
LEVEL CW:2d Fallout



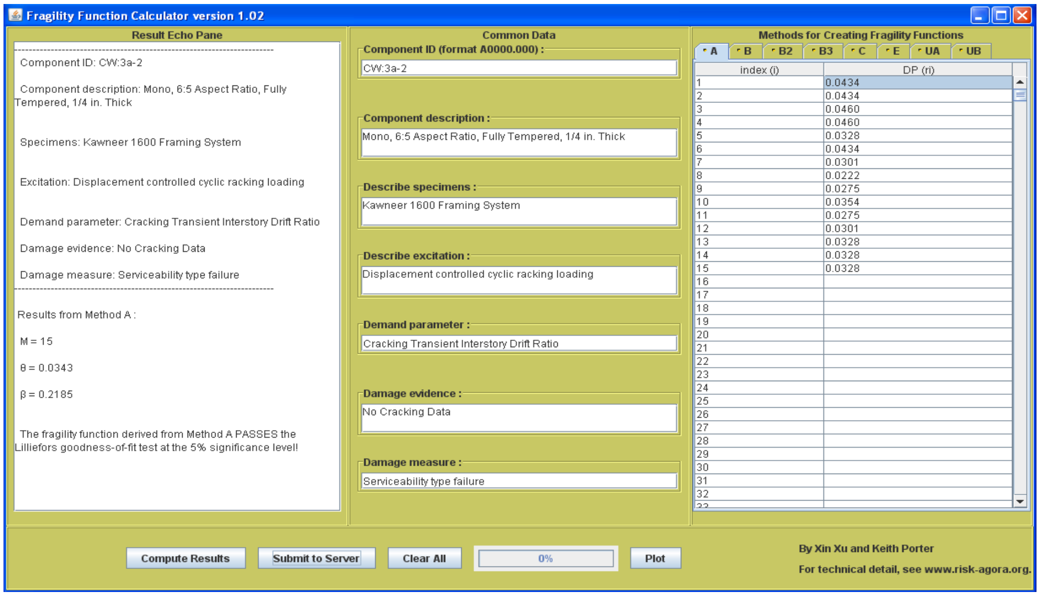
LEVEL CW:3a-1 Cracking



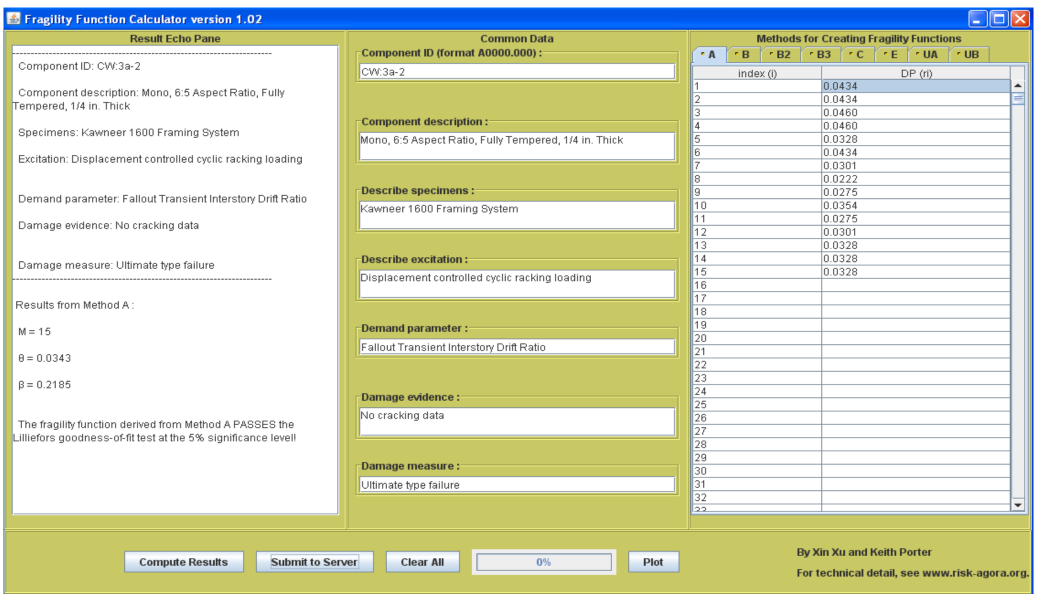
LEVEL CW:3a-1 Fallout



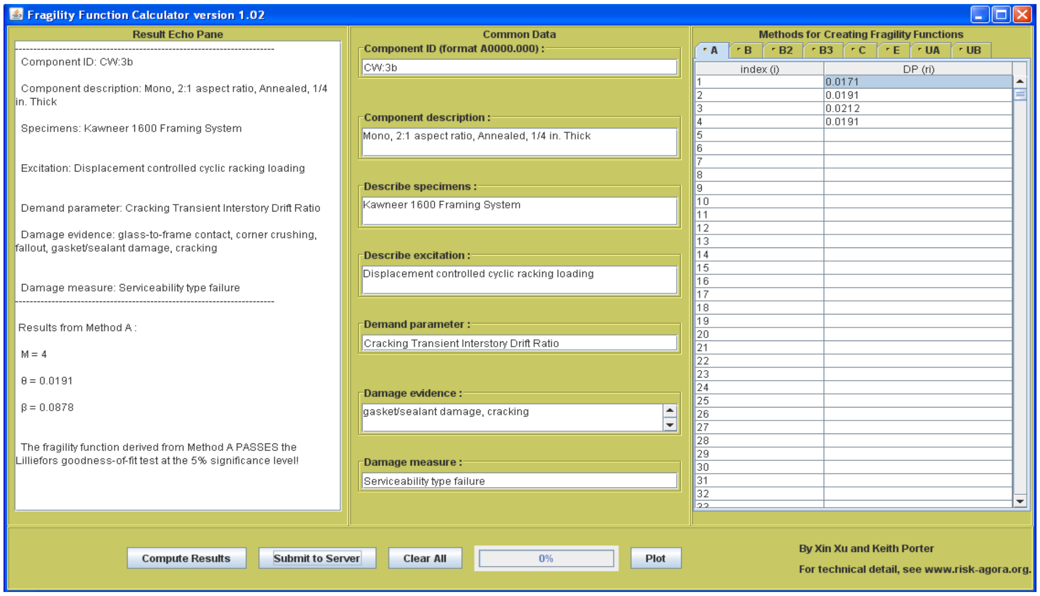
LEVEL CW:3a-2 Cracking



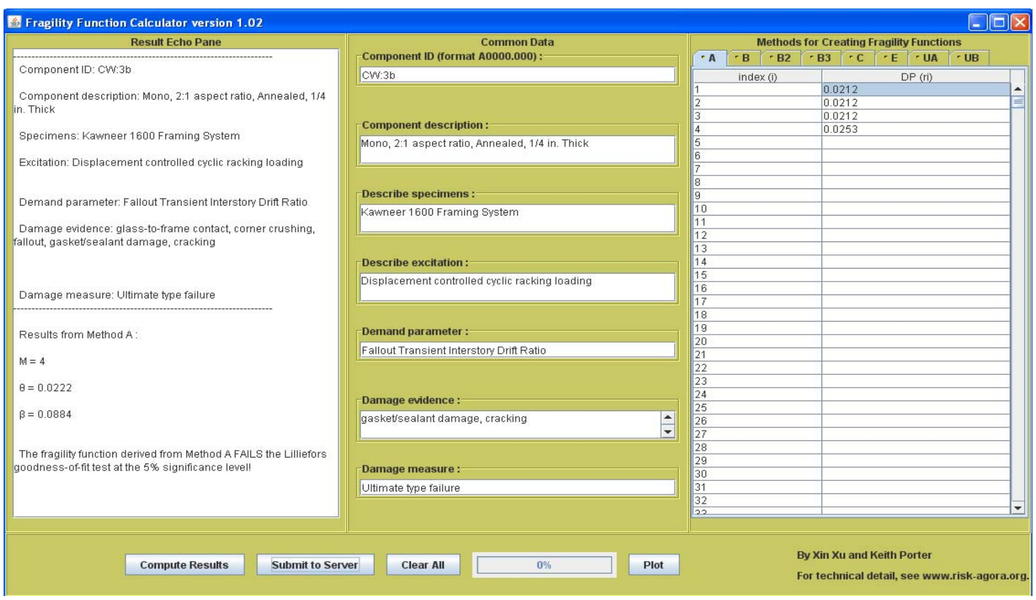
LEVEL CW:3a-2 Fallout



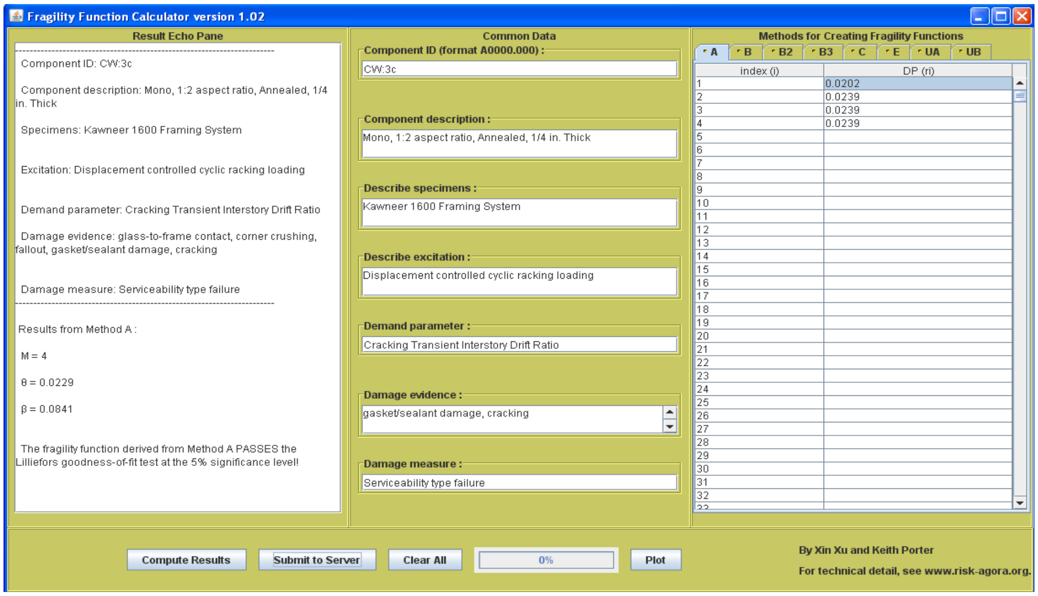
LEVEL CW:3b Cracking



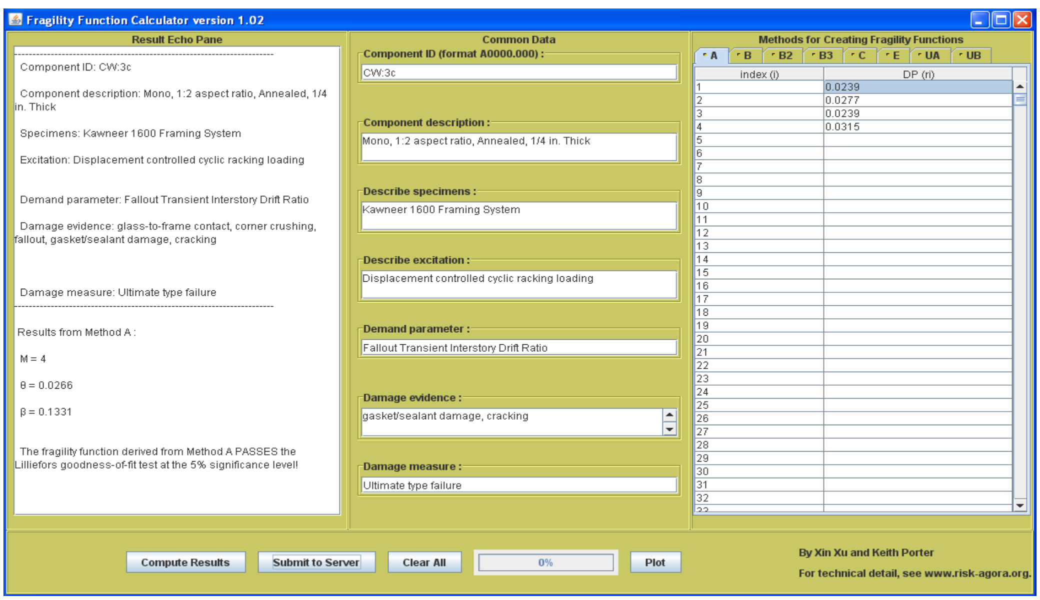
LEVEL CW:3b Fallout



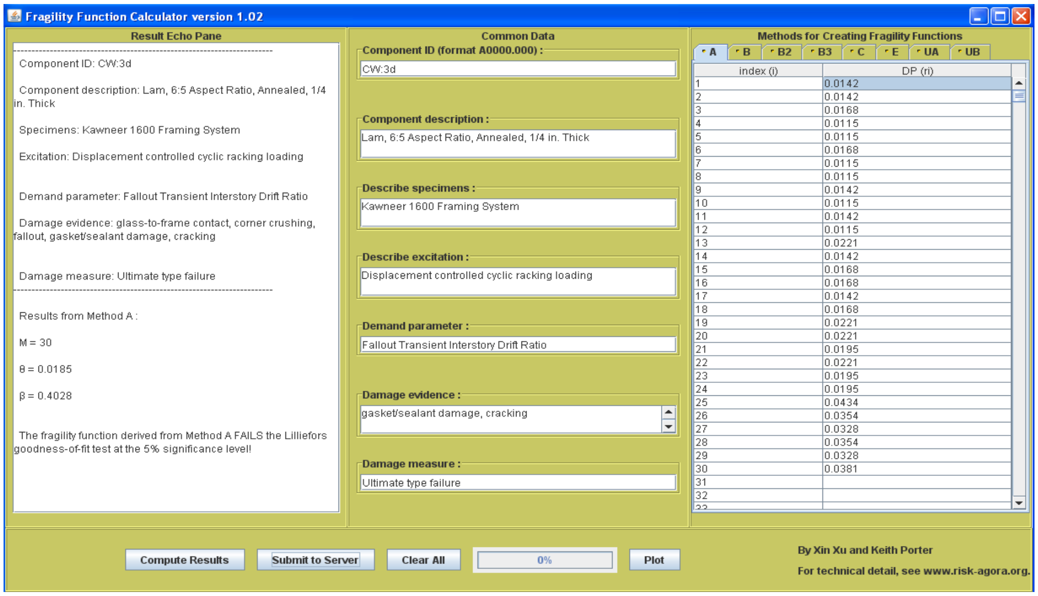
LEVEL CW:3c Cracking



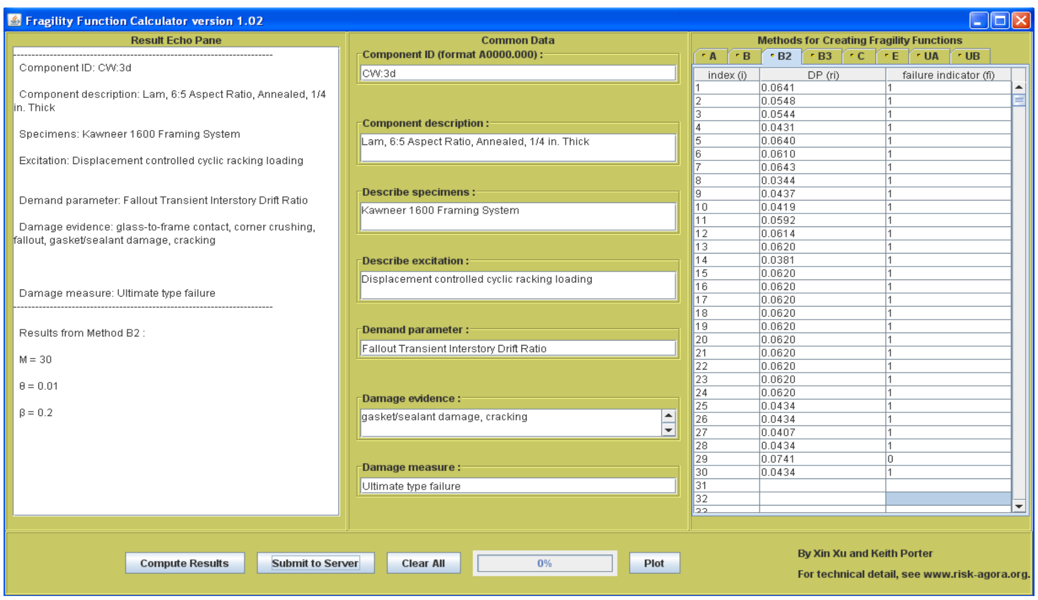
LEVEL CW:3c Fallout



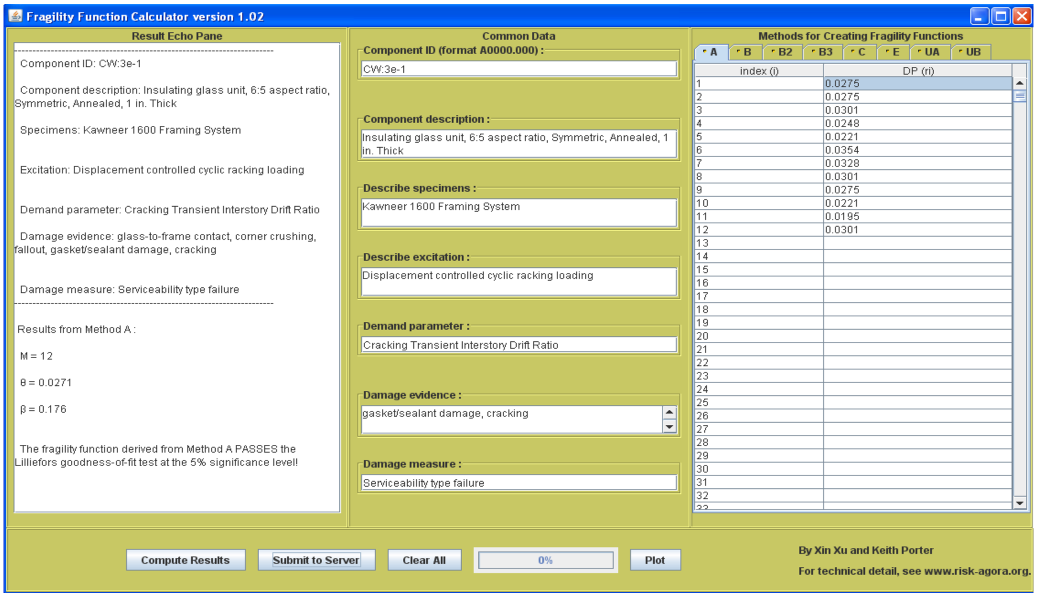
LEVEL CW:3d Cracking



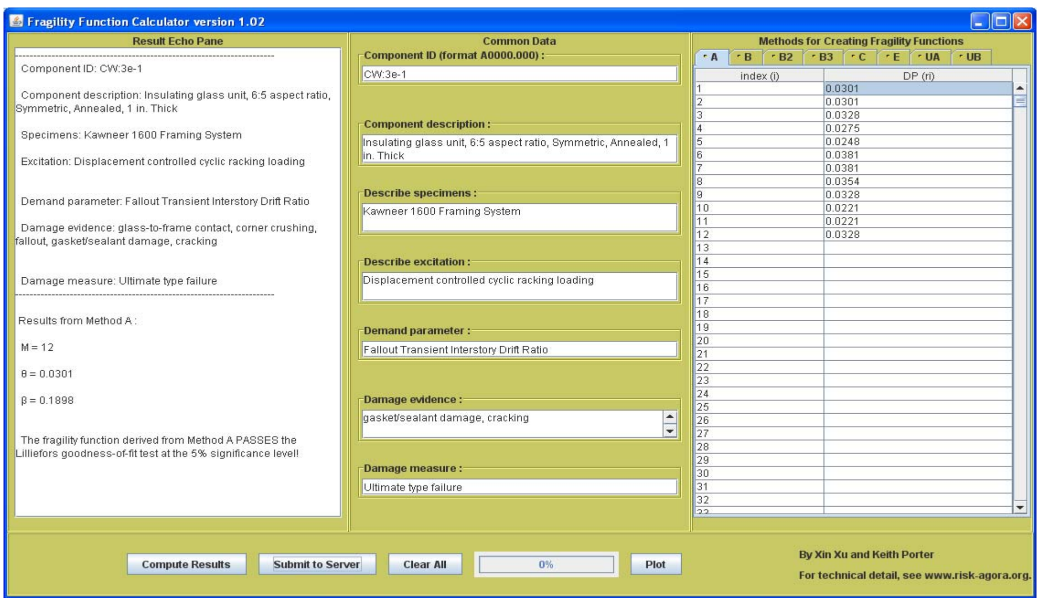
LEVEL CW:3d Fallout



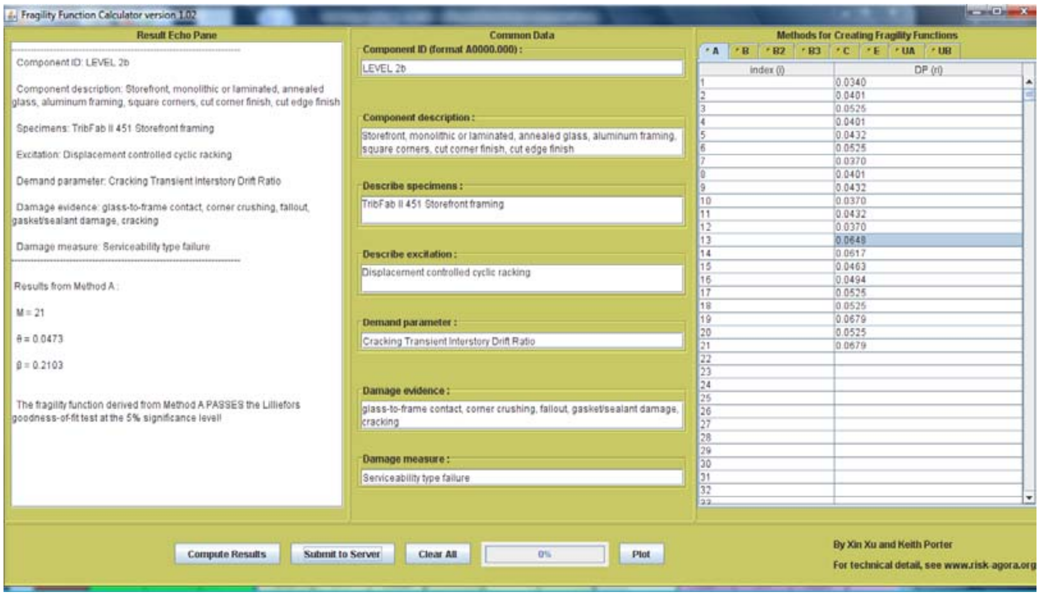
LEVEL CW:3e-1 Cracking



LEVEL CW:3e-1 Fallout



LEVEL SF:2b Cracking



LEVEL SF:2b Cracking