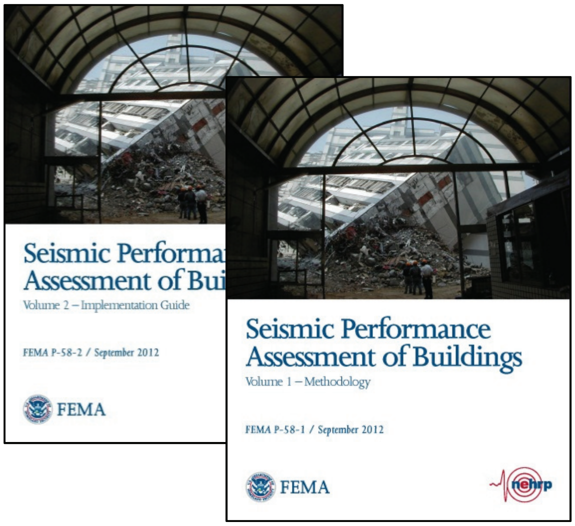

Background Document

FEMA P-58/BD-3.8.10

Damage States and Fragility Curves for Reinforced Masonry Shear Walls

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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contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Users of information in this document assume all liability arising from such use.

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*.

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Final Report Submitted to the Applied Technology Council

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ABSTRACT

This study is to identify the damage modes and level of damage that could develop in reinforced masonry shear walls (RMSW's) in a seismic event, and to develop the corresponding fragility curves to be used for the seismic performance assessment of these structures. The study has been conducted as part of the ATC-58 project carried out by the Applied Technology Council to develop "Next-Generation Performance-Based Seismic Design Guidelines". Because of the lack of pertinent information on the out-of-plane behavior of RMSW's, the study focuses on the damage states related to the in-plane response. Both fully-grouted and partially-grouted walls are considered here.

The damage modes of RMSW's are classified into flexure, diagonal shear, and sliding shear. They are assumed to be mutually exclusive even though this may not be exactly the case in reality. Each damage mode can be further classified into slight, moderate, and severe damage. Flexure behavior is relatively ductile, for which it is reasonable and practical to consider slight, moderate, and severe damage. Wall behavior dominated by diagonal shear is brittle, for which the first observable major damage can be considered moderate. For sliding shear damage, only the severe level is considered as slight or moderate sliding will not affect the structural integrity, and, therefore, does not warrant repair, which can be costly even if it is possible. This results in a total of six damage states, identified as DS1 through DS6. Damage states DS1 through DS3, which are sequential, are for flexure-critical walls. Damage states DS4 and DS5 are for shear-critical walls. Damage state DS6 represents severe sliding shear failure.

Two classes of fragility curves have been developed. Class A uses the story-drift ratio as the demand parameter, which is required for the simplified analysis method adopted in the ATC-58 guidelines. Class B uses a set of normalized demand parameters, which are individually tailored for the different damage modes and which account for the design details and loading conditions of individual wall components in a structure. The use of the latter fragility curves requires more refined analytical models. Methods for calculating the values of the demand parameters for Class A fragility curves are also provided.

The experimental data used for the development of the fragility curves are mainly from fully-grouted concrete masonry walls. Little data are available for partially-grouted walls or walls with hollow clay blocks. The behavior of partially-grouted walls is, in general, not as desirable and consistent as that of fully-grouted walls. The fragility curves for these walls have been derived by adjusting the median value of the demand parameter and the total dispersion of the corresponding fragility function for fully-grouted walls. This adjustment is based on the comparison of the limited experimental data available for partially-grouted walls to the data for fully-grouted walls. This results in a lower median and a larger dispersion of the fragility function for a partially-grouted wall.

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1 INTRODUCTION AND SCOPE OF WORK

A study has been conducted to identify the damage modes and level of damage that could develop in reinforced masonry shear walls (RMSW's) in a seismic event, and to develop the corresponding fragility curves to be used for the seismic performance assessment of these structures. Because of the lack of pertinent information on the out-of-plane behavior of RMSW's, the study focuses on the damage states related to the in-plane response. This work is part of the ATC-58 project carried out by the Applied Technology Council to develop "Next-Generation Performance-Based Seismic Design Guidelines".

A variety of RMSW's exists and they were built over different periods of time as discussed in FEMA 306 (ATC 1998). After the 1933 Long Beach Earthquake, all masonry structures built in California are reinforced. These structures can be constructed of hollow concrete or clay blocks, which can be either fully or partially grouted. In recent construction in California, RMSW's are typically fully grouted to have better seismic performance. However, partially-grouted RMSW's are often used in regions east of the Rock Mountain Range, where severe seismic activities are infrequent. In older buildings, RMSW's can be constructed of two wythes of clay bricks with a reinforced and fully-grouted cavity in between. Design of reinforced masonry structures has gone through major changes in the last twenty years gradually moving from allowable stress design to strength design. However, allowable stress design is still frequently used by engineers nowadays. According to current codes (MSJC 2008, ASCE/SEI 7-05), RMSW's are classified into three types based on their anticipated ductility. They are special, intermediate, and ordinary RMSW's, while only special RMSW's are allowed for Seismic Design Category (SDC) D or above.

FEMA 306 (ATC 1998) identifies three behavior modes for reinforced masonry components: high ductility, moderate ductility, and low (or no) ductility. Walls with high ductility are dominated by flexure. They are normally subjected to moderate axial loads and have relatively low quantity of flexural reinforcement. Walls with no or low ductility are dominated by diagonal shear or sliding shear failure, while those with moderate ductility may have the initial behavior governed by flexure but their displacement ductility is limited by the diagonal shear or sliding shear behavior that may develop later. A high axial compression or a high quantity of flexural reinforcement will also limit the ductility of a wall in flexure.

This study is to identify and document damage states and develop fragility curves for both fully and partially-grouted reinforced masonry bearing wall systems, which were identified as Systems 43 and 44 in Table C-1 of the 50% draft of *ATC-58 Guidelines for Seismic Performance Assessment of Buildings* (ATC 2009). The description of these wall types is reproduced in Table 1.

According to the ATC-58 50% draft document, walls with limited ductility are those that are not designed with specific detailing or provisions to ensure ductility and, therefore, do not necessarily meet the minimum design requirements for ordinary systems per ASCE/SEI 7-05, and those with moderate ductility should have design requirements comparable to those for intermediate systems per ASCE/SEI 7-05. The draft document precludes RMSW's that satisfy the special RMSW design requirements of the current codes. Hence, following the original scope of work would not have covered all RMSW's that may be in existent to-date or that may be built in the future. Furthermore, distinguishing the fragility curves for limited and moderate ductility walls as defined in the draft document presents some issues. First, the distinction is subjective as there is no clear line between the two wall types. Walls not designed with specific detailing or provisions to ensure ductility may still exhibit a certain level of ductility. The ductility of an RMSW depends on many factors, such as the level of the applied axial compressive load, the quantity and layout of the flexural and shear reinforcement, the wall aspect ratio, and the confinement scheme used in the boundary elements. Ductility is more a continuous function of these factors than a discrete function.

Table 1 – Systems 43 and 44 in the ATC-58 50% Draft Guidelines

Material/System Designation	Seismic Ductility	Seismic Behavior Characteristics	Numerical Designation	Code Equivalency	No.
Reinforced Masonry Bearing Walls (RM)	Limited	Basic strength design w/o special detailing	RM-1a	-	43
	Moderate	Strength design with seismic detailing	RM-2a	-	44

With the above considerations, the classification of RMSW's has been revised here to distinguish between fully-grouted and partially-grouted walls and include walls having high ductility. Table 2 shows the revised wall classification used in this study. For each wall type, two classes of fragility curves are developed here. Class A uses the story-drift ratio as the demand parameter, which is required for the simplified analysis method adopted in the ATC-58 guidelines. Class B uses a set of normalized demand parameters, which are individually tailored for the different damage modes and which account for the design details and loading conditions of individual wall components in a structure. The use of the latter fragility curves requires more refined analytical models. For Class A fragility curves, five damage states have been identified. Three corresponds to the flexure-dominated failure mode, and two to the diagonal shear-dominated failure mode. The flexure and shear-dominated modes are assumed to be mutually exclusive. For Class B fragility curves, a sixth damage state, which corresponds to the sliding shear behavior, has been included. These are the most common failure modes of RMSW's as identified in prior research (e.g., Shing et al. 1991) and in FEM 306. Each damage state reflects a certain level of difficulty or cost in repair and restoration to the original state.

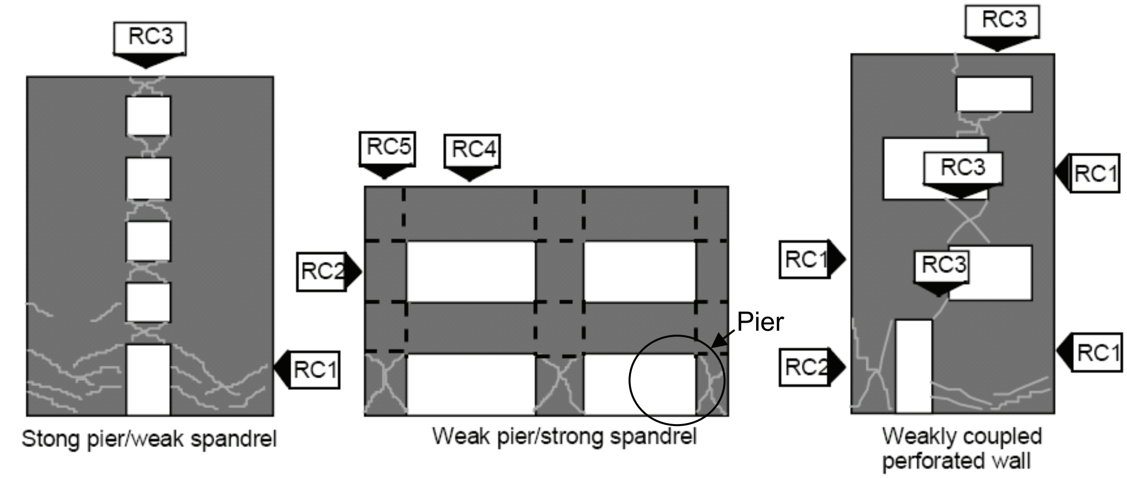
The experimental data available for the development of the fragility curves are mainly from fully-grouted concrete masonry walls. Little data are available for partially-grouted walls or walls with hollow clay blocks. The study by Shing et al. (1991) has shown that the behavior of clay masonry walls is very similar to that of concrete masonry walls. However, clay masonry may exhibit a more brittle behavior because of its higher compressive strength. The behavior of partially-grouted walls is, in general, not as desirable and consistent as that of fully-grouted walls. For this reason, a separate set of fragility curves have been developed for partially-grouted walls. The fragility curves have been developed with the procedure described in Appendix F of the ATC-58 50% draft document. The curves for fully-grouted walls are based on the actual demand data (Method A in Appendix F), with the only exception being the sliding shear damage state, for which the fragility curves have to be derived analytically (Method D in Appendix F) due to limited quantitative experimental data. All the fragility curves for partially-grouted walls except one are based on the opinions of the authors (Method E in Appendix F) because of the lack of experimental data.

Table 2 – Revised RM Wall Classification in the Report

Material/System Designation	Seismic Ductility	Seismic Behavior Characteristics	Numerical Designation	Code Equivalency
Reinforced Masonry Bearing Walls (RM)	Limited	Shear-dominated Partially-grouted	RM-1a	Ordinary/Intermediate Walls
	Low/Moderate	Flexure-dominated Partially-grouted	RM-2a	Ordinary/Intermediate Walls
	Limited	Shear-dominated Fully-grouted	RM-1b	Ordinary/Intermediate
	Moderate/High	Flexure-dominated Fully-grouted	RM-3a	Special Walls

The fragility curves developed here are applicable to all the wall configurations shown in Figure 1. One is cantilever walls, which can be single walls or walls with weak coupling beams as shown in Figure 1(a). This type of walls is referred to as strong piers (RM1) in FEMA 306. Their behavior can be governed by flexural hinging, diagonal shear failure, or sliding at the base. The other is piers that are connected to strong spandrels as shown in Figure 1(b). The latter is referred to as weak piers (RM2) in FEMA 306 and has a high tendency to develop diagonal shear failures even though flexural plastic hinges can sometimes develop at the top and bottom of a pier. The experimental data used in this study are obtained from cantilever walls. Little test data are available for weak pier configurations. However, the fragility curves developed in this report will be applicable to both wall configurations with the main difference being how the demand parameter is evaluated. Furthermore, little experimental data are available for perforated shear walls such as the one shown in Figure 1(c). Nevertheless, one can often identify strong and weak pier components (RM1 and RM 2) in such walls as shown in the figure. Weak spandrels (RM3) as shown in Figure 1(a) and (c) can be treated in the same way as weak piers (RM2).

The development of the fragility curves for RMSW’s is described in the following sections. Section 2 discusses the damage modes of different RMSW’s and defines the damage states considered in this study. Relevant experimental data are reviewed, criteria used to indentify the damage states are presented, and methods of repair are discussed. Section 3 presents the demand parameters used to construct the fragility curves, the method used to develop these curves, and the criteria to distinguish shear-critical and flexure-critical walls. Sections 4 and 5 present the Class A fragility curves for fully-grouted and partially-grouted walls, respectively. Sections 6 and 7 present the Class B fragility curves for these walls. Experimental data used to develop Class A and Class B fragility curves are presented in Appendices A through D. Appendix E contains supplemental information on the scope of repair for different damage states. Appendices F through I contain tables of fragility specification summarizing the damage states and consequence functions for each fragility group.



(a) Weak Coupling (b) Strong Coupling (c) Perforated Wall

Figure 1 - Coupled Walls (from FEMA 306, RC be replaced by RM for Masonry)

2 DAMAGE STATES AND REPAIR METHODS

2.1 Damage Behavior of Reinforced Masonry Shear Walls

For the purpose of developing fragility curves, distinct damage states that are associated with different levels of repair and restoration effort and costs have been identified. They are associated with different behavior modes of a wall. Based on experimental observations (e.g., see Shing et al. 1991), the behavior modes of RMSW's can be classified into three main types: (a) flexure; (b) diagonal shear cracking; and (c) sliding shear.

Flexural damage may involve flexural cracking, the yielding, buckling, and fracture of the flexural reinforcement, masonry crushing at wall toes, the slip of lap splices, and the out-of-plane buckling in the compression zone of a wall as summarized in FEMA 306. Walls dominated by flexure can exhibit a relatively ductile behavior. Figure 2 shows the hysteresis curves obtained from a reinforced clay masonry wall (indentified as Specimen 17) tested by Shing et al. (1991) that exhibited a moderately ductile behavior. The wall had a flexural reinforcement ratio of 0.40% and was subjected to an axial compressive stress of 280 psi during the test. The flexural yielding of the extreme vertical reinforcement in a wall normally starts at a lateral load that is 60 to 70% of the peak strength, depending on the level of the applied axial compressive load and the flexural reinforcement ratio. The larger the axial compressive load and the flexural reinforcement ratio are, the later will be the flexural yielding and the less ductile the wall will be. Figure 3 shows the crack pattern in the wall (Specimen 17) when it was loaded to about 80% of its peak strength while the first yield occurred at 65 kips. It can be seen that the cracks were very minor probably requiring only cosmetic repair. Figure 4 shows the crack pattern of the same wall right after reaching the peak lateral load of 103 kips. At this stage, noticeable but limited toe crushing, signified by vertical cracks in the toe regions, can be observed from the picture. Similar damage evolution can be observed for walls with different axial compressive loads and flexural reinforcement ratios. Sometimes, light toe spalling could be observed at the peak load. The occurrence of out-of-plane buckling, severe toe crushing, or bar buckling or fracture will significantly minimize the post-peak resistance and stability of a wall. Flexural reinforcement may buckle in the compression toe after severe masonry spalling, as shown in Figure 5, has occurred. Repeated buckling and straightening of a bar under load cycles will induce severe localized bending strains, and, thereby, lead to bar fracture at a relatively low average tensile strain of the bar. Walls with higher axial compressive loads and higher flexural reinforcement ratios are more vulnerability to out-of-plane buckling, severe toe crushing, and bar buckling. The occurrence of these severe damage states is normally preceded by a drop of the lateral resistance by 20% or more. The repair of such damage can be difficult and costly if not impossible. Even though flexural behavior can be improved by introducing well confined boundary elements, this is not easy and generally not practical for reinforced masonry walls because of the constructability issue.

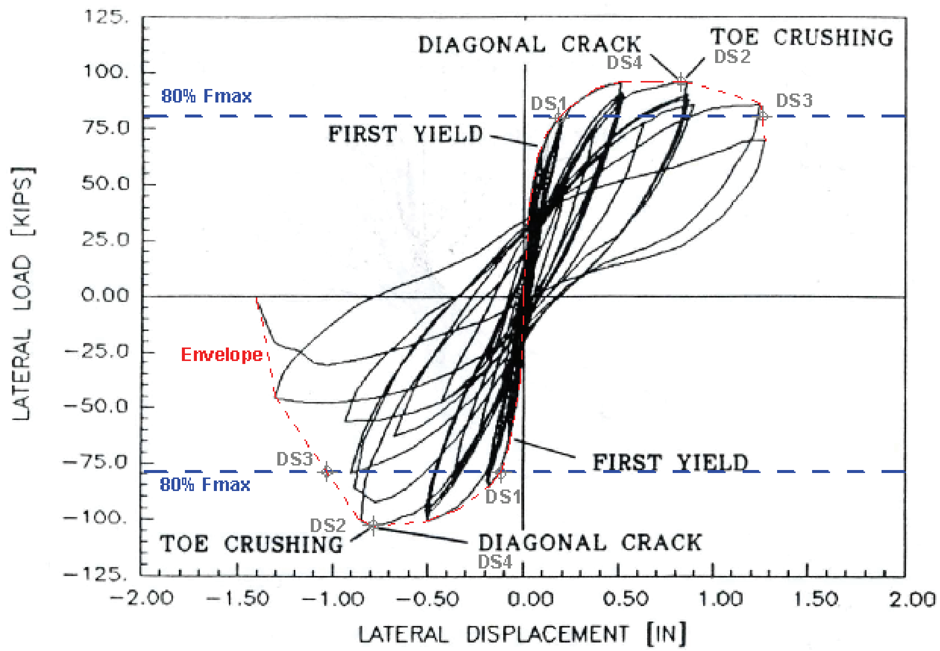


Figure 2 – Hysteresis Curves for a Flexure-Dominated Wall (Specimen 17, Shing et al. 1991)

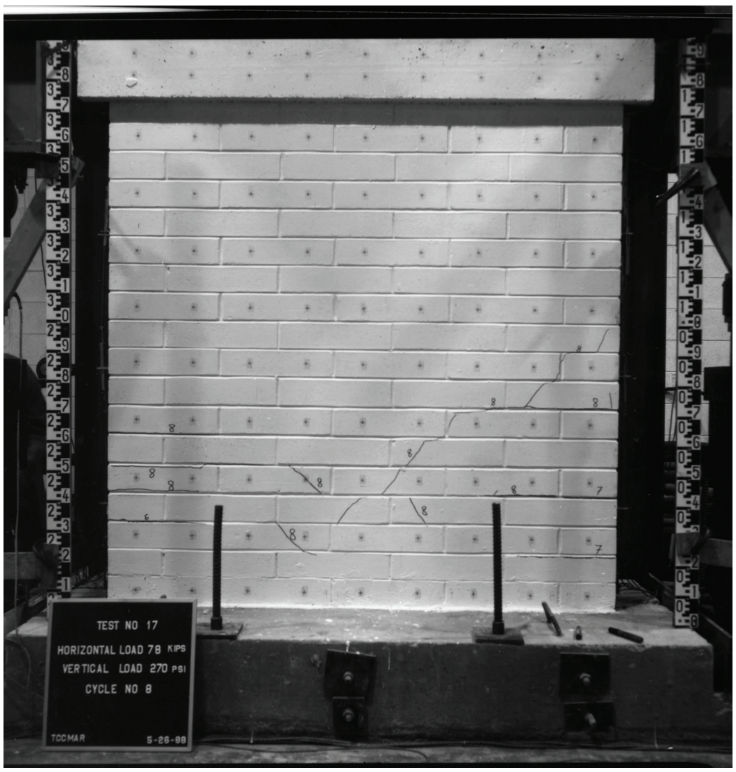


Figure 3 – Crack Pattern of Specimen 17 at 80% of Peak Load (Shing et al. 1991)

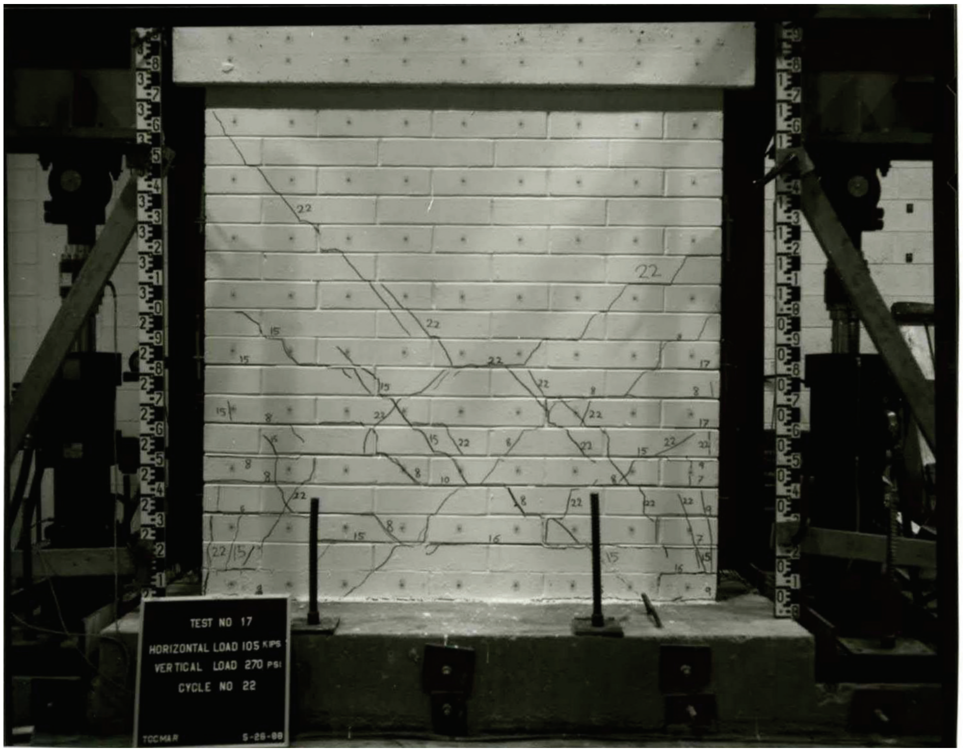


Figure 4 – Crack Pattern of Specimen 17 at Peak Load (Shing et al. 1991)

Figure 5 – Cracking and Crushing of Specimen 17 right after 20% Load Drop (Shing et al. 1991)

The behavior of walls dominated by diagonal shear cracks is often very brittle as demonstrated by the hysteresis curves shown in Figure 6 obtained from a shear dominated wall. Before the shear capacity of a wall has been reached, diagonal cracks will normally remain restrained as shown in Figure 7, and such cracks can often be repaired by epoxy injection. However, the lateral resistance of the wall can drop rapidly once the peak load has been reached and a major diagonal crack has opened suddenly as shown in Figure 8. When this occurs, the wall should be considered non-reparable and should be replaced. The shear strength of a wall depends on the wall aspect ratio, the tensile and compressive strengths of the masonry, the quantity of the shear reinforcement, and the applied axial compressive load. Walls with low height-to-length (*H*/*L*) ratios and low quantity of shear reinforcement will most likely exhibit this type of behavior.

Since a significant portion of the shear resistance can be provided by the masonry in compression at the wall base, diagonal shear failure can happen in flexure-dominated walls when the masonry resistance is weakened by toe crushing. In these walls, the initial behavior and peak resistance are governed by flexure, and shear failure occurs at a later stage, which may significantly impair the displacement ductility. This type of damage is called flexure/shear failure (Shing et al. 1991, FEMA 306). However, fine diagonal shear cracks can occur in a flexure-dominated wall in an early stage, but they may not be able to open wide enough to result in a brittle shear failure when sufficient shear and flexural reinforcement is present to restrain the cracks. This situation is shown in Figure 4. These cracks can be relatively easy to repair.

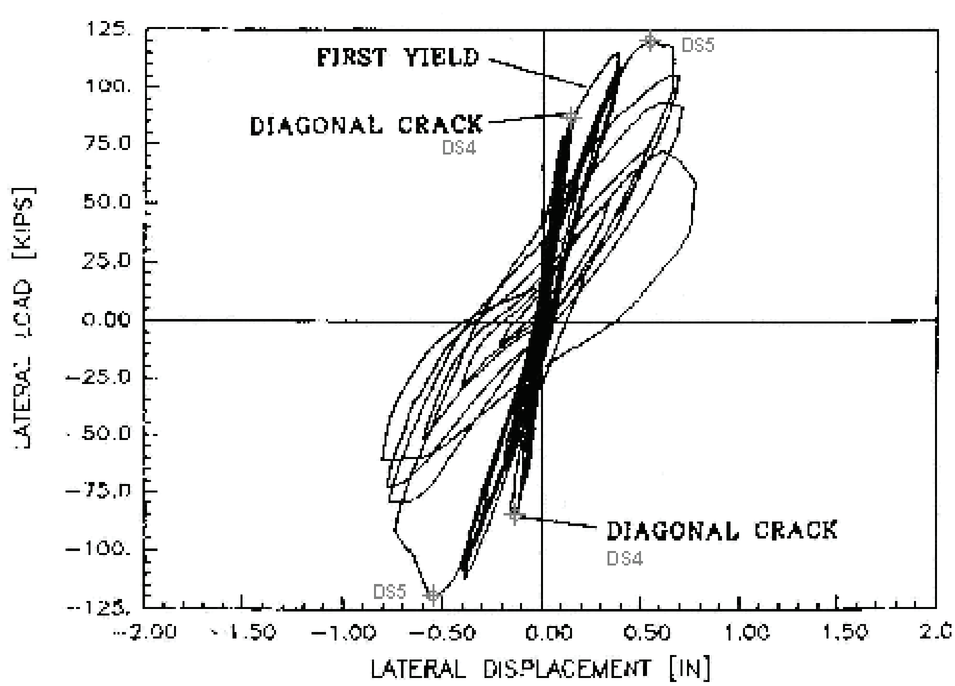


Figure 6 - Hysteresis Curves for a Shear Dominated Wall (Specimen 16, Shing et al. 1991)

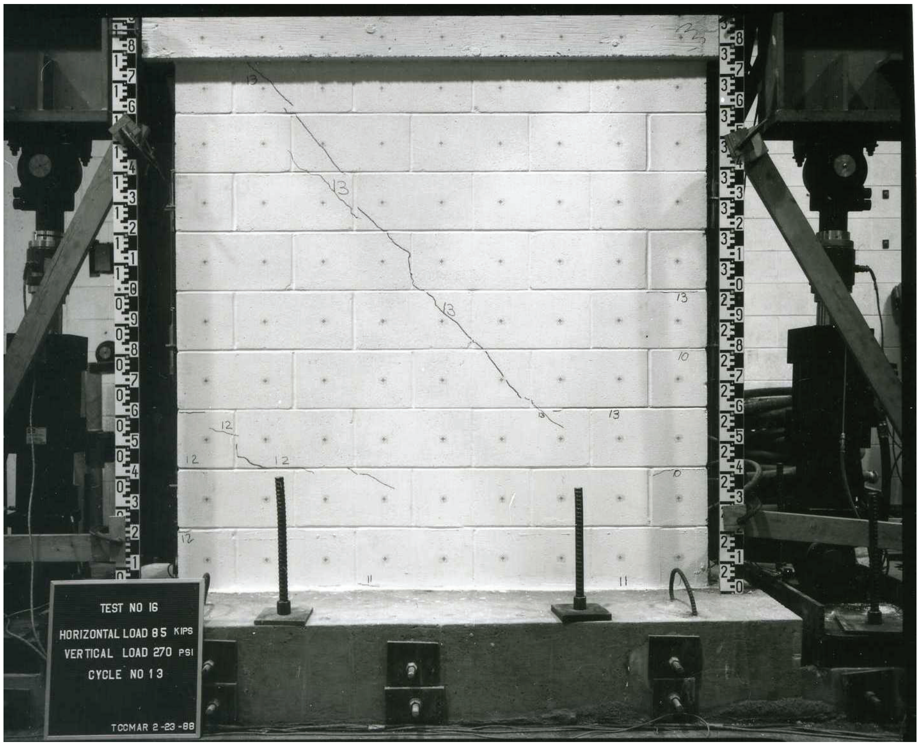


Figure 7 – Occurrence of First Major Diagonal Crack in Specimen 16 (Shing et al. 1991)

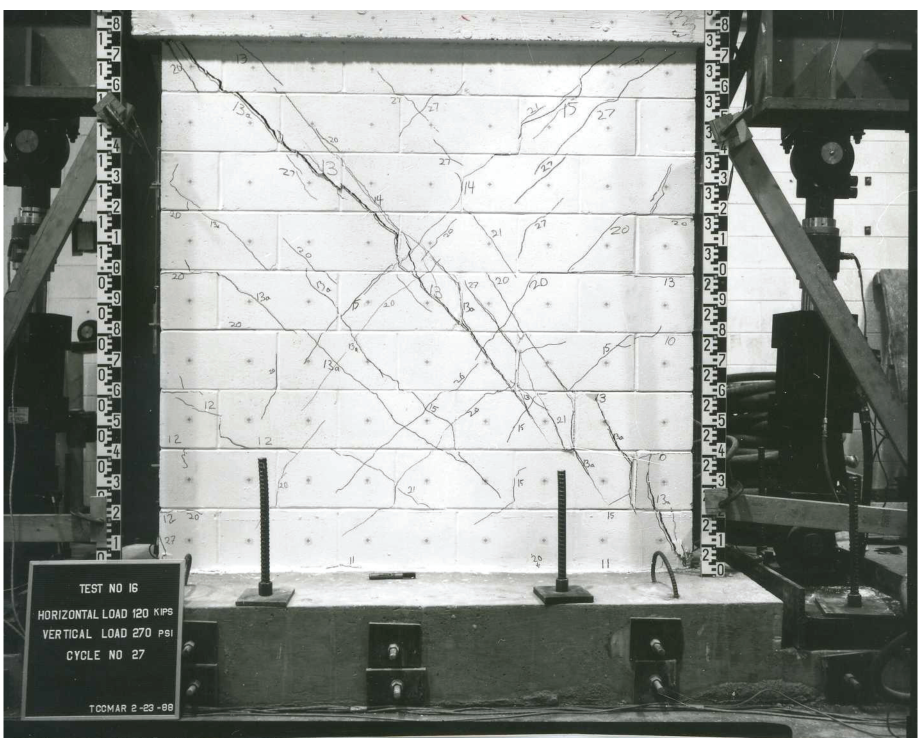


Figure 8 – Diagonal Cracks in Specimen 16 at Shear Capacity (Shing et al. 1991)

The sliding shear resistance of a wall depends on the surface roughness, the normal restraint provided by the flexural reinforcement, the applied axial compressive load, and, to a lesser extent, the dowel action of the flexural reinforcement. It can be estimated with the Coulomb friction law. Walls with a low aspect ratio and low axial compressive load have a high tendency to exhibit the sliding shear behavior. It may occur early or after the peak flexural resistance of a wall has been passed when the shear resistance has been weakened by the flexural damage at the base. The latter is called flexure/sliding shear failure (FEMA 306, Shing et al. 1991). It can impair the flexural ductility of a wall by accelerating the wall damage, such as masonry spalling and bar buckling, at the base. Significant base sliding may also induce severe damage to other structural and non-structural components. Hence, sliding shear failure is generally considered as undesirable and classified as a brittle behavior (FEMA 306). This type of damage is difficult to repair. However, limited shear sliding normally will not affect the structural integrity.

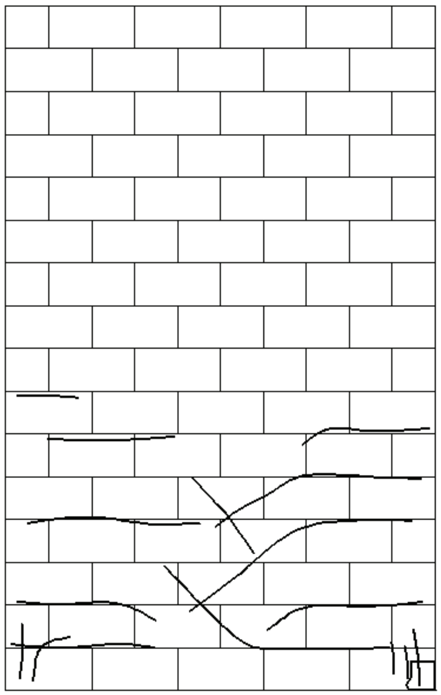
2.2 Definition of Damage States

Based on the above observations, the damage modes considered in this study are classified into flexure, diagonal shear, and sliding shear. They are assumed to be mutually exclusive even though this may not be exactly the case in reality as discussed above. Each damage mode can be further classified into slight, moderate, and severe damage. Flexure behavior is relatively ductile, for which it is reasonable and practical to consider slight, moderate, and severe damage. Wall behavior dominated by diagonal shear is brittle, for which the first observable major damage can be considered moderate. For sliding shear damage, only the severe level is considered as slight or moderate sliding will not affect the structural integrity, and, therefore, does not warrant repair, which can be costly even if it is possible. This results in a total of six damage states, identified as DS1 through DS6, as shown in Table 3. Damage states DS1 through DS3, which are sequential, are for flexure-critical walls. Damage states DS4 and DS5 are for shear-critical walls and are also sequential. Damage state DS6 represents severe sliding shear failure. It normally occurs in low-rise walls with low axial compressive loads, for which the sliding-shear resistance is lower than the flexural and shear capacities. Even though the three damage modes are assumed to be mutually exclusive in the fragility assessment, DS1 and DS2 may have slight or moderate shear cracks, and DS3 may have severe base sliding in cases where the axial compressive load is low. However, these are indirectly accounted for in this study by including shear cracks in the repair cost estimates for DS1 and DS2, whereas DS3 calls for a total replacement of the wall component. The damage states and possible repair methods are summarized in Table 3. Damage states DS2 through DS5 are illustrated in Figure 9.

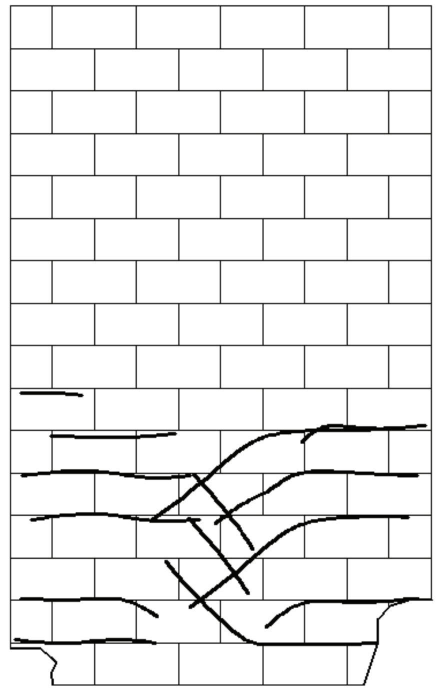
FEMA 306 characterizes the severity of damage of reinforced masonry walls with four levels: insignificant, slight, moderate, and extreme. For damage to be considered insignificant, crack widths are not to exceed 1/16 in.; and for slight damage, crack widths are not to exceed 1/8 in. In both cases, no significant masonry spalling should occur. Moderate damage is signified by moderate spalling or vertical cracking in toe regions; while extreme damage is signified by severe masonry spalling, and reinforcement buckling or fracture. However, crack widths are in general difficult to measure objectively in a wall or to predict accurately in an analysis. Furthermore, such information is normally not complete in experimental study reports. After the disappearance of lateral loads, flexural and shear cracks may close under gravity loads if the reinforcement has not reached or has barely passed the yield limit. For this reason, this study avoids the use of crack widths to quantify the severity of a damage state. Rather, based on experimental data, the level of damage is calibrated against the maximum lateral load a wall has been subjected to with respect to its peak resistance or against the degree of strength degradation. This reduces the subjectivity in data interpretation. The criteria used to identify the various damage states from experimental data are described below and are summarized in Table 4.

Table 3 – Definition of Damage States

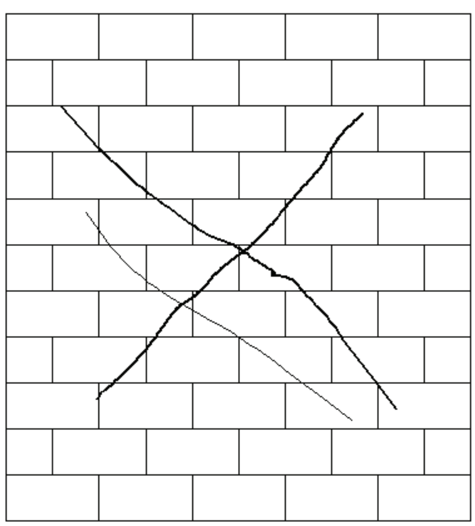
Damage State	Description	Repair Measures (Fully-grouted)	Repair Measures (Partially-grouted)
DS1 Slight Flexure Damage	- A few flexural and shear cracks with hardly noticeable residual crack widths. - Slight yielding of extreme vertical reinforcement. - No spalling. - No fracture or buckling of vertical reinforcement. - No structurally significant damage.	- Cosmetic repair. - Patch cracks and paint each side.	- Cosmetic repair. - Patch cracks and paint each side.
DS2 Moderate Flexure Damage	- Numerous flexural and diagonal cracks. - Mild toe crushing with vertical cracks or light spalling at wall toes. - No fracture or buckling of reinforcement. - Small residual deformation.	- Epoxy injection to repair cracks. - Remove loose masonry. - Patch spalls with non-shrink grout. - Paint each side.	- Remove loose masonry. - Patch spalls with non-shrink grout. - Grout wall cavities. - Grout injection into remaining cracks. - Paint each side.
DS3 Severe Flexure Damage	- Severe flexural cracks. - Severe toe crushing and spalling. - Fracture or buckling of vertical reinforcement. - Significant residual deformation.	- Shore. - Demolish existing wall. - Construct new wall.	- Shore. - Demolish existing wall. - Construct new wall.
DS4 Moderate Shear Damage	- First occurrence of major diagonal cracks. - Cracks remain closed with hardly noticeable residual crack widths after load removal.	- Epoxy injection. - Paint each side.	- Grout wall cavities. - Grout injection into remaining cracks. - Paint each side.
DS5 Severe Shear Damage	- Wide diagonal cracks with typically one or more cracks in each direction. - Crushing or spalling at wall toes.	- Shore. - Demolish existing wall. - Construct new wall.	- Shore. - Demolish existing wall. - Construct new wall.
DS6 Severe Sliding Shear	- Large permanent wall offset. - Spalling and crushing at the wall toes due to dowel action and flexure. - Shear fracture of vertical reinforcement or dowels.	- Shore. - Demolish existing wall. - Construct new wall.	- Shore. - Demolish existing wall. - Construct new wall.



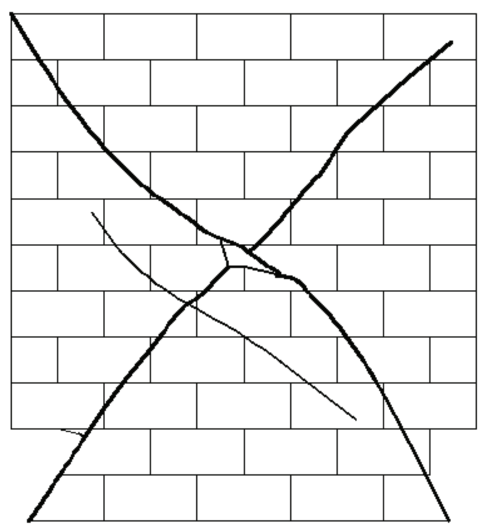
(a) Typical Appearance for DS2



(b) Typical Appearance for DS3



(c) Typical Appearance for DS4



(d) Typical Appearance for DS5

Figure 9 – Damage States DS2 through DS 5 of Reinforced Masonry Walls

Table 4 – Criteria for Identifying Damage States

Damage State	Identification Criteria
DS1 Slight Flexural Damage	When a flexure-critical wall was loaded to 80% of its peak in-plane lateral resistance.
DS2 Moderate Flexure Damage	When a flexure-critical wall was loaded to its peak in-plane lateral resistance.
DS3 Severe Flexure Damage	When a flexure-critical wall was loaded beyond its peak resistance and exhibited a load drop of 20% with respect to the peak.
DS4 Moderate Shear Damage	When major diagonal cracks crossing almost the entire length of a wall first occurred, based on experimental observations.
DS5 Severe Shear Damage	When a shear-critical wall reached the peak shear resistance.
DS6 Severe Sliding Shear Failure	When sliding was so severe that it induced a significant residual displacement, the spalling of the masonry at wall toes, and the bending or shear fracture of the vertical reinforcement or dowels. However, due to the lack of reported experimental observations on this behavior, the fragility curve for this damage state has been derived analytically.

2.2.1 Flexural Damage and Repair Methods

Damage state DS1 represents slight flexural damage that is characterized by a few flexural and, sometimes, shear cracks, similar to the condition shown in Figure 3. In this state, the flexural reinforcement might have slightly passed the yield limit. However, the cracks will close upon unloading, and no crushing or spalling of masonry should have occurred. The damage is structurally insignificant. Based on experimental observations (Shing et al. 1992), DS1 corresponds more or less to a state at which the wall is loaded to 80% of its peak resistance. Hence, this load level is used as the criterion to identify the damage state from experimental data. This is point at which the associated demand parameter is evaluated. Walls with DS1 will only require minor cosmetic repair by patching the cracks.

Damage state DS2 represents moderate flexural damage that is characterized by numerous flexural and shear cracks. Some residual crack opening may be noticeable. The wall has barely reached the crushing point with some vertical cracks or slight spalling occurring in the toe regions. A sample damage pattern is shown in Figure 4. The flexural reinforcement should have yielded but no buckling or fracturing of bars should have occurred. It corresponds to a state at which the wall has just reached its maximum flexural resistance (as shown in Figure 2). This load level is used as the criterion to identify the damage state from experimental data. At this point, the wall should be reparable. The cracks can be repaired by epoxy injection. To do this, both sides of a crack needs to be sealed and injection ports be installed at 6 to 12-inch spacing on one or both sides of a crack, depending on the wall thickness, together with some monitoring ports. Then, epoxy will be injected with a pump. If spalling has occurred, the loose masonry should be removed, and replaced by a non-shrink grout. If a wall is partially-grouted, the wall cavities may have to be fully filled with grout and the remaining cracks will then be injected with more fluid non-shrink grout.

Damage state DS3 represents severe flexural damage. This is normally associated with significant masonry spalling accompanied by the buckling and fracture of the bars, as shown in Figure 5. In this state, the wall may have developed a significant residual displacement. Experimental data have shown that such damage normally occurs after the wall resistance has passed its peak and has dropped by at least 20%. Hence, a 20% load drop is a good indication that such damage might have occurred or is imminent. It can be identified from the envelope of the displacement-load curves as shown in Figure 2. With such damage, repair or partial replacement of the wall may not be the most economical solution. Most likely, the entire wall component will have to be replaced. This will call for the shoring of the structure, the removal of the wall component, and the construction of a new wall.

2.2.2 Diagonal Shear Damage and Repair Methods

Damage state DS4 represents moderate diagonal shear damage that is characterized by the first occurrence of major diagonal cracks as shown in Figure 7. The cracks will be closed but observable upon unloading. For the wall specimen shown in Figure 6, this occurred at a load that is about 75% of the shear capacity. However, sometimes, such cracks may develop right before shear failure is eminent as shown in Figure 10. This damage state is identified from experimental data based on visual observations. Such cracks need to be repaired by epoxy or grout injection with procedures similar to those described for DS2.

Damage state DS5 represents severe diagonal shear damage that is characterized by widely opened diagonal cracks and sometimes toe crushing and spalling. Experimental data have shown that this can occur when a shear-critical wall is loaded to its peak strength. Hence, this load level is used as the criterion to identify the damage state from experimental data, as shown in Figure 6 and Figure 10. The post-peak behavior of a shear-critical wall is unpredictable and cannot be relied upon as shown by the hysteresis curves in the figures. The entire wall component should be replaced after reaching this damage state.

2.2.3 Sliding Shear Damage and Repair Methods

Damage state DS6 represents severe sliding shear damage that is characterized by the spalling of the masonry at the wall toes due to the dowel action of the vertical reinforcement, and the bending or shear fracture of the vertical reinforcement or dowels. It may be associated with a significant residual sliding displacement. Such damage may occur in a severe earthquake when the sliding shear resistance of a wall is close to or less than the flexural or diagonal-shear strength. However, due to the lack of experimental data, the Class B fragility curve for this damage state is derived analytically using Method D in Appendix F of the ATC-58 50% guidelines. This damage state cannot be easily quantified with the demand parameter based on story drift. Hence, no Class A fragility curve is derived for this damage state. Walls with such damage are difficult to repair, and should be replaced.

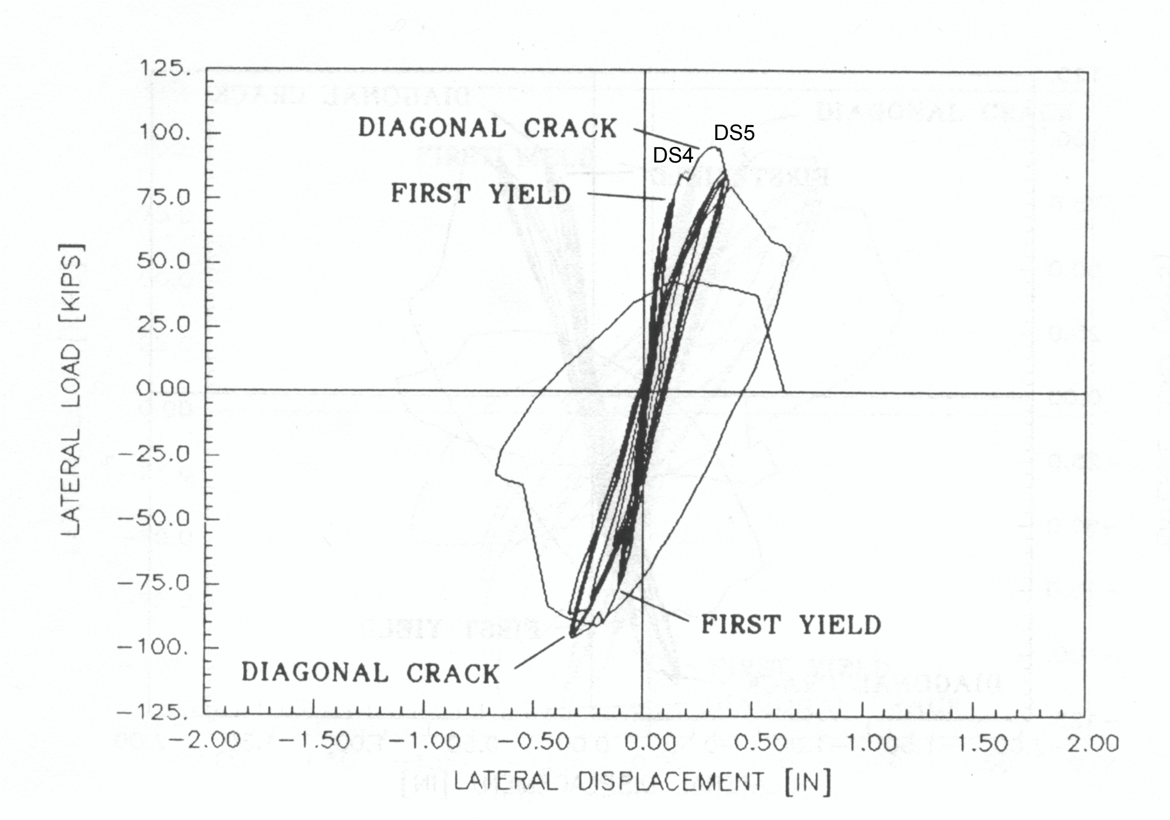


Figure 10 - Hysteresis Curves for Specimen 9 (Shear Dominated) of Shing et al. (1991)

2.3 Experimental Data

The majority of the experimental data gathered here, as described below, is from single-story fully-grouted reinforced masonry cantilever walls. Data on multi-story walls and partially-grouted walls are very limited. For walls subjected to cyclic load reversals, two points of data are obtained per wall for each damage state with one from each loading direction. The design details and axial load conditions for these walls are given in Appendices A through C.

1) Shing et al. (1991) tested twenty-four 6-ft.-by-6-ft. cantilever RMSW's. Different levels of axial loads, reinforcement ratios, and unit types (concrete or clay masonry hollow units) were considered in the tests. All the specimens were subjected to fully reversed lateral cyclic loading except two that were subjected to monotonically increasing loads. The results show different predominant damage modes: flexure, diagonal shear, sliding shear, and combined flexure/shear. These tests provide data for damage states DS1 through DS5 and also limited information on DS6.

2) Brunner (1994) tested three fully-grouted reinforced clay masonry cantilever shear walls with low aspect ratios (i.e., with height/length ratios less than one). One of the specimens was tested under cyclic loading and two with monotonically increasing loads. All the walls showed diagonal shear dominated behavior. These tests provide data for damage states DS4 and DS5.

3) Ibrahim and Sutter (1999) tested five fully-grouted reinforced concrete masonry cantilever shear walls under cyclic loading. The variables considered in these tests include the applied vertical load, quantity of vertical reinforcement, and wall aspect ratio (with all height/length ratios less than or equal to one). One of the walls showed mixed flexure/shear behavior, exhibiting damage states DS1, DS2, DS3, and DS4. The rest of the walls had behavior dominated by diagonal tensile cracking (DS4 and DS5).

4) Shedid et al. (2008) tested six fully-grouted reinforced concrete masonry cantilever shear walls under cyclic loading. The walls had a height/length ratio of two with different reinforcement ratios and axial compressive loads. All the walls showed flexure-dominated behavior.

5) Voon and Ingham (2006) tested eight fully-grouted and two partially-grouted reinforced concrete masonry cantilever shear walls under cyclic loading. Different height/length ratios (0.6, 1, and 2), reinforcement ratios, and axial loads were considered. All the specimens except two showed shear-dominated behavior. The others showed combined flexure/shear behavior (with the predominant failure mode being diagonal cracking) and flexure/sliding behavior (with failure caused by significant sliding at the base). Data for DS4, DS5 and DS6 have been gathered from these tests.

6) Priestley (1976) tested six reinforced concrete masonry cantilever shear walls under cyclic loading. All the walls had a height/length ratio of 0.75. Different vertical reinforcement ratios and axial loads were considered. All the specimens showed flexural failure, but exhibited some diagonal cracking and shear sliding as well. Data for DS1, DS2, DS3, and DS4 as well as limited information on DS6 have been gathered from these tests.

7) Ingham et al. (2001) tested partially-grouted concrete masonry walls with different aspect ratios, reinforcement quantities, and opening configurations. Nine of the walls that had no openings are considered here. These walls had different height/length ratios, ranging from 0.6 to 3, and reinforcement distributions. All of them showed diagonal shear failure because of the lack of shear reinforcement. Only data for DS5 are available from these tests.

8) Ghanem et al. (1992 and 1993) studied the influence of steel distribution and axial compression in six partially-grouted masonry shear walls with a height/length ratio of one. The specimens showed flexure, shear and combined flexure/shear behaviors. Data for DS1, DS2, DS3, DS4, and DS5 have been obtained.

It should be mentioned that 85% of the flexure-dominated fully-grouted walls in this data set met the maximum flexural reinforcement requirement for special RMSW's in the strength design provisions of the MSJC code (2008).

3 DEMAND PARAMETERS AND FRAGILITY EVALUATION

Two classes of fragility curves have been developed in this study. They are distinguished by the demand parameters used. Class A curves use the story-drift ratio as the demand parameter, which is the most common measure of seismic demand on a structure or structural component and is also suitable for the simplified analysis procedure recommended in the ATC-58 50% draft guidelines. However, this parameter may not properly reflect the flexural demand on an RMSW and may not necessarily be a good index of the severity of damage caused by diagonal shear or sliding shear. It should be noted that the experimental data used to develop the fragility curves are from a specific set of wall specimens that might not truly reflect the actual design details and loading condition of a wall system being evaluated. The values of the story-drift ratio reflecting different damage states may vary as the design and loading conditions change. For this reason, a second set of demand parameters, which account for the actual design and loading conditions of a wall system, is considered as well. Class B fragility curves are based on these demand parameters. They can be used if one chooses to conduct a more detailed analysis of a wall system.

3.1 Demand Parameters for Class A Fragility Curves

Class A fragility curves use the story-drift ratio (i.e., the story drift divided by the story height) as the demand parameter. The story drift in a wall system can be contributed by flexural and shear deformations as well as shear sliding. However, the flexural and shear deformations of a wall are often difficult to quantify accurately from the test data. Furthermore, simplified analytical models used for performance assessment often do not distinguish these deformation components. Hence, only the lump-sum story drift is used to derive the fragility curves. To this end, the total story-drift ratios corresponding to the damage states defined above are obtained from the experimental data. However, when using these curves for performance assessment, the calculation of the story drift requires special attention. In a multi-story cantilever wall, much of the story drift of an upper-story wall component can be caused by the rigid-body rotation induced by the flexural deformation in the lower stories. This rigid-body rotation should be taken out from the numerical result not to over-estimate the flexural demand on the wall component.

3.2 Demand Parameters for Class B Fragility Curves

For Class B fragility curves, the demand parameters associated with flexural and shear damage are defined differently. The damage of flexure-dominated walls can be related to the level of flexural deformation, while that caused by diagonal shear or sliding shear is more related to the shear force demand as compared to the shear capacity because of the brittle and sudden nature of the latter. Hence, it is proposed that the demand parameter for the former (i.e., DS1, DS2, and DS3) be displacement based and that for latter (i.e., DS4, DS5, and DS6) be force based.

3.2.1 Flexural Demand

As mentioned in Sec. 2.1, flexural ductility depends on several parameters. Walls with higher axial compressive loads and higher quantities of flexural reinforcement tend to deform less before severe damage will develop. Flexural ductility can be enhanced by properly confining the boundary elements (Pauley and Priestley 1992) even though it may not be easy for reinforced masonry walls from the constructability standpoint. Flexural ductility is a continuous function of these parameters. Hence, to have fragility curves that represent a broad range of flexural behavior, a normalized displacement-based demand parameter is introduced here. As discussed previously, story drift is not a good measure of the severity of flexural deformation for cantilever walls. A large portion of the story drift in the upper stories of a tall wall can be caused by the rigid-body rotation of the wall about the plastic hinge formed in the bottom stories. A taller wall will have a longer plastic-hinge region and may, therefore, have larger story drifts in the upper stories, which evidently have little influence on damage.

Since the experimental data used here were obtained from cantilever wall specimens, such wall configuration is used as an example to introduce the demand parameter proposed here. Curvature at the wall base could be a suitable demand parameter that reflects the level of flexural damage in a cantilever wall. Nevertheless, curvature is difficult to determine accurately from experimental data, and the prediction of curvature demand at the base of a wall depends, to a large extent, on the modeling assumptions, which may affect the length of the plastic hinge in which plastic deformation will localize. Hence, the following normalized flexural deformation (*NFD*) is proposed as the demand parameter for flexure.

$$NFD = \left| \frac{u}{u_m} \right| \tag{1}$$

in which u is the displacement at the top of a cantilever wall due to flexure and u_m is the theoretical wall displacement at which the maximum (peak) flexural resistance develops. A less ductile wall will have a lower magnitude of u_m. The normalization is to account for the variations in wall geometry, flexural reinforcement level, material properties, and the applied axial load, which may result in different flexural ductilities, and to result in fragility curves that are independent of these variables.

The calculation of u_m could follow the method proposed by Pauley and Priestley (1993) as shown in Figure 11(c), which suggests that

$$u_m = u_y + u_p = \phi_y \frac{H_e^2}{3} + (\phi_m - \phi_y) l_p (H_e - 0.5 l_p) \tag{2}$$

in which ϕ_m is the theoretical curvature that corresponds to the maximum (peak) moment, ϕ_y is a nominal yield curvature, l_p is the assumed effective plastic-hinge length, and H_e is the effective wall height at which the resultant lateral load is located in the cantilever wall. However, since the computation of ϕ_y requires assumptions that may introduce additional variability to the value of u_m, the simplification shown in Figure 11(b) has been adopted. This results in the following expression for u_m.

$$u_m = \phi_m l_p (H_e - 0.5 l_p) \tag{3}$$

The above expression is deemed adequate for the purpose of calculating the normalized demand parameter. The evaluation of ϕ_m should be based on a set of consistent assumptions. For this purpose, the assumptions stipulated in Sec. 3.3.2 of the masonry design code (MSJC 2008) are recommended. Nevertheless, the expected material strengths should be used instead of the nominal strengths.

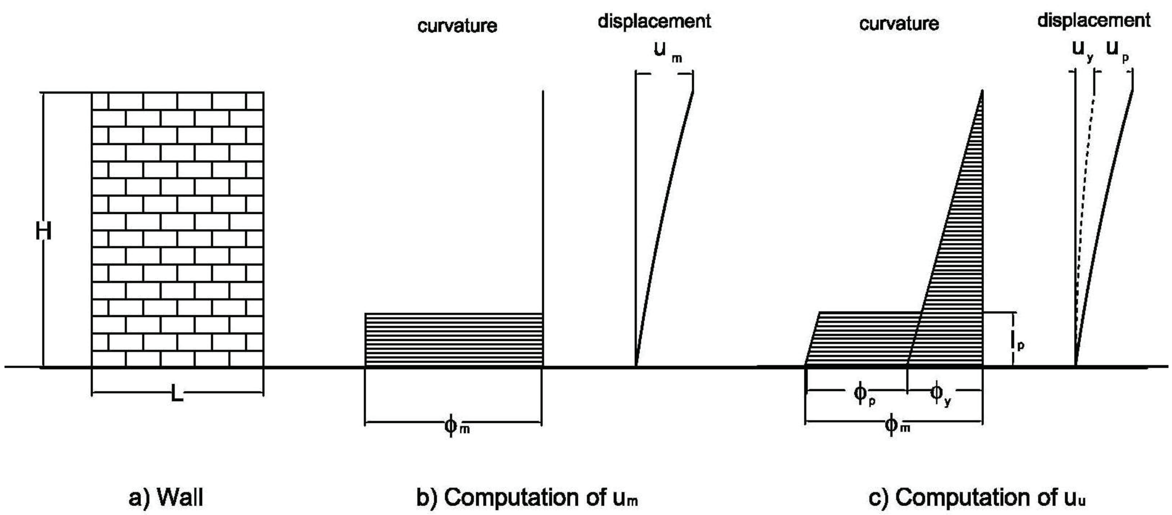


Figure 11 – Computation of u_m

The calculation of u_m relies on the knowledge of the plastic-hinge length. Paulay and Priestley (1993) have suggested the following formula to estimate the effective plastic-hinge length for reinforced concrete walls.

$$l_p = 0.2L + 0.04H_e \tag{4}$$

in which L is the length of the wall. The above formula has also been used for masonry shear walls. However, based on the experimental data gathered in this study, this expression seems to underestimate the effective plastic-hinge length by a factor of two for walls with an H_e/L ratio equal to two (Shedid et al. 2008), while it results in a reasonable estimate of the average plastic-hinge length for walls with an H_e/L ratio equal to one (Shing et al. 1991) in spite of the large scatter of the experimental data. Hence, the following simple formula is proposed to estimate the effective plastic-hinge length for calculating the demand parameter.

$$l_p = 0.22H_e \tag{5}$$

which results in a better match of the experimental data for walls with different height-to-length ratios. For walls with H_e/L around one, Equations (4) and (5) lead to similar results.

The above development is based on the consideration of a cantilever wall that has a plastic hinge at the base. However, sometimes plastic deformation could develop in the upper stories of a cantilever wall due to the higher-mode effect; and, every often, walls can be coupled by strong spandrel beams or perforated with openings. In the latter cases, damage may develop in piers or spandrels as shown in Figure 1(b) and (c). To cover these situations in performance assessment, the demand parameter *NFD* given by Equations (1) and (3) can be generalized to a story or component-level demand parameter as follows.

$$NFD = \left| \frac{\bar{\phi}}{\phi_m} \right| \tag{6}$$

in which $\bar{\phi}$ is the average wall curvature in the effective plastic-hinge region of the wall component. Methods to calculate $\bar{\phi}$ for different loading situations of wall components are shown in Table 5. For the case of double curvature (Case 2), Table 5 assumes a condition that $m_b \geq m_t$. If this is not the situation, the effective height H_e should be calculated with respect to the top of the wall component and θ_b be replaced by θ_t for the calculation of u. In the table, H_s is the wall height at each story, the clear height of a pier, or the clear span of a spandrel beam, and l_p is the effective plastic-hinge length estimated with Equation (5) using the effective wall height H_e identified from the moment diagram for the wall component as shown in Table 5. The generalized flexural demand parameter *NFD* given in Equation (6) can be used for wall components at any story level in a cantilever wall system or for wall components shown in Figure 1(b) and (c).

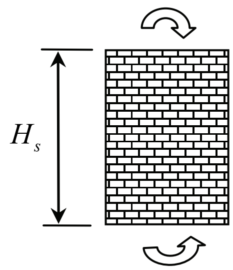
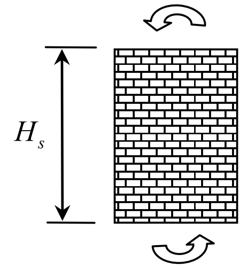
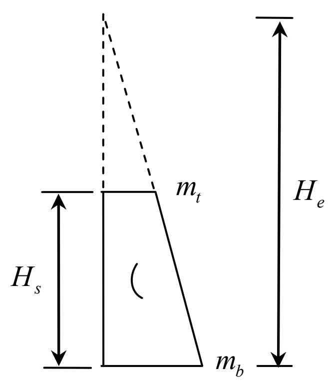
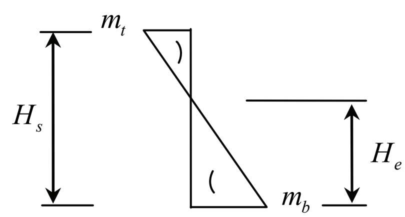
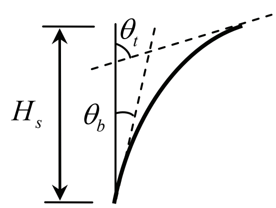
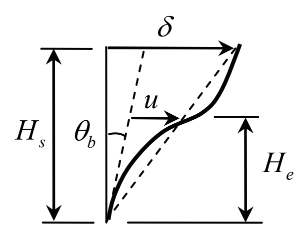
3.2.2 Diagonal Shear Demand

Diagonal shear cracks tend to develop suddenly, and walls dominated by diagonal shear often exhibit a very brittle behavior. Since the post-peak shear behavior is not of interest here because of its brittle nature, damage in shear can be best determined in terms of the shear force developed. To account for the variations in wall geometry, the quantity of shear reinforcement, material properties, and the applied axial load, the shear force demand needs to be normalized with respect to the nominal shear strength of a wall that accounts for all these factors. In this report, we propose the following normalized diagonal shear demand parameter (*NDSD*) for damage states DS4 and DS5 as defined in Table 3.

$$NDSD = \frac{V}{V_n} \tag{7}$$

in which V is the absolute maximum shear force developed in a wall section and V_n is the nominal shear capacity given in Sec. 3.3.4.1.2 of the masonry design code (MSJC 2008). This parameter is applicable to wall components in any wall systems.

Table 5 - Calculation of Average Wall Curvature $\bar{\phi}$

	Case 1 – Single Curvature	**Case 2 – Double Curvature**
Applied Moment		
Moment Diagram		 for $m_b \geq m_t$
Wall Deflection		
Calculation of $\bar{\phi}$	$\bar{\phi} = \dfrac{\theta_t - \theta_b}{\min\{l_p, H_s\}}$	$u \approx \left(\dfrac{\delta}{H_s} - \theta_b\right) H_e$ $\bar{\phi} = \dfrac{u}{l_p (H_e - 0.5 l_p)}$

3.2.3 Sliding Shear Demand

Similar to diagonal shear damage, sliding shear occurs suddenly once the shear resistance has been overcome at the base of a wall. Sliding shear resistance depends on the level of the axial compressive load, the restraint provided by the flexural reinforcement, and the roughness of the sliding plane at the base of a wall. Hence, the normalized sliding shear demand parameter (*NSSD*) defined for damage state DS6 assumes the same form as *NDSD*.

$$NSSD = \frac{V}{V_{sn}} \tag{8}$$

in which V_{sn} is the sliding shear capacity that is estimated with the formula recommended in Sec. 6.3.4 of FEMA 306.

$$V_{sn} = \mu(P + A_s f_y) \tag{9}$$

in which P is the axial compressive load exerted on the sliding plane, A_s is the total area of the reinforcement crossing the sliding plane, f_y is the expected yield strength of the reinforcement, and μ is the coefficient of friction at the sliding plane. The friction coefficient may assume a value of 0.7.

3.3 Development of Fragility Curves

Fragility curves for RM shear walls are developed based on the guidelines provided in Appendix F of the ATC-58 50% draft guidelines. The fragility curves are assumed to take the form of a lognormal cumulative distribution function:

$$F_i(D) = \Phi\left(\frac{\ln(D/\theta_i)}{\beta_i}\right) \tag{10}$$

in which θ is the median, β is the logarithmic standard deviation (or dispersion), $F_i(D)$ is the conditional probability that a component will have a damage state *i* or a more severe damage state when the value of the demand parameter is *D,* and Φ is the standard normal (Gaussian) cumulative distribution function. The values of θ and β are to be obtained for each component type and damage state. When demand data are available, the median can be calculated as:

$$\theta = e^{\left(\frac{1}{M}\sum_{j=1}^{M}\ln(D_j)\right)} \tag{11}$$

in which M is the number of specimens that were tested to at least the initiation of the damage state and D_j is the value of the demand parameter in test j at which the damage state was first observed.

The dispersion parameter consists of two parts as follows.

$$\beta = \sqrt{\beta_r^{\,2} + \beta_u^{\,2}} \tag{12}$$

in which β_r accounts for the random variability of the test data and β_u accounts for the uncertainty that the tests represent the actual conditions in a real building. The parameter β_r is calculated with the following formula.

$$\beta_r = \sqrt{\frac{1}{M-1}\sum_{j=1}^{M}\left(\ln(D_j/\theta)\right)^2} \quad (13)$$

In this study, β_u is assumed to be 0.25 for Class A fragility curves and 0.10 for Class B fragility curves in view of the fact that the latter curves use the normalized demand parameters that better account for different loading and design conditions in real buildings. The Lilliefors test has been used to assess the goodness of fit of the fragility functions obtained as explained in Appendix F of the ATC-58 50% draft report.

3.4 Classification of Wall Components

The three set of damage states (DS1, DS2, DS3), (DS4 and DS5), and DS6 are assumed to be mutually exclusive. Hence, to apply the fragility curves developed here, one needs to determine if the wall component considered is flexure critical, shear critical, or sliding critical. The following criteria are recommended for such assessment. For a wall to be considered flexure critical, its nominal shear strength and sliding shear resistance have to be at least 1.25 times the shear corresponding to the development of the nominal flexural strength of the wall. If this condition is not met and the diagonal shear strength is higher than the sliding shear resistance, then the wall is sliding critical. Otherwise, it is diagonal shear critical. The calculation of the nominal flexural and diagonal shear strengths should follow the strength design provisions of the MSJC code or other validated analytical methods, while the sliding shear resistance can be calculated with Equation (9).

However, it should be mentioned that damage states DS1 and DS2 may have slight to moderate diagonal shear cracks, and DS4 may have slight to moderate flexural cracks. These are indirectly accounted for in the estimation of crack density as described in Appendix E. DS6 represents severe sliding damage, which requires wall replacement. Therefore, the concurrence of other damage states in this situation is not important.

4 CLASS A FRAGILITY CURVES FOR FULLY-GROUTED WALLS

Class A fragilities curves use the story-drift ratio as the demand parameter as discussed in Sec 3.1. For fully-grouted walls, the fragility curves for damage states DS1, DS2, DS3, DS4, and DS5 are developed using the actual demand data method (Method A in Appendix F of ATC-58 50% draft). The demands for the different damage states are obtained from the experimental data according to the criteria shown in Table 4, and the median and dispersion of the demand parameter for each fragility curve are determined using the method summarized in Sec. 3.3. The actual demand data used for the derivation are shown in Appendix A of this report. However, there are insufficient experimental data to derive a fragility curve for damage state DS6, which is also not easy to be correlated to the story drift as the demand parameter. For these reasons, no Class A fragility curve is derived for DS6.

4.1 Class A Fragility Curves for Damage States DS1, DS2, and DS3

It should be noted that 85% of the flexure-dominated wall specimens considered here met the maximum reinforcement ratio requirement for special walls stipulated in the strength design provisions of the MSJC code (2008). In the absence of test data for less ductile fully-grouted walls, it is assumed that the fragility curves developed here are applicable to other cases. However, the demand parameters proposed for Class B fragility curves, as presented in Sec. 3.2, mitigate this drawback. The fragility curves are plotted in Figure 12, where DS1 is slight damage, DS2 is moderate damage, and DS3 is severe damage. The median and dispersion of the drift demand are shown in Table 6. The number of samples used and the results of the Lilliefors tests (based on 5% significance level) to assess the goodness of fit of the fragility curves are also presented in Table 6.

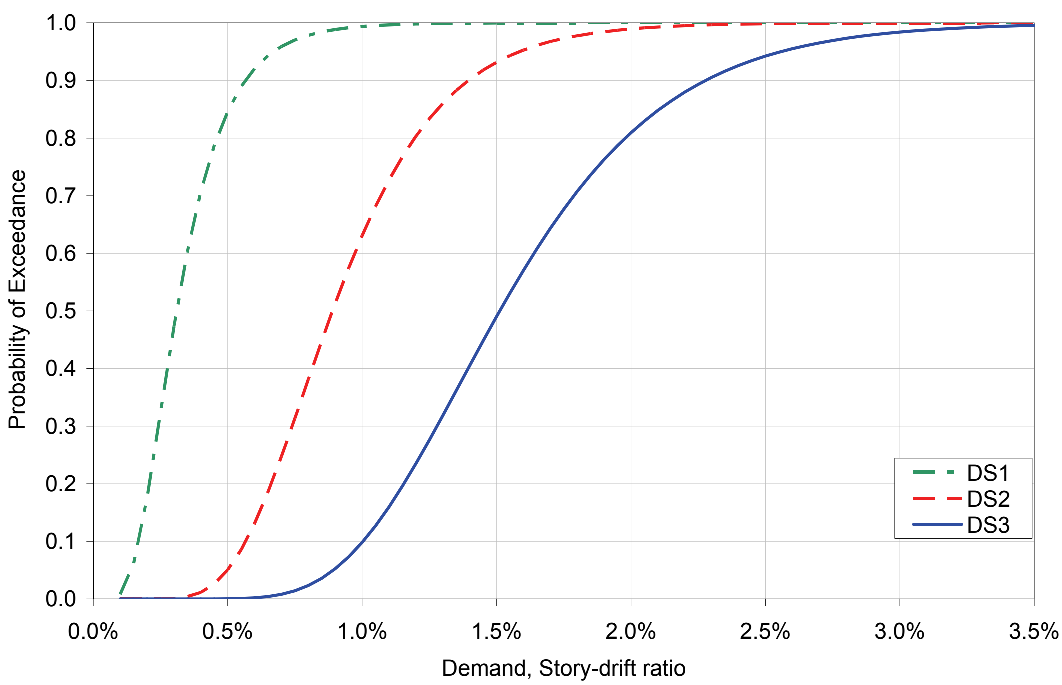


Figure 12 - Class A Fragility Curves for Flexural Damage of Fully-grouted Shear Walls

Table 6 - Class A Demand Parameters for Flexural Damage of Fully-grouted Shear Walls

Damage State	Demand Parameter	Median θ	Random Dispersion β_r	Total Dispersion β	Number of Samples	Lilliefors Test
DS1	Story-drift ratio	0.31%	0.40	0.47	44	Pass
DS2	Story-drift ratio	0.87%	0.27	0.37	43	Pass
DS3	Story-drift ratio	1.51%	0.20	0.32	38	Fail

4.2 Class A Fragility Curves for Damage States DS4 and DS5

The fragility curves for damage related to diagonal shear behavior are plotted in Figure 13, where DS4 is moderate damage and DS5 is severe damage. The median and dispersion of the drift demand are shown in Table 7. The number of samples used and the results of the Lilliefors tests are also presented in Table 7.

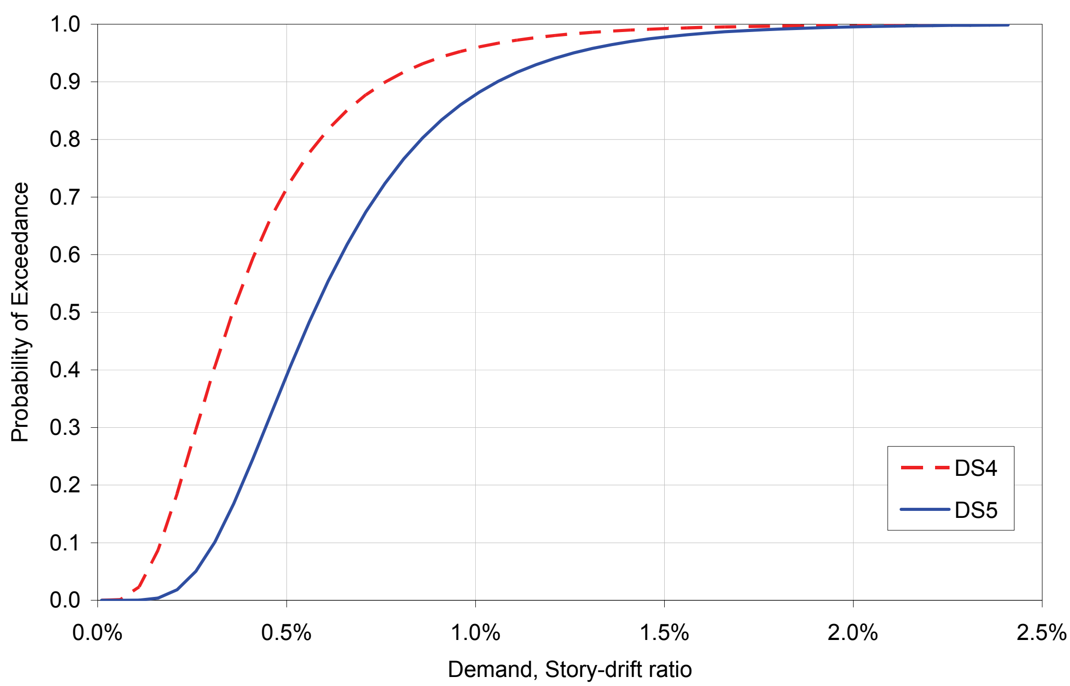


Figure 13 - Class A Fragility Curves for Diagonal Shear Damage of Fully-grouted Shear Walls

Table 7 - Class A Demand Parameters for Diagonal Shear Damage of Fully-grouted Shear Walls

Damage State	**Demand Parameter**	**Median** θ	**Random Dispersion** β_r	**Total Dispersion** β	**Number of Samples**	**Lilliefors Test**
DS4	Story-drift ratio	0.36%	0.54	0.59	57	Fail
DS5	Story-drift ratio	0.59%	0.44	0.51	50	Pass

5 CLASS A FRAGILITY CURVES FOR PARTIALLY-GROUTED WALLS

The fragility curves for partially-grouted walls are derived in two steps. In the first step, the fragility curve for DS5 is derived with the demand data method. However, for DS1, DS2, DS3, and DS4, the curves are derived based on the authors' opinion because of the lack of experimental data. The values of θ and β for these curves are determined by decreasing the median and increasing the dispersion obtained for the same respective damage states of fully-grouted walls in view of the fact that the behavior of partially-grouted walls exhibits a higher variability. These adjustments are based on the assumption that the differences in the fragility curve parameters for DS1 through DS4 of the two wall types are the same as those for DS5. The comparison of the fragility curve data obtained for DS5 of the two wall types using the actual demand data has indicated that the value of θ for partially-grouted walls is 57% of that for fully-grouted walls. Furthermore, the random dispersion β_r observed for partially-grouted walls is higher than that for fully-grouted walls by 0.30. Based on this observation, the total dispersion for each of the damage states DS1 through DS4 of partially-grouted walls is calculated as follows:

$$\beta = \sqrt{(\beta_{r,FG} + \Delta\beta_{r,PG})^2 + \beta_u^{\ 2}} \qquad (14)$$

in which $\beta_{r,FG}$ is the random dispersion for the same damage state of fully-grouted walls, and $\Delta\beta_{r,FG}$ is the additional dispersion for partially-grouted walls and is assumed to be 0.30 for all the damage states. The median θ for each damage state of partially-grouted walls is assumed to be 57% of that of fully-grouted walls.

For a given story-drift ratio, partially-grouted masonry walls are expected to have a higher probability of failure. By decreasing the median and increasing the dispersion as described above, the probability of failure for partially-grouted walls will be higher than that for fully-grouted walls for drift demands at the lower tail of the fragility curves. However, the fragility curves for the two wall types may intersect at a point of high drift demand, resulting in a higher probability of failure for fully-grouted walls beyond that point. To avoid such a situation for drift demands within the regime of interest, we adopt a criterion that the intersection of the two fragility curves be at a drift demand not less than the mean plus three times the standard deviation of the demand values for fully-grouted walls. Hence, in the second step of the derivation, the total dispersion β for each damage state of partially-grouted walls is reduced as necessary, while keeping the median θ constant, to meet above condition.

5.1 Class A Fragility Curves for Damage States DS1, DS2, and DS3

The fragility curves for damage related to flexural behavior are plotted in Figure 14, where DS1 is slight damage, DS2 is moderate damage, and DS3 is severe damage. The median and dispersion of the drift demand are shown in Table 8.

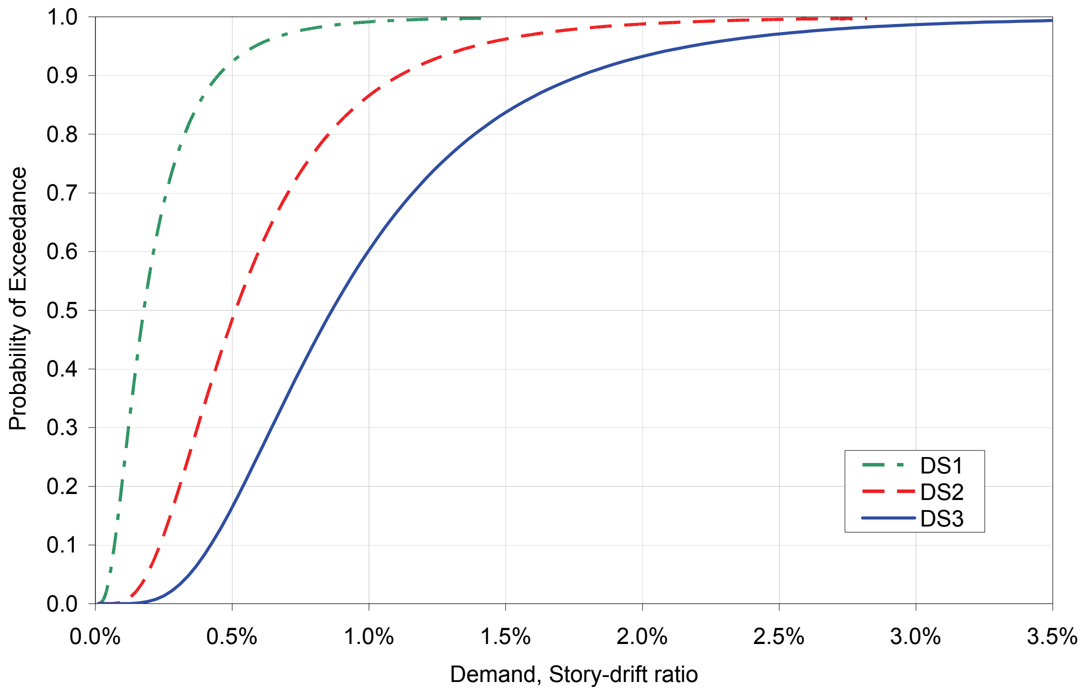


Figure 14 - Class A Fragility Curves for Flexural Damage of Partially-grouted Shear Walls

Table 8 - Class A Demand Parameters for Flexural Damage of Partially-grouted Shear Walls

Damage State	Demand Parameter	Median θ	Total Dispersion β
DS1	Story-drift ratio	0.18%	0.73
DS2	Story-drift ratio	0.51%	0.60
DS3	Story-drift ratio	0.86%	0.56

5.2 Class A Fragility Curves for Damage States DS4 and DS5

The fragility curves for damage related to diagonal shear behavior are plotted in Figure 15, where DS4 is moderate damage and DS5 is severe damage. The median and dispersion of the drift demand are shown in Table 9.

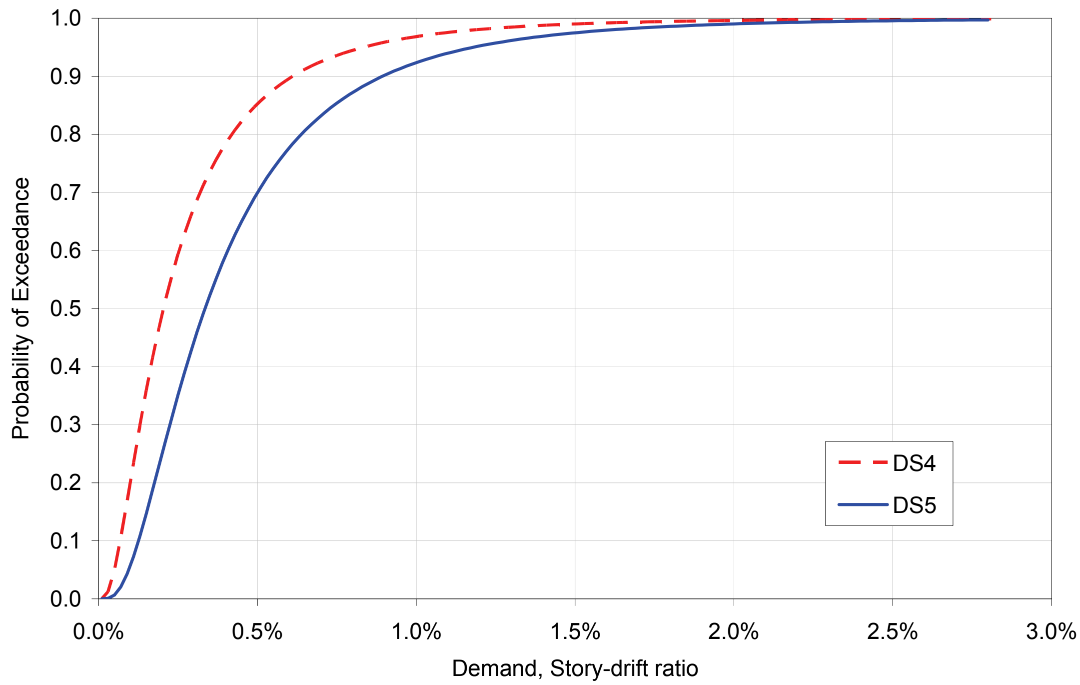


Figure 15 - Class A Fragility Curves for Diagonal Shear Damage of Partially-grouted Shear Walls

Table 9 - Class A Demand Parameters for Diagonal Shear Damage of Partially-grouted Shear Walls

Damage State	**Demand Parameter**	**Median θ**	**Random Dispersion β_r**	**Total Dispersion β**	**Number of Samples**	**Lilliefors Test**
DS4	Story-drift ratio	0.20%	-	0.86	-	-
DS5	Story-drift ratio	0.33%	0.74	0.77	16	Pass

6 CLASS B FRAGILITY CURVES FOR FULLY-GROUTED WALLS

Class B fragility curves are based on the more refined demand parameters presented in Sec. 3.2, which take into account the design details and loading condition of a wall component. Like the Class A curves, Class B fragility curves for damage states DS1 through DS5 are derived based the demand data. However, the dispersion β_u, which accounts for the uncertainty that the tests represent the actual conditions in a real building, is reduced in this case from 0.25 to 0.10 based on the fact that the use of the normalized demand parameters better reflects different conditions in real buildings. The fragility curve for DS6 is derived using the analytical derivation method (Method D in Appendix F of the ATC-58 50% draft) because of the lack of experimental data. The derivation is based on a single calculation with the assumption that severe sliding shear damage will develop when the demand parameter *NSSD* defined in Equations (8) and (9) is equal to one. According to Appendix F of the draft guidelines, the median demand parameter for this damage state is calculated as $\theta = 0.92 \cdot NSSD$, and the dispersion β is assumed to be 0.40. Since *NSSD* = 1, we have $\theta = 0.92$.

Since all the wall specimens are cantilever walls, the values of the flexural demand parameter *NFD* are calculated from the experimentally measured wall deflections with Equations (1) and (3). However, the majority of the experimental data considered here are from walls with relatively low aspect ratios, for which shear deformation cannot be ignored. An accurate evaluation of the shear deformation of a cracked wall is difficult. The test data of Shing et al. (1991) have shown that for flexure-dominated cantilever walls that had a height/length ratio of one, as much as 55% of the top displacement at the peak load could be contributed by shear, while this contribution is calculated to be 42% based on the elastic theory. Hence, shear deformation should be taken into consideration in estimating the demand parameter *NFD* from the test data. To estimate the shear deformations of the wall specimens, the percentage of shear contribution to the total wall displacement is first calculated for an elastic uncracked wall. For a cantilever wall, this is

$$\text{\% Shear Deformation} = \frac{K_f}{K_s + K_f} = \frac{0.6(1+\nu)}{0.6(1+\nu) + \left(\frac{H}{L}\right)^2} \tag{15}$$

in which *H* is the wall height, *L* is the length of the wall, and ν is Poisson's ratio, which can be assume to be 0.2. It is assumed that the percentage shear contribution at damage states DS1, DS2, and DS3 is equal to that calculated with Equation (15) multiplied by a factor of 1.3. To calculate the demand parameter *NFD*, the calculated shear deformation is subtracted from the measured total deflection of a wall to obtain the flexural deformation.

6.1 CLASS B Fragility Curves for Damage States DS1, DS2, and DS3

The fragility curves for damage related to flexural behavior are plotted in Figure 16, where DS1 is slight damage, DS2 is moderate damage, and DS3 is severe damage. The median and dispersion of the demand parameter *NFD* defined in Equation (1) are shown in Table 10. The number of samples used and the results of the Lilliefors tests to assess the goodness of fit of the fragility curves are also presented in Table 10.

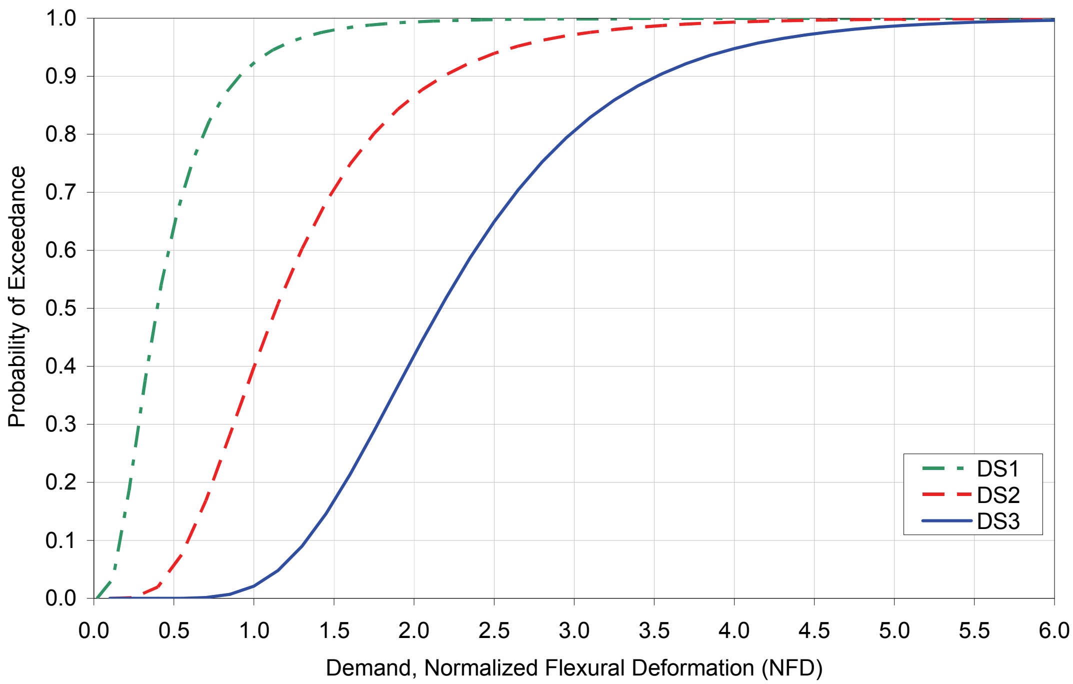


Figure 16 - Fragility Curves for Flexural Damage of Fully-grouted Shear Walls

Table 10 - Demand Parameters for Flexural Damage of Fully-grouted Shear Walls

Damage State	Demand Parameter	Median θ	Random Dispersion β_r	Total Dispersion β	Number of Samples	Lilliefors Test
DS1	*NFD*	0.39	0.64	0.65	44	Pass
DS2	*NFD*	1.14	0.50	0.51	44	Pass
DS3	*NFD*	2.16	0.37	0.38	38	Pass

6.2 CLASS B Fragility Curves for Damage States DS4 and DS5

The fragility curves for damage related to diagonal shear behavior are plotted in Figure 17, where DS4 is moderate damage and DS5 is severe damage. The median and dispersion of the demand parameter *NDSD* defined in Equation (7) are shown in Table 11. The number of samples used and the results of the Lilliefors tests are also presented in Table 11.

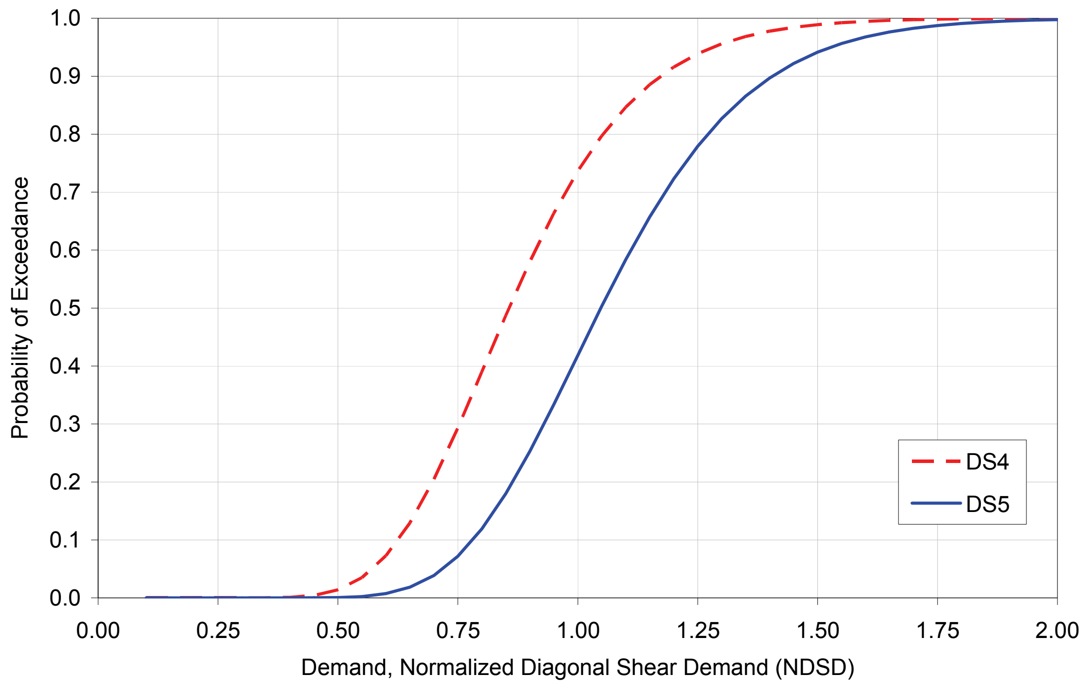


Figure 17 - Fragility Curves for Diagonal Shear Damage of Fully-grouted Shear Walls

Table 11 - Demand Parameters for Diagonal Shear Damage of Fully-grouted Shear Walls

Damage State	**Demand Parameter**	**Median** θ	**Random Dispersion** β_r	**Total Dispersion** β	**Number of Samples**	**Lilliefors Test**
DS4	*NDSD*	0.86	0.22	0.24	67	Fail
DS5	*NDSD*	1.05	0.21	0.23	50	Pass

6.3 CLASS B Fragility Curve for Damage State DS6

The fragility curve for the sliding shear damage (DS6) is plotted in Figure 18. The median and dispersion of the demand parameter *NSSD* defined in Equation (8) are shown in Table 12. These are obtained analytically based on a single calculation.

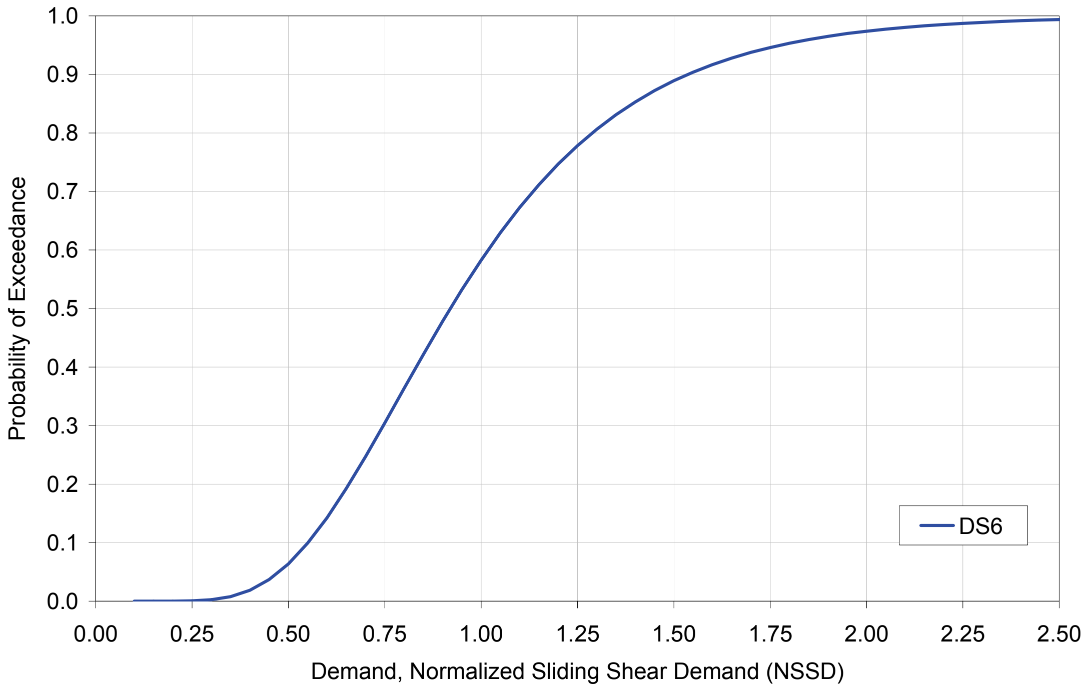


Figure 18 - Fragility Curve for Sliding Shear Damage of Fully-grouted Shear Walls

Table 12 - Demand Parameters for Sliding Shear Damage of Fully-grouted Shear Walls

Damage State	Demand Parameter	Median θ	Total dispersion β
DS6	*NSSD*	0.92	0.40

7 CLASS B FRAGILITY CURVES FOR PARTIALLY-GROUTED WALLS

The Class B fragility curves for partially-grouted walls are derived in two steps using the same procedure as described in Chapter 5. In the first step, the fragility curve for DS5 is derived with the demand data method. Then, the curves for DS1, DS2, DS3, and DS4 are derived based on the authors' opinion with the values of θ and β determined by decreasing the median and increasing the dispersion obtained for the same respective damage states of fully-grouted walls. These adjustments are based on the assumption that the differences in the fragility curve parameters for DS1 through DS4 of the two wall types are the same as those for DS5. Based on this, the median θ for each damage state of partially-grouted walls is assumed to be 88% of that of fully-grouted walls, and $\Delta\beta_{r,FG}$ in Equation (14) is assumed to be 0.18 for all the damage states.

In the second step of the derivation, the total dispersion β for each damage state of partially-grouted walls is reduced as necessary, while keeping the median θ constant, so that the intersection of the two fragility curves for the same damage state of fully and partially-grouted walls be at a demand value not less than the mean plus three times the standard deviation of the demand values for fully-grouted walls.

7.1 CLASS B Fragility Curves for Damage States DS1, DS2, and DS3

The fragility curves for damage related to flexural behavior are plotted in Figure 19, where DS1 is slight damage, DS2 is moderate damage, and DS3 is severe damage. The median and dispersion of the demand parameter *NFD* defined in Equation (1) are shown in Table 13.

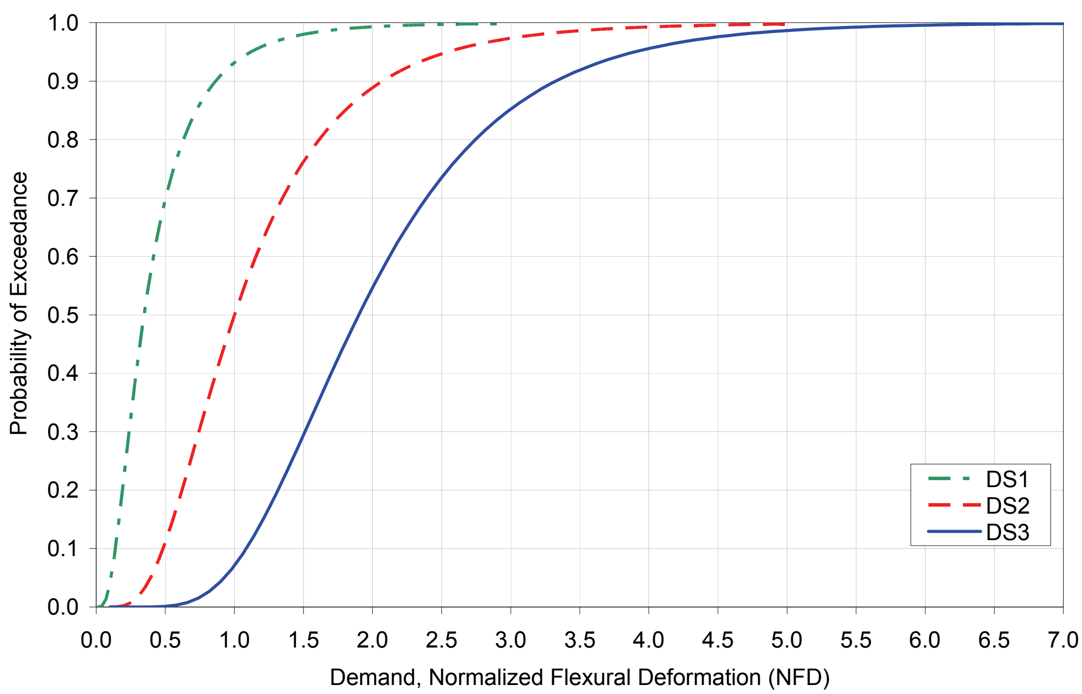


Figure 19 - Fragility Curves for Flexural Damage of Partially-grouted Shear Walls

Table 13 - Demand Parameters for Flexural Damage of Partially-grouted Shear Walls

Damage State	Demand Parameter	Median θ	Total Dispersion β
DS1	*NFD*	0.35	0.71
DS2	*NFD*	1.00	0.57
DS3	*NFD*	1.90	0.44

7.2 CLASS B Fragility Curves for Damage States DS4 and DS5

The fragility curves for damage related to diagonal shear behavior are plotted in Figure 20, where DS4 is moderate damage and DS5 is severe damage. The median and dispersion of the demand parameter *NDSD* defined in Equation (7) are shown in Table 14.

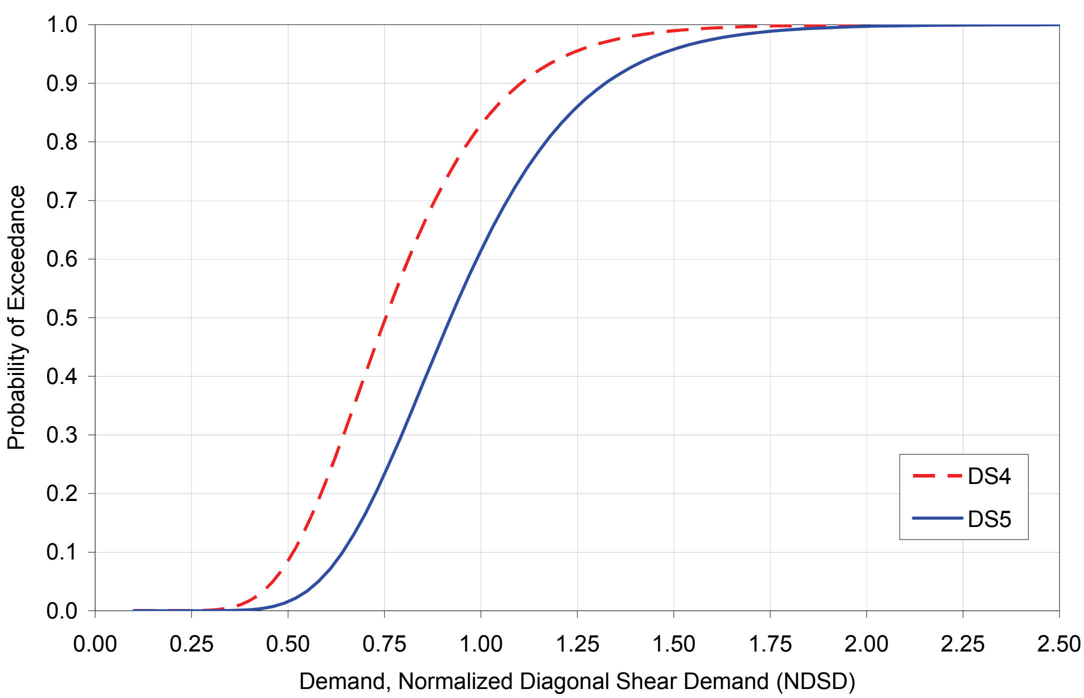


Figure 20 - Fragility Curves for Diagonal Shear Damage of Partially-grouted Shear Walls

Table 14 - Demand Parameters for Diagonal Shear Damage of Partially-grouted Shear Walls

Damage State	Demand Parameter	Median θ	Random Dispersion β_r	Total Dispersion β	Number of Samples	Lilliefors Test
DS4	*NDSD*	0.75	-	0.30	-	-
DS5	*NDSD*	0.92	0.38	0.28	20	Pass

7.3 CLASS B Fragility Curves for Damage State DS6

The fragility curve for the shear sliding damage state (DS6) is plotted in Figure 21. The median and dispersion of the demand parameter *NSSD* defined in Equation (8) are shown in Table 15.

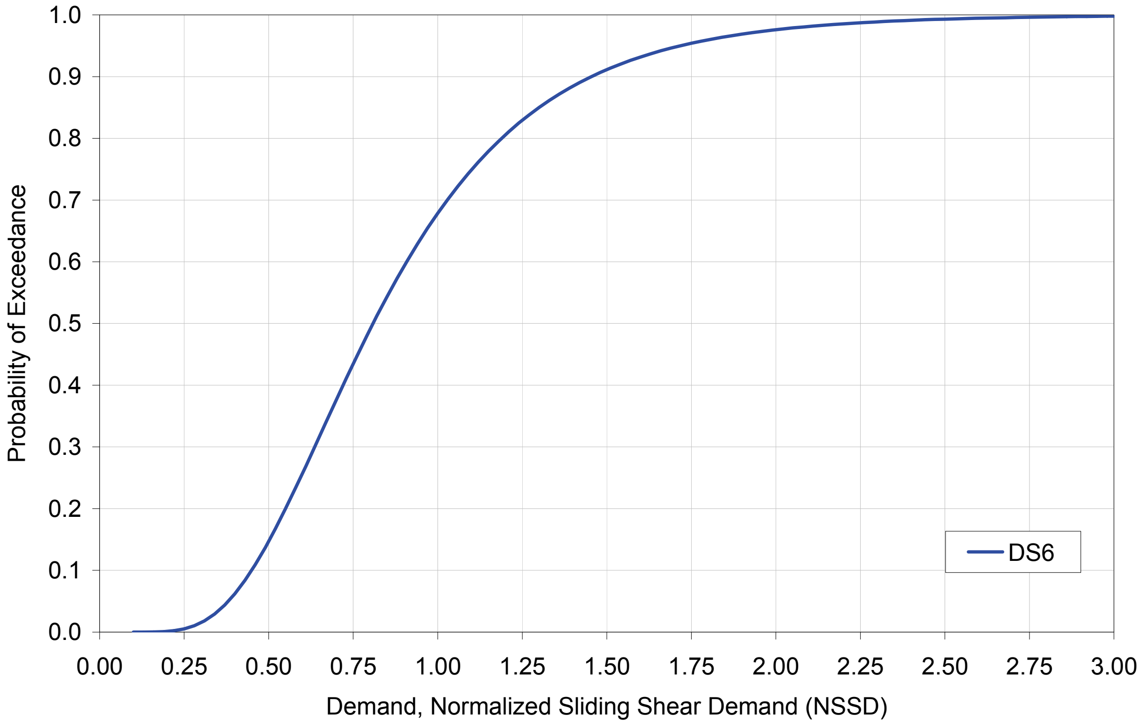


Figure 21 - Fragility Curve for Sliding Shear Damage of Partially-grouted Shear Walls

Table 15 - Demand Parameters for Sliding Shear Damage of Partially-grouted Shear Walls

Damage State	**Demand Parameter**	**Median θ**	**Total Dispersion β**
DS6	*NSSD*	0.81	0.46

8 SUMMARY OF FRAGILITY PARAMETERS FOR RM SHEAR WALLS

A summary of the fragility parameters derived for fully and partially-grouted reinforced masonry shear walls is provided in the following tables. The total dispersion β has been rounded to the nearest 0.05. It is interesting to note that for damage states DS1, DS2, and DS3, the Class A fragility curves have a smaller dispersion of the demand parameter than the Class B curves even though the demand parameter for the latter is considered more elaborate in that it takes into account the design details and loading condition of a wall. The larger dispersion of the latter can be attributed to two sources. One is the estimation of the shear deformations of the wall specimens and the other is the estimation of the effective plastic-hinge lengths. The experimental data have shown a large scatter of these values. Furthermore, 85% of the flexure-dominated wall specimens considered in this study met the maximum reinforcement ratio requirement for special walls in the MSJC code (2008). This possibly reduces the dispersion of the Class A fragility curves, which do not account for the variation in the quantify of the flexural reinforcement or the level of the axial compressive load. Nevertheless, for DS4 and DS5, the shear-dominated damage states, the Class A fragility curves show a much larger dispersion.

Furthermore, if the analytical model used in the performance assessment does not account for shear deformation, the Class B curves should provide better results than the Class A curves for DS1 through DS3 as the demand parameter for the former is based on flexural deformation alone. Shear deformation is difficult to estimate in a reliable manner unless a refined finite element model is used for the analysis.

Table 16 - Summary of Class A Fragility Parameters for Fully-Grouted RM Shear Walls

Damage State	**Demand Parameter**	**Median θ**	**Total Dispersion β**	**Derivation Method**
DS1	Story-drift ratio	0.31%	0.45	Actual demand data
DS2	Story-drift ratio	0.87%	0.35	Actual demand data
DS3	Story-drift ratio	1.51%	0.30	Actual demand data
DS4	Story-drift ratio	0.36%	0.60	Actual demand data
DS5	Story-drift ratio	0.59%	0.50	Actual demand data

Table 17 - Summary of Class A Fragility Parameters for Partially-Grouted RM Shear Walls

Damage State	**Demand Parameter**	**Median θ**	**Total Dispersion β**	**Derivation Method**
DS1	Story-drift ratio	0.18%	0.75	Authors' opinion
DS2	Story-drift ratio	0.51%	0.60	Authors' opinion
DS3	Story-drift ratio	0.86%	0.55	Authors' opinion
DS4	Story-drift ratio	0.20%	0.85	Authors' opinion
DS5	Story-drift ratio	0.33%	0.75	Actual demand data

Table 18 - Summary of Class B Fragility Parameters for Fully-grouted RM Shear Walls

Damage State	Demand Parameter	Median θ	Total Dispersion β	Derivation Method
DS1	*NFD*	0.39	0.65	Actual demand data
DS2	*NFD*	1.14	0.50	Actual demand data
DS3	*NFD*	2.16	0.40	Actual demand data
DS4	*NDSD*	0.86	0.25	Actual demand data
DS5	*NDSD*	1.05	0.25	Actual demand data
DS6	*NSSD*	0.92	0.40	Analytical derivation

Table 19 - Summary of Class B Fragility Parameters for Partially-grouted RM Shear Walls

Damage State	Demand Parameter	Median θ	Total Dispersion β	Derivation Method
DS1	*NFD*	0.35	0.70	Authors' opinion
DS2	*NFD*	1.00	0.55	Authors' opinion
DS3	*NFD*	1.90	0.45	Authors' opinion
DS4	*NDSD*	0.75	0.30	Authors' opinion
DS5	*NDSD*	0.92	0.30	Actual demand data
DS6	*NSSD*	0.81	0.45	Authors' opinion

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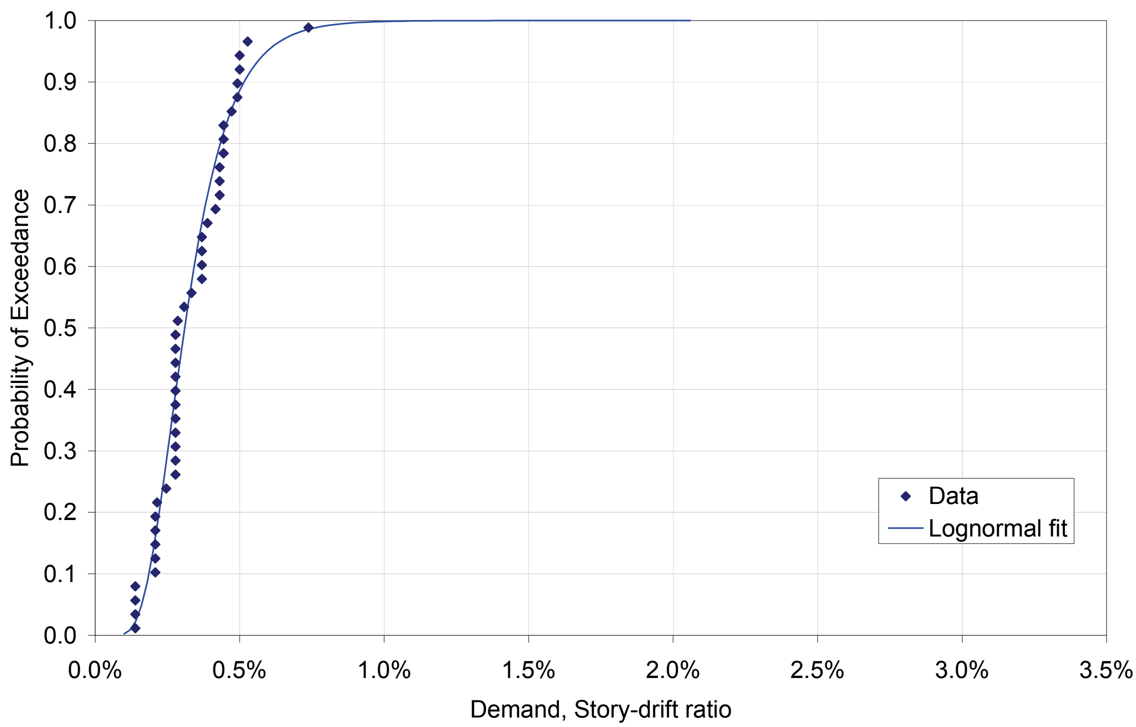
APPENDIX A. CLASS A FRAGILITY CURVE DATA FOR FULLY-GROUTED WALLS

Class A fragility curves use story drift as the demand parameter.

DAMAGE STATE DS1 - FULLY-GROUTED RM SHEAR WALLS (Class A)

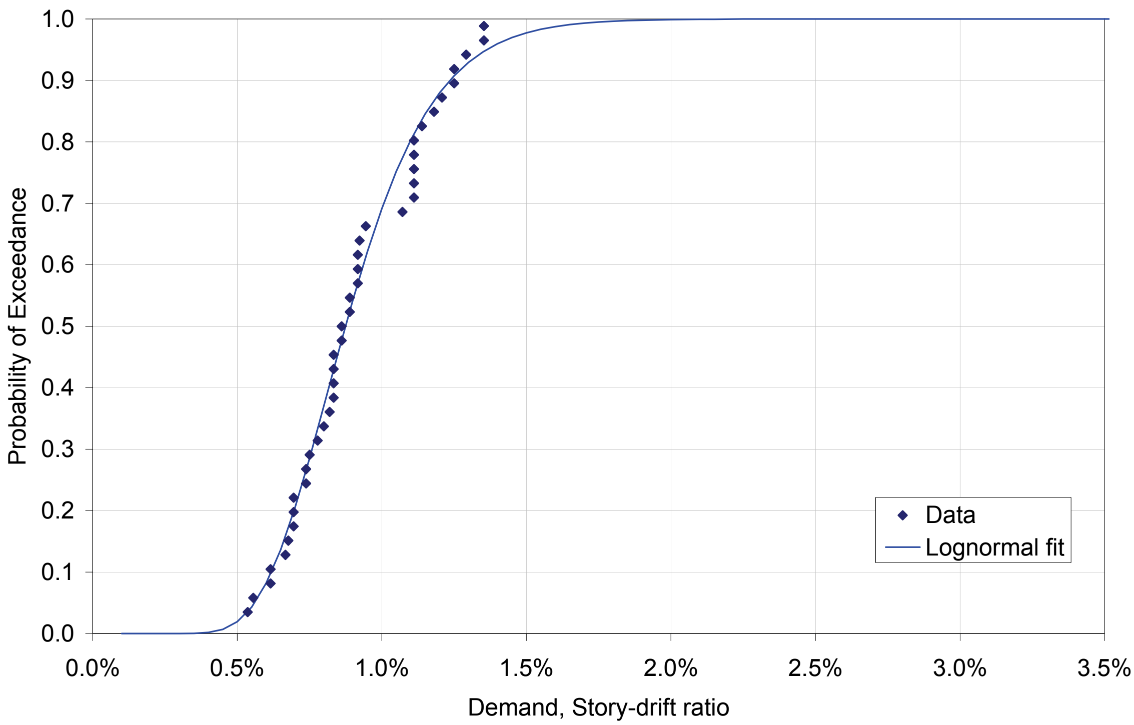
Median θ	Random Dispersion β_r
0.31%	0.40



Passes Lilliefors test:
D= 0.1305 < D_{crit} = 0.1326

DAMAGE STATE DS2 - FULLY-GROUTED RM SHEAR WALLS (Class A)

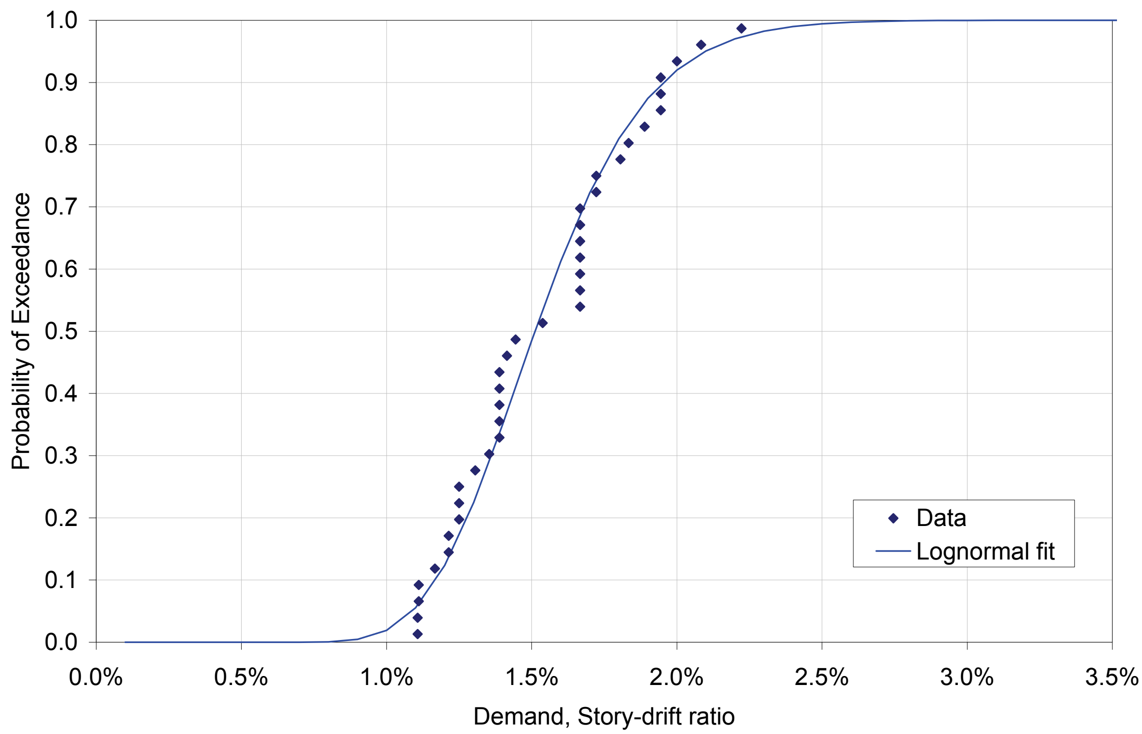
Median θ	Random Dispersion β_r
0.87%	0.27



Passes Lilliefors test:
$D = 0.1039 < D_{crit} = 0.1340$

DAMAGE STATE DS3 - FULLY-GROUTED RM SHEAR WALLS (Class A)

Median θ	Random Dispersion β_r
1.51%	0.20



Fails Lilliefors test:
D= 0.1484 > D_{crit} = 0.1422

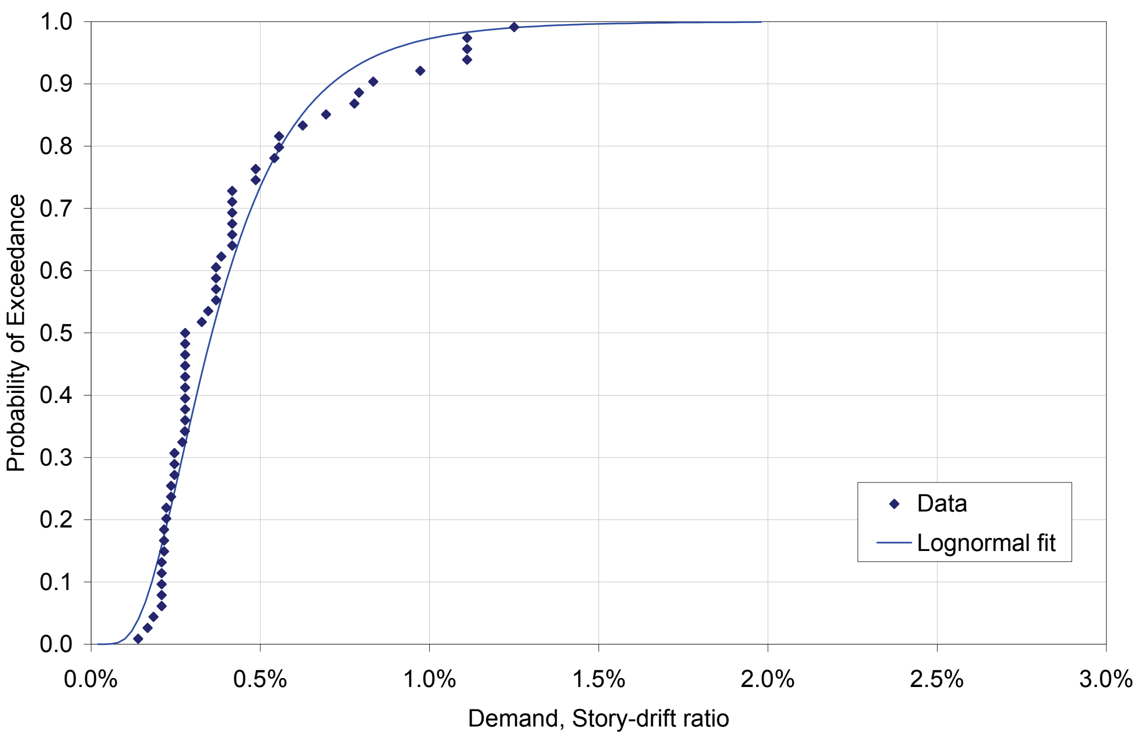
Summary of Test Data for Flexure-dominated Fully-grouted Walls

Reference	Specimen	Direction	Aspect Ratio (*H*/*L*)	$P/(A_n f'_m)$	ρ_h (%)	ρ_v (%)	Drift Ratio for DS1 (%)	Drift Ratio for DS2 (%)	Drift Ratio for DS3 (%)
Shing et al.	1	P	1.00	0.07	0.24	0.38	0.28	1.14	1.67
Shing et al.	1	N	1.00	0.07	0.24	0.38	0.21	0.82	1.11
Shing et al.	2	P	1.00	0.09	0.24	0.38	0.21	0.69	1.1%
Shing et al.	2	N	1.00	0.09	0.24	0.38	0.28	0.75	1.39
Shing et al.	10	P	1.00	0.03	0.14	0.38	0.14	1.11	1.67
Shing et al.	10	N	1.00	0.03	0.14	0.38	0.21	1.11	1.67
Shing et al.	12	P	1.00	0.03	0.24	0.38	0.14	0.86	1.67
Shing et al.	12	N	1.00	0.03	0.24	0.38	0.28	1.21	1.67
Shing et al.	15	P	1.00	0.03	0.24	0.55	0.28	1.25	1.94
Shing et al.	15	N	1.00	0.03	0.24	0.55	0.28	0.69	1.94
Shing et al.	17	P	1.00	0.07	0.26	0.40	0.28	1.25	1.81
Shing et al.	17	N	1.00	0.07	0.26	0.40	0.28	1.11	1.39
Shing et al.	18	P	1.00	0.07	0.26	0.40	0.14	0.42	1.39
Shing et al.	18	N	1.00	0.07	0.26	0.40	0.21	0.56	1.25
Shing et al.	19	P	1.00	0.07	0.26	0.40	0.21	1.11	1.94
Shing et al.	19	N	1.00	0.07	0.26	0.40	0.28	1.18	2.22
Shing et al.	20	P	1.00	0.07	0.26	0.40	0.14	0.83	1.39
Shing et al.	20	N	1.00	0.07	0.26	0.40	0.28	1.11	1.67
Ibrahim and Sutter	1	P	1.00	0.03	0.20	0.99	0.21	0.54	1.21
Ibrahim and Sutter	1	N	1.00	0.03	0.20	0.99	0.29	1.07	1.21
Shedid et al.	1	P	2.00	0.00	0.08	0.31	0.28	0.89	2.08
Shedid et al.	1	N	2.00	0.00	0.08	0.31	0.28	0.89	2.00
Shedid et al.	2	P	2.00	0.00	0.13	0.83	0.33	0.92	1.83
Shedid et al.	2	N	2.00	0.00	0.13	0.83	0.39	0.92	1.89
Shedid et al.	3	P	2.00	0.00	0.13	0.77	0.44	0.67	1.25
Shedid et al.	3	N	2.00	0.00	0.13	0.77	0.44	0.78	1.17
Shedid et al.	4	P	2.00	0.00	0.26	1.39	0.50	0.83	1.67
Shedid et al.	4	N	2.00	0.00	0.26	1.39	-	0.83	1.44
Shedid et al.	5	P	2.00	0.04	0.26	1.39	0.44	0.69	1.25
Shedid et al.	5	N	2.00	0.04	0.26	1.39	0.42	0.92	1.31
Shedid et al.	6	P	2.00	0.09	0.26	1.39	0.53	0.94	1.39
Shedid et al.	6	N	2.00	0.09	0.26	1.39	0.50	0.83	1.72
Priestley	1	P	0.75	0.00	0.98	0.66	0.37	0.92	1.11
Priestley	1	N	0.75	0.00	0.98	0.66	0.43	0.62	-
Priestley	2	P	0.75	0.00	0.68	0.34	0.37	0.74	-
Priestley	2	N	0.75	0.00	0.68	0.34	0.31	0.86	-
Priestley	3	P	0.75	0.00	0.98	0.66	0.37	1.29	1.72
Priestley	3	N	0.75	0.00	0.98	0.66	0.37	0.62	1.11
Priestley	4	P	0.75	0.00	0.68	0.34	0.43	2.58	-
Priestley	4	N	0.75	0.00	0.68	0.34	0.25	0.80	-
Priestley	5	P	0.75	0.04	0.98	0.66	0.49	1.35	1.54
Priestley	5	N	0.75	0.04	0.98	0.66	0.43	0.74	1.35

Priestley	6	P	0.75	0.03	0.98	0.66	0.74	1.35	1.41
Priestley	6	N	0.75	0.03	0.98	0.66	0.49	0.68	-

DAMAGE STATE DS4 - FULLY-GROUTED RM SHEAR WALLS (Class A)

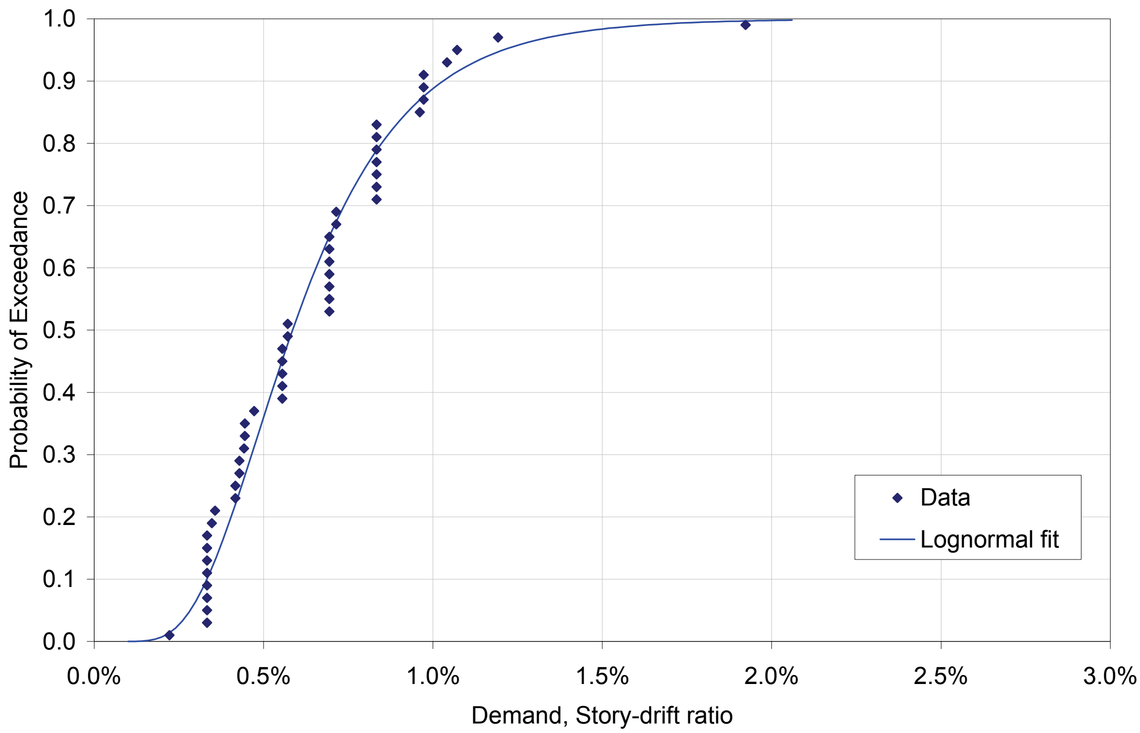
Median θ	Random Dispersion β_r
0.36%	0.54



Fails Lilliefors test:
D= 0.1798 > D_{crit} = 0.1170

DAMAGE STATE DS5 - FULLY-GROUTED RM SHEAR WALLS (Class A)

Median θ	Random Dispersion β_r
0.59%	0.44



Passes Lilliefors test:
$D = 0.1207 < D_{crit} = 0.1246$

Summary of Test Data for Shear-dominated Fully-grouted Walls

Reference	Specimen	Direction	Aspect Ratio (*H*/*L*)	$P / (A_n f'_m)$	ρ_h (%)	ρ_v (%)	Drift Ratio for DS4 (%)	Drift Ratio for DS5 (%)
Shing et al.	3	P	1.00	0.09	0.14	0.74	0.97	0.97
Shing et al.	3	N	1.00	0.09	0.14	0.74	0.24	0.97
Shing et al.	4	P	1.00	0.00	0.14	0.74	0.17	0.47
Shing et al.	4	N	1.00	0.00	0.14	0.74	0.24	0.69
Shing et al.	5	P	1.00	0.04	0.14	0.74	0.22	0.69
Shing et al.	5	N	1.00	0.04	0.14	0.74	0.22	0.69
Shing et al.	7	P	1.00	0.04	0.14	0.74	0.21	0.56
Shing et al.	7	N	1.00	0.04	0.14	0.74	0.14	0.83
Shing et al.	9	P	1.00	0.08	0.14	0.38	0.28	0.35
Shing et al.	9	N	1.00	0.08	0.14	0.38	0.42	0.42
Shing et al.	11	P	1.00	0.00	0.24	0.74	0.21	0.97
Shing et al.	11	N	1.00	0.00	0.24	0.74	0.21	0.83
Shing et al.	13	P	1.00	0.08	0.24	0.55	0.28	0.42
Shing et al.	13	N	1.00	0.08	0.24	0.55	0.83	0.83
Shing et al.	14	P	1.00	0.08	0.14	0.55	0.28	0.69
Shing et al.	14	N	1.00	0.08	0.14	0.55	0.42	0.56
Shing et al.	16	P	1.00	0.11	0.24	0.74	0.21	0.83
Shing et al.	16	N	1.00	0.11	0.24	0.74	0.21	0.83
Shing et al.	17	P	1.00	0.07	0.26	0.40	1.25	-
Shing et al.	17	N	1.00	0.07	0.26	0.40	1.11	-
Shing et al.	18	P	1.00	0.07	0.26	0.40	0.56	-
Shing et al.	18	N	1.00	0.07	0.26	0.40	0.63	-
Shing et al.	19	P	1.00	0.07	0.26	0.40	1.11	-
Shing et al.	20	P	1.00	0.07	0.26	0.40	0.42	-
Shing et al.	20	N	1.00	0.07	0.26	0.40	1.11	-
Shing et al.	21	P	1.00	0.07	0.14	0.57	0.28	0.83
Shing et al.	21	N	1.00	0.07	0.14	0.57	0.42	0.69
Shing et al.	22	P	1.00	0.03	0.14	0.57	0.28	0.69
Shing et al.	22	N	1.00	0.03	0.14	0.57	0.56	0.83
Shing et al.	23	0	1.00	0.07	0.14	0.55	0.28	1.04
Shing et al.	24	0	1.00	0.10	0.24	0.55	0.42	0.69
Brunner	1	0	0.93	0.09	0.13	0.59	0.27	1.92
Brunner	2	P	0.72	0.08	0.13	0.57	0.35	0.96
Brunner	2	N	0.72	0.08	0.13	0.57	0.38	1.19
Brunner	3	0	0.59	0.08	0.13	0.56	0.33	0.44
Ibrahim and Stutter	2	P	0.64	0.03	0.20	0.40	-	1.07
Ibrahim and Stutter	2	N	0.64	0.03	0.20	0.40	-	0.71
Ibrahim and Stutter	3	P	0.47	0.03	0.20	0.40	-	0.71
Ibrahim and Stutter	3	N	0.47	0.03	0.20	0.40	-	0.43
Ibrahim and Stutter	4	P	0.64	0.03	0.20	0.60	-	0.36
Ibrahim and Stutter	4	N	0.64	0.03	0.20	0.60	-	0.57
Ibrahim and Stutter	5	P	0.64	0.08	0.20	0.40	-	0.43

Ibrahim and Stutter	5	N	0.64	0.08	0.20	0.40	-	0.57
Voon and Ingham	1	P	1.00	0.00	0.05	0.62	-	0.56
Voon and Ingham	1	N	1.00	0.00	0.05	0.62	-	0.33
Voon and Ingham	2	P	1.00	0.00	0.01	0.62	-	0.33
Voon and Ingham	2	N	1.00	0.00	0.01	0.62	-	-
Voon and Ingham	3	P	1.00	0.00	0.14	0.62	-	0.44
Voon and Ingham	3	N	1.00	0.00	0.14	0.62	-	0.33
Voon and Ingham	4	P	1.00	0.00	0.06	0.62	-	0.44
Voon and Ingham	4	N	1.00	0.00	0.06	0.62	-	0.33
Voon and Ingham	7	P	1.00	0.03	0.05	0.62	-	0.33
Voon and Ingham	7	N	1.00	0.03	0.05	0.62	-	0.33
Voon and Ingham	8	P	1.00	0.01	0.05	0.62	-	0.33
Voon and Ingham	8	N	1.00	0.01	0.05	0.62	-	0.33
Voon and Ingham	9	P	2.00	0.01	0.05	0.97	-	0.56
Voon and Ingham	9	N	2.00	0.01	0.05	0.97	-	0.56
Voon and Ingham	10	P	0.60	0.01	0.05	0.60	-	0.22
Priestley	1	P	0.75	0.00	0.98	0.66	0.22	-
Priestley	1	N	0.75	0.00	0.98	0.66	0.22	-
Priestley	2	P	0.75	0.00	0.68	0.34	0.37	-
Priestley	2	N	0.75	0.00	0.68	0.34	0.37	-
Priestley	3	P	0.75	0.00	0.98	0.66	0.22	-
Priestley	3	N	0.75	0.00	0.98	0.66	0.18	-
Priestley	4	P	0.75	0.00	0.68	0.34	0.25	-
Priestley	4	N	0.75	0.00	0.68	0.34	0.25	-
Priestley	5	P	0.75	0.04	0.98	0.66	0.25	-
Priestley	5	N	0.75	0.04	0.98	0.66	0.28	-
Priestley	6	P	0.75	0.03	0.98	0.66	0.37	-
Priestley	6	N	0.75	0.03	0.98	0.66	0.37	-

DAMAGE STATE DS6 - FULLY-GROUTED RM SHEAR WALLS (Class A)

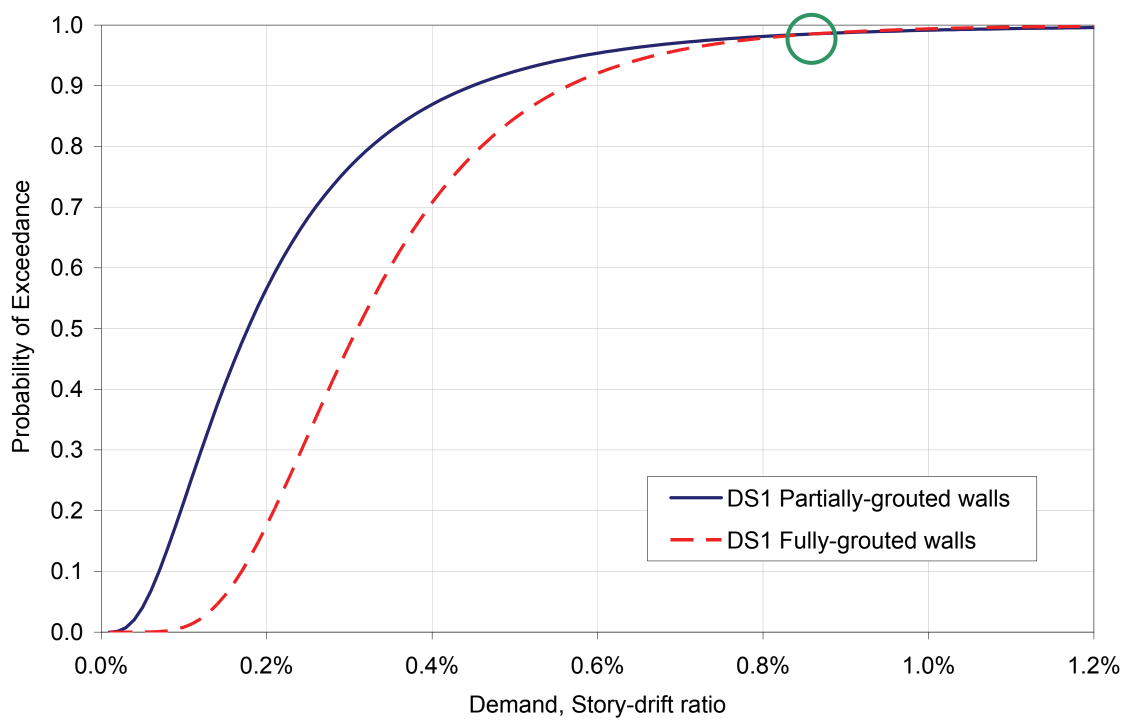
The fragility curve for this damage state cannot be developed because of lack of relevant experimental data.

APPENDIX B. CLASS A FRAGILITY CURVE DATA FOR PARTIALLY-GROUTED WALLS

DAMAGE STATE DS1 - PARTIALLY-GROUTED RM SHEAR WALLS (Class A)

The fragility curve cannot be derived using the actual demand data because of the lack of experimental data. Instead, it is derived based on the authors' opinion.

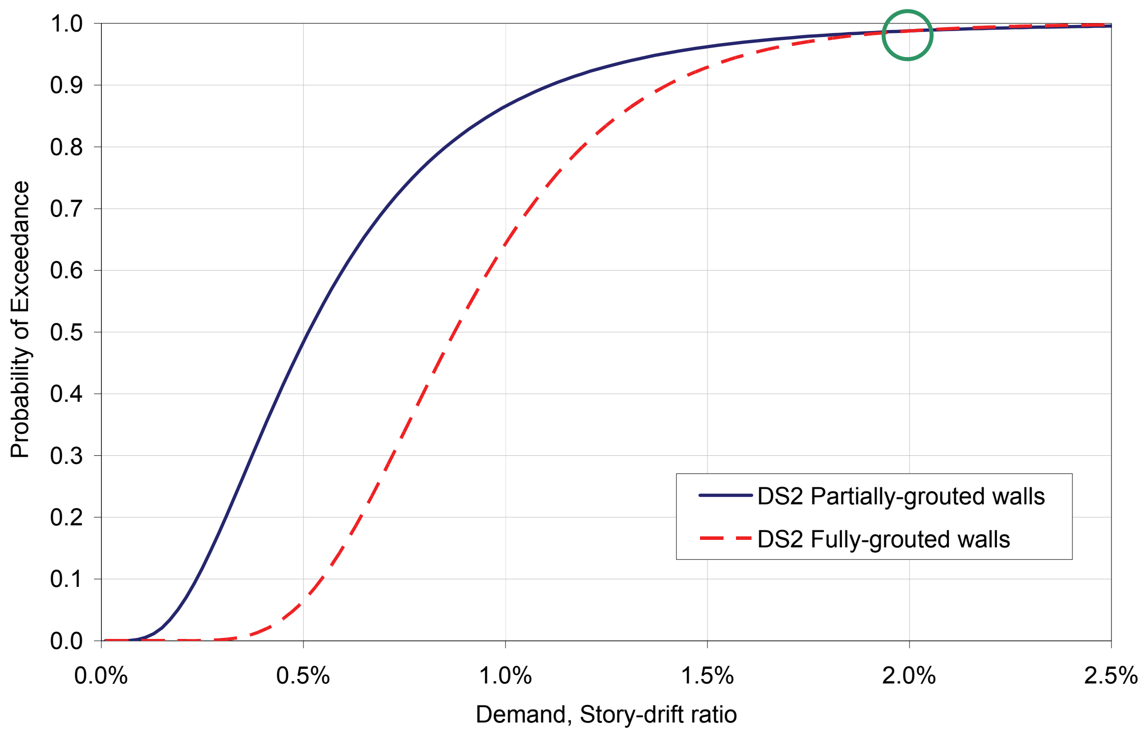
The θ value for fully-grouted walls is taken to be 57% of that of partially-grouted walls based on the data for DS5 as described in Chapter 5 of this report. The random dispersion β_r is initially increased by $\Delta\beta_{r,PG}$=0.30 based on that observed for DS5, which is derived using the actual demand data. The total dispersion is then reduced in such a way that the intersection of the curves for fully-grouted and partially-grouted walls is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



DAMAGE STATE DS2 - PARTIALLY-GROUTED RM SHEAR WALLS (Class A)

The fragility curve cannot be developed using the actual demand data because of the lack of experimental data. Instead, it is derived based on the authors' opinion.

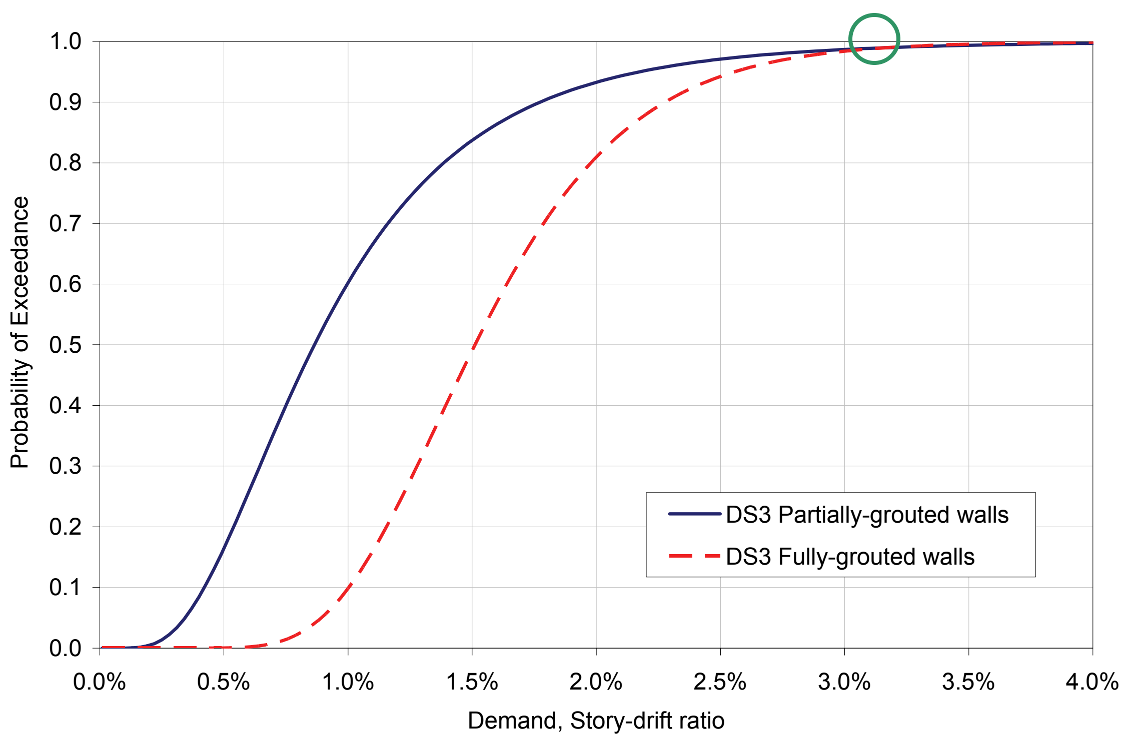
The θ value for fully-grouted walls is 57% of that for partially-grouted walls. The random dispersion is initially increased by $\Delta\beta_{r,PG}$=0.30. The total dispersion is then reduced in such a way that the intersection of the curves for fully-grouted and partially-grouted walls is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



DAMAGE STATE DS3 - PARTIALLY-GROUTED RM SHEAR WALLS (Class A)

The fragility curve cannot be developed using the actual demand data because of the lack of experimental data. Instead, it is derived based on the authors' opinion.

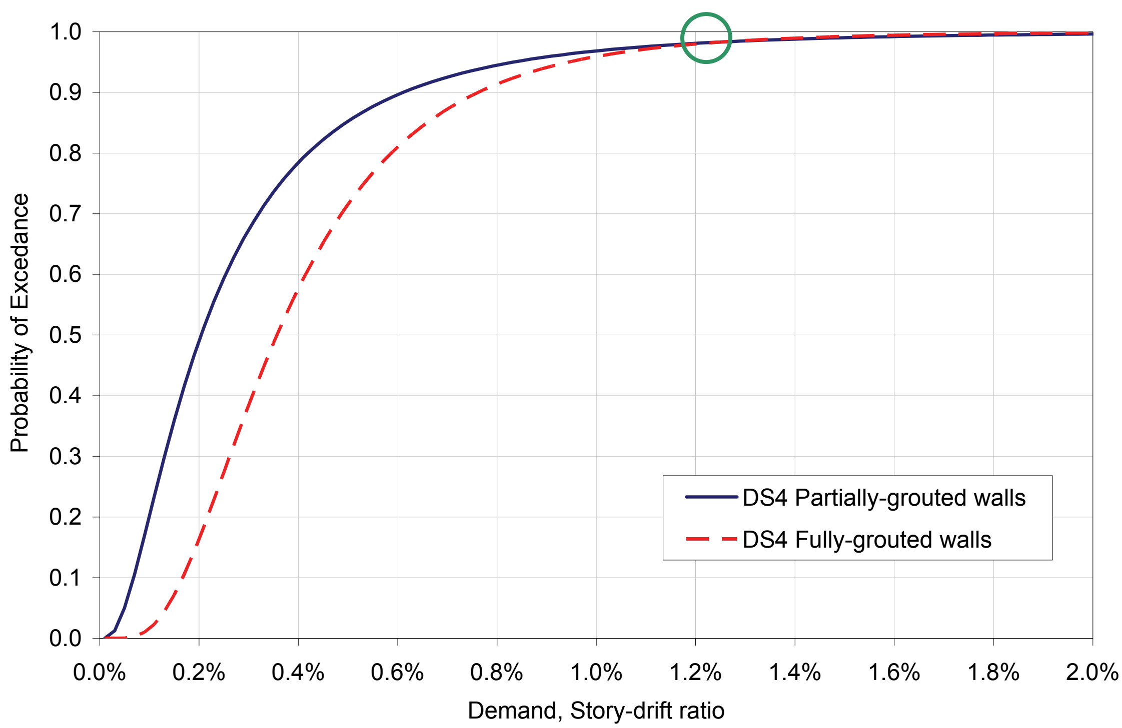
The θ value for fully-grouted walls is 57% of that for partially-grouted walls. The random dispersion is initially increased by $\Delta\beta_{r,PG}$=0.30. For DS3, it is not necessary to reduce the dispersion because the intersection of the fragility curves for fully-grouted and partially-grouted walls is obtained at a demand value that is already higher than the mean plus three times the standard deviation as shown in the graph below.



DAMAGE STATE DS4 - PARTIALLY-GROUTED RM SHEAR WALLS (Class A)

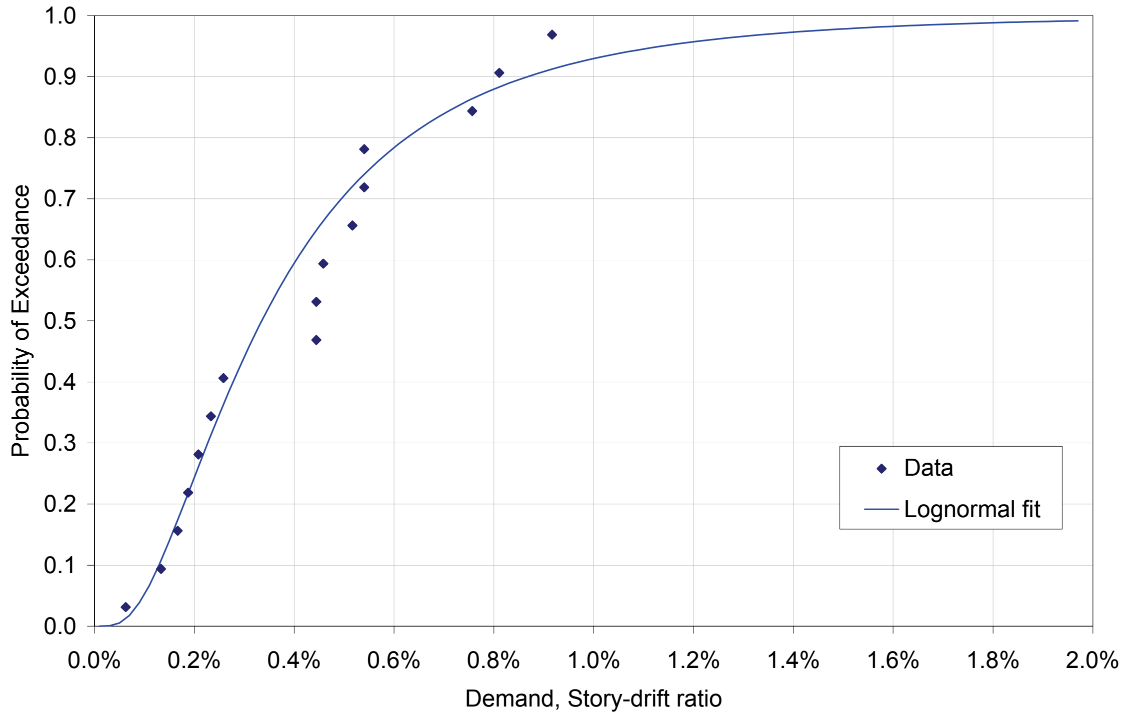
The fragility curve cannot be developed using the actual demand data because of the lack of experimental data. Instead, it is derived based on the authors' opinion.

The θ value for fully-grouted walls is 57% of that for partially-grouted walls. The random dispersion is initially increased by $\Delta\beta_{r,PG}$=0.30. The total dispersion is then reduced in such a way that the intersection of the curves for fully-grouted and partially-grouted walls is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



DAMAGE STATE DS5 - PARTIALLY-GROUTED RM SHEAR WALLS (Class A)

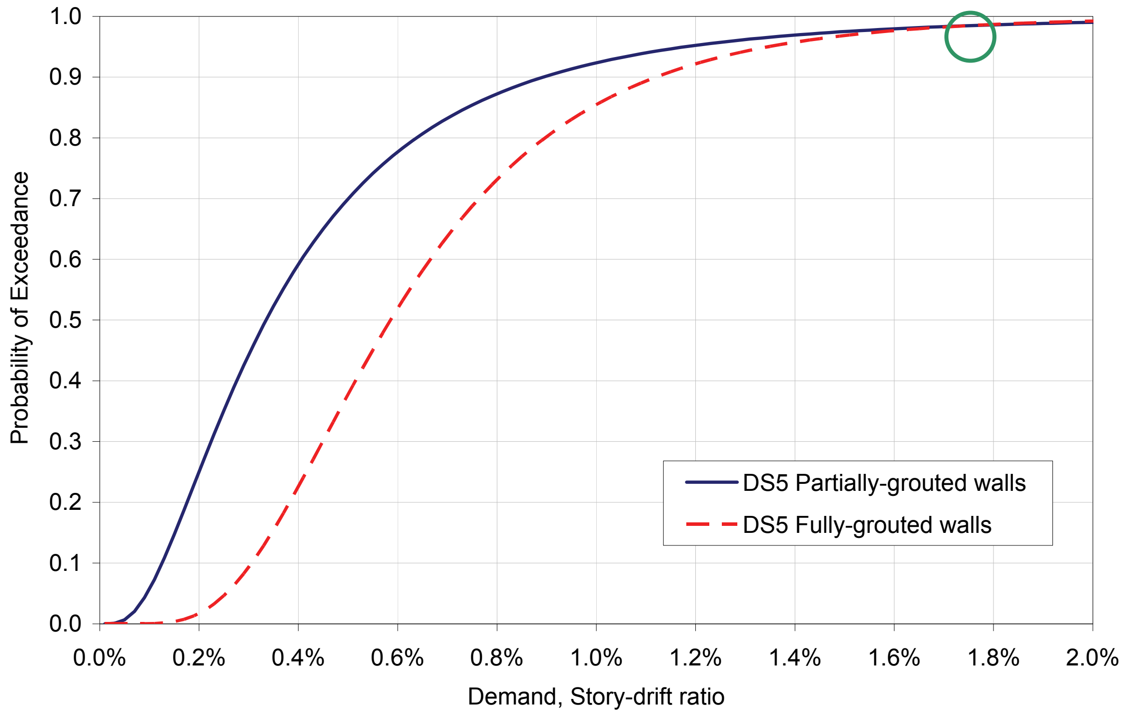
Median θ	Random Dispersion β_r
0.33%	0.74



Passes Lilliefors test:

D= 0.1795 < D_{crit} = 0.2130

The curve is first generated with the actual demand data. Its comparison with the test data is shown above. The total dispersion β is then reduced from 0.78 to 0.77 to ensure that the intersection of the fragility curves for fully-grouted and partially-grouted curves is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



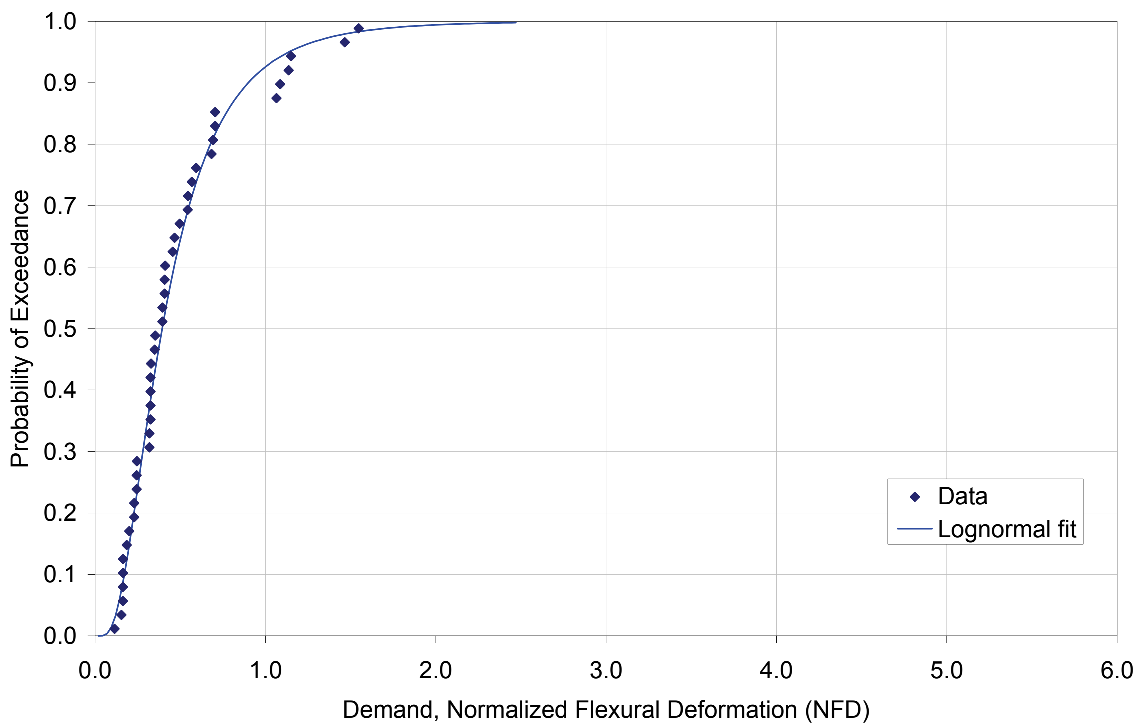
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Probability of Exceedance
0.0%
0.2%
0.4%
0.6%
0.8%
1.0%
1.2%
1.4%
1.6%
1.8%
2.0%
Demand, Story-drift ratio
DS5 Partially-grouted walls
DS5 Fully-grouted walls

APPENDIX C. CLASS B FRAGILITY CURVE DATA FOR FULLY-GROUTED WALLS

Class B fragility curves use normalized displacement-based and force-based demand parameters.

DAMAGE STATE DS1 - FULLY-GROUTED RM SHEAR WALLS (Class B)

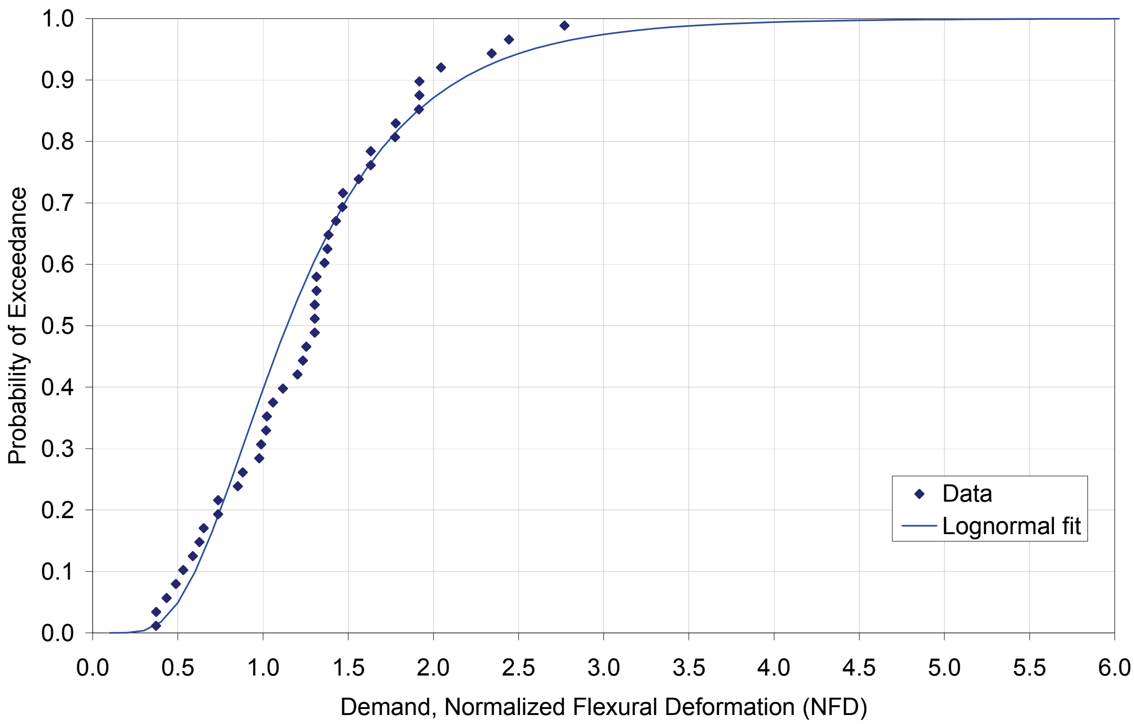
Median θ	Random Dispersion β_r
0.39	0.64



Passes Lilliefors test:
D= 0.0756 < D_{crit} = 0.1326

DAMAGE STATE DS2 - FULLY-GROUTED RM SHEAR WALLS (Class B)

Median θ	Random Dispersion β_r
1.14	0.50

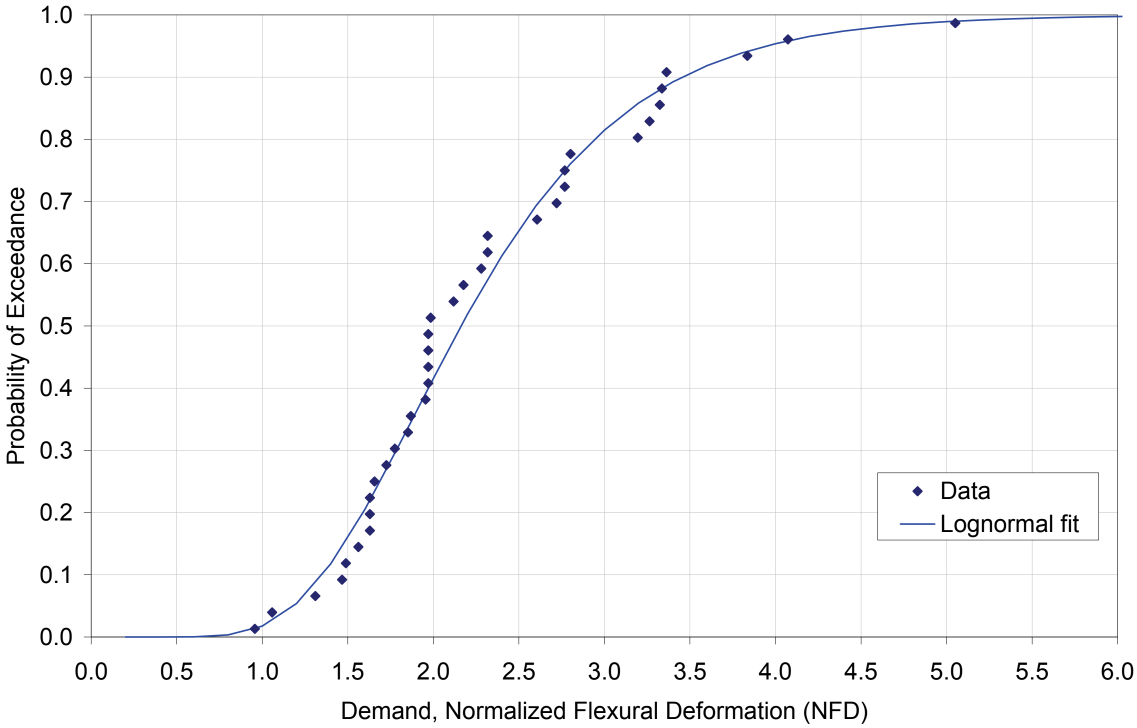


Passes Lilliefors test:

D= 0.1226 < D_{crit} = 0.1326

DAMAGE STATE DS3 - FULLY-GROUTED RM SHEAR WALLS (Class B)

Median θ	Random Dispersion β_r
2.16	0.37



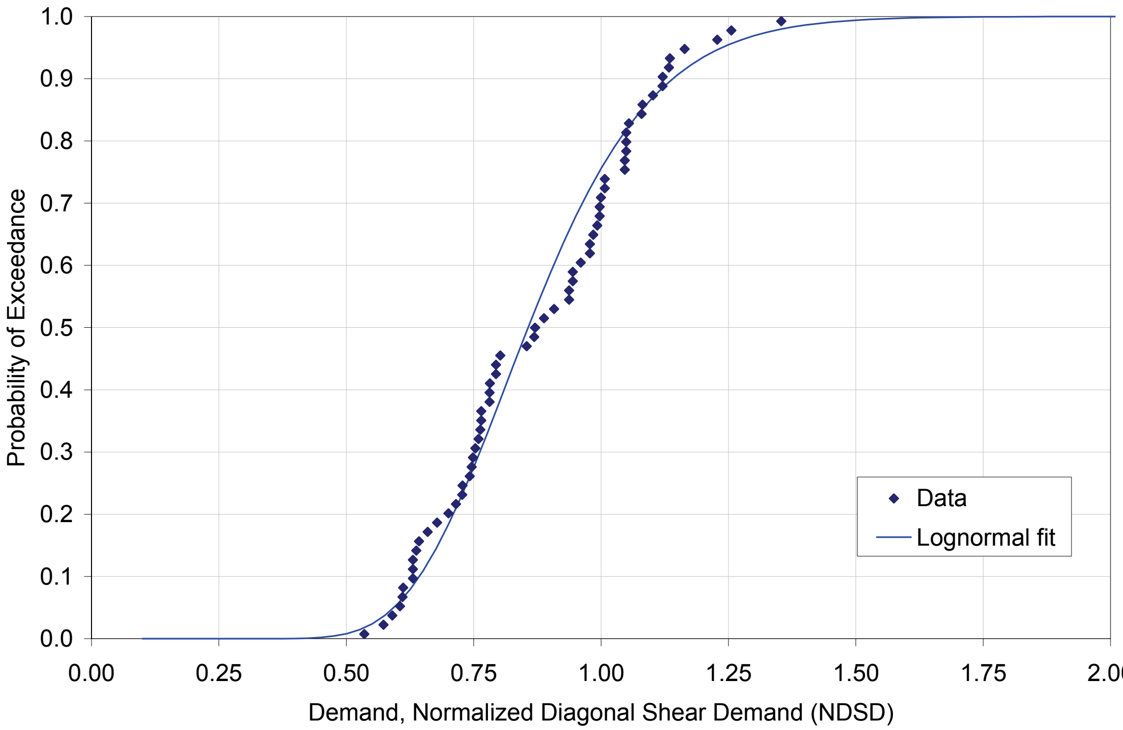
Passes Lilliefors test:
$D = 0.1058 < D_{crit} = 0.1422$

Summary of Test Data for Flexure-dominated Fully-grouted Walls

Reference	Specimen	Direction	Aspect Ratio (H/L)	$P/(A_n f'_m)$	ρ_h (%)	ρ_v (%)	*NFD* for DS1	*NFD* for DS2	*NFD* for DS3
Shing et al.	1	P	1.00	0.07	0.24	0.38	0.47	1.91	2.80
Shing et al.	1	N	1.00	0.07	0.24	0.38	0.35	1.38	1.87
Shing et al.	2	P	1.00	0.09	0.24	0.38	0.41	1.36	2.18
Shing et al.	2	N	1.00	0.09	0.24	0.38	0.54	1.47	2.72
Shing et al.	10	P	1.00	0.03	0.14	0.38	0.16	1.31	1.97
Shing et al.	10	N	1.00	0.03	0.14	0.38	0.25	1.31	1.97
Shing et al.	12	P	1.00	0.03	0.24	0.38	0.16	1.02	1.97
Shing et al.	12	N	1.00	0.03	0.24	0.38	0.33	1.43	1.97
Shing et al.	15	P	1.00	0.03	0.24	0.55	0.40	1.78	2.77
Shing et al.	15	N	1.00	0.03	0.24	0.55	0.40	0.99	2.77
Shing et al.	17	P	1.00	0.07	0.26	0.40	0.33	1.47	2.12
Shing et al.	17	N	1.00	0.07	0.26	0.40	0.33	1.30	1.63
Shing et al.	18	P	1.00	0.07	0.26	0.40	0.16	0.49	1.63
Shing et al.	18	N	1.00	0.07	0.26	0.40	0.24	0.65	1.47
Shing et al.	19	P	1.00	0.07	0.26	0.40	0.24	1.30	2.28
Shing et al.	19	N	1.00	0.07	0.26	0.40	0.33	1.38	2.61
Shing et al.	20	P	1.00	0.07	0.26	0.40	0.16	0.98	1.63
Shing et al.	20	N	1.00	0.07	0.26	0.40	0.33	1.30	1.95
Ibrahim and Sutter	1	P	1.00	0.03	0.20	0.99	0.41	1.02	2.32
Ibrahim and Sutter	1	N	1.00	0.03	0.20	0.99	0.55	2.05	2.32
Shedid et al.	1	P	2.00	0.00	0.08	0.31	0.23	0.74	1.73
Shedid et al.	1	N	2.00	0.00	0.08	0.31	0.23	0.74	1.66
Shedid et al.	2	P	2.00	0.00	0.13	0.83	0.59	1.63	3.26
Shedid et al.	2	N	2.00	0.00	0.13	0.83	0.69	1.63	3.36
Shedid et al.	3	P	2.00	0.00	0.13	0.77	0.71	1.06	1.98
Shedid et al.	3	N	2.00	0.00	0.13	0.77	0.71	1.23	1.85
Shedid et al.	4	P	2.00	0.00	0.26	1.39	1.15	1.92	3.84
Shedid et al.	4	N	2.00	0.00	0.26	1.39	1.09	1.92	3.32
Shedid et al.	5	P	2.00	0.04	0.26	1.39	1.14	1.77	3.19
Shedid et al.	5	N	2.00	0.04	0.26	1.39	1.06	2.34	3.34
Shedid et al.	6	P	2.00	0.09	0.26	1.39	1.55	2.77	4.07
Shedid et al.	6	N	2.00	0.09	0.26	1.39	1.47	2.44	5.05
Priestley	1	P	0.75	0.00	0.98	0.66	0.35	0.88	1.06
Priestley	1	N	0.75	0.00	0.98	0.66	0.41	0.59	-
Priestley	2	P	0.75	0.00	0.68	0.34	0.19	0.37	-
Priestley	2	N	0.75	0.00	0.68	0.34	0.16	0.43	-
Priestley	3	P	0.75	0.00	0.98	0.66	0.32	1.12	1.49
Priestley	3	N	0.75	0.00	0.98	0.66	0.32	0.53	0.96
Priestley	4	P	0.75	0.00	0.68	0.34	0.20	1.20	-
Priestley	4	N	0.75	0.00	0.68	0.34	0.11	0.37	-
Priestley	5	P	0.75	0.04	0.98	0.66	0.57	1.56	1.78
Priestley	5	N	0.75	0.04	0.98	0.66	0.50	0.85	1.56
Priestley	6	P	0.75	0.03	0.98	0.66	0.68	1.25	1.31
Priestley	6	N	0.75	0.03	0.98	0.66	0.46	0.63	-

DAMAGE STATE DS4 - FULLY-GROUTED RM SHEAR WALLS (Class B)

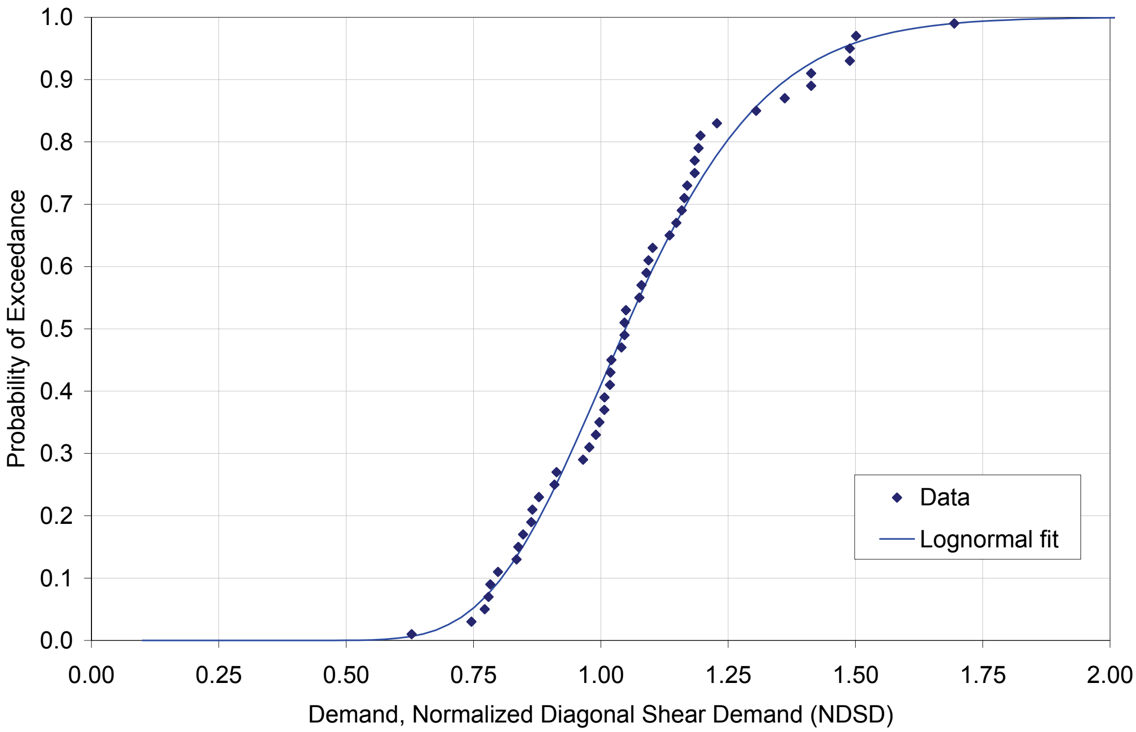
Median θ	Random Dispersion β_r
0.86	0.22



Fails Lilliefors test:
D= 0.1116 > D_{crit} = 0.1081

DAMAGE STATE DS5 - FULLY-GROUTED RM SHEAR WALLS (Class B)

Median θ	Random Dispersion β_r
1.05	0.21



Passes Lilliefors test:
D= 0.0709 < D_{crit} = 0.1246

Summary of Test Data for Shear-dominated Fully-grouted Walls

Reference	Specimen	Direction	Aspect Ratio (*H*/*L*)	$P/(A_n f'_m)$	ρ_h (%)	ρ_v (%)	*NDSD* for DS4	*NDSD* for DS5
Shing et al.	3	P	1.00	0.09	0.14	0.74	1.13	1.13
Shing et al.	3	N	1.00	0.09	0.14	0.74	0.91	1.19
Shing et al.	4	P	1.00	0.00	0.14	0.74	0.76	1.08
Shing et al.	4	N	1.00	0.00	0.14	0.74	0.76	1.30
Shing et al.	5	P	1.00	0.04	0.14	0.74	0.78	1.16
Shing et al.	5	N	1.00	0.04	0.14	0.74	0.78	1.09
Shing et al.	7	P	1.00	0.04	0.14	0.74	0.79	1.18
Shing et al.	7	N	1.00	0.04	0.14	0.74	0.79	1.18
Shing et al.	9	P	1.00	0.08	0.14	0.38	1.00	1.04
Shing et al.	9	N	1.00	0.08	0.14	0.38	1.00	1.00
Shing et al.	11	P	1.00	0.00	0.24	0.74	0.63	1.02
Shing et al.	11	N	1.00	0.00	0.24	0.74	0.63	1.09
Shing et al.	13	P	1.00	0.08	0.24	0.55	1.16	1.16
Shing et al.	13	N	1.00	0.08	0.24	0.55	1.23	1.23
Shing et al.	14	P	1.00	0.08	0.14	0.55	1.05	1.05
Shing et al.	14	N	1.00	0.08	0.14	0.55	1.12	1.20
Shing et al.	16	P	1.00	0.11	0.24	0.74	1.05	1.49
Shing et al.	16	N	1.00	0.11	0.24	0.74	1.08	1.49
Shing et al.	21	P	1.00	0.07	0.14	0.57	0.94	1.05
Shing et al.	21	N	1.00	0.07	0.14	0.57	1.05	1.10
Shing et al.	17	P	1.00	0.07	0.26	0.40	1.01	-
Shing et al.	17	N	1.00	0.07	0.26	0.40	1.05	-
Shing et al.	18	P	1.00	0.07	0.26	0.40	0.94	-
Shing et al.	18	N	1.00	0.07	0.26	0.40	1.01	-
Shing et al.	19	P	1.00	0.07	0.26	0.40	1.05	-
Shing et al.	20	P	1.00	0.07	0.26	0.40	1.10	-
Shing et al.	20	N	1.00	0.07	0.26	0.40	1.13	-
Shing et al.	22	P	1.00	0.03	0.14	0.57	1.05	1.17
Shing et al.	22	N	1.00	0.03	0.14	0.57	0.98	1.05
Shing et al.	23	0	1.00	0.07	0.14	0.55	0.89	1.15
Shing et al.	24	0	1.00	0.10	0.24	0.55	1.26	1.36
Brunner	1	0	0.93	0.09	0.13	0.59	1.00	1.69
Brunner	2	P	0.72	0.08	0.13	0.57	1.12	1.41
Brunner	2	N	0.72	0.08	0.13	0.57	1.08	1.41
Brunner	3	0	0.59	0.08	0.13	0.56	1.35	1.50
Ibrahim and Sutter	1	P	1.00	0.03	0.20	0.40	0.61	-
Ibrahim and Sutter	1	N	1.00	0.03	0.20	0.40	0.59	-
Ibrahim and Sutter	2	P	0.64	0.03	0.20	0.40	0.54	0.78
Ibrahim and Sutter	2	N	0.64	0.03	0.20	0.40	0.61	0.86
Ibrahim and Sutter	3	P	0.47	0.03	0.20	0.40	0.73	0.83
Ibrahim and Sutter	3	N	0.47	0.03	0.20	0.40	0.78	0.80
Ibrahim and Sutter	4	P	0.64	0.03	0.20	0.60	0.80	0.88
Ibrahim and Sutter	4	N	0.64	0.03	0.20	0.60	0.70	0.87
Ibrahim and Sutter	5	P	0.64	0.08	0.20	0.40	0.61	0.63

Ibrahim and Sutter	5	N	0.64	0.08	0.20	0.40	0.75	0.85
Voon and Ingham	1	P	1.00	0.00	0.05	0.62	-	0.98
Voon and Ingham	1	N	1.00	0.00	0.05	0.62	-	0.91
Voon and Ingham	2	P	1.00	0.00	0.01	0.62	-	0.97
Voon and Ingham	3	P	1.00	0.00	0.14	0.62	-	0.84
Voon and Ingham	3	N	1.00	0.00	0.14	0.62	-	0.78
Voon and Ingham	4	P	1.00	0.00	0.06	0.62	-	1.02
Voon and Ingham	4	N	1.00	0.00	0.06	0.62	-	0.91
Voon and Ingham	7	P	1.00	0.03	0.05	0.62	-	1.02
Voon and Ingham	7	N	1.00	0.03	0.05	0.62	-	1.01
Voon and Ingham	8	P	1.00	0.01	0.05	0.62	-	1.01
Voon and Ingham	8	N	1.00	0.01	0.05	0.62	-	0.99
Voon and Ingham	9	P	2.00	0.01	0.05	0.97	-	0.77
Voon and Ingham	9	N	2.00	0.01	0.05	0.97	-	0.75
Voon and Ingham	10	P	0.60	0.01	0.05	0.60	-	1.08
Priestley	1	P	0.75	0.00	0.98	0.66	0.68	-
Priestley	1	N	0.75	0.00	0.98	0.66	0.76	-
Priestley	2	P	0.75	0.00	0.68	0.34	0.64	-
Priestley	2	N	0.75	0.00	0.68	0.34	0.57	-
Priestley	3	P	0.75	0.00	0.98	0.66	0.66	-
Priestley	3	N	0.75	0.00	0.98	0.66	0.74	-
Priestley	4	P	0.75	0.00	0.68	0.34	0.63	-
Priestley	4	N	0.75	0.00	0.68	0.34	0.64	-
Priestley	5	P	0.75	0.04	0.98	0.66	0.87	-
Priestley	5	N	0.75	0.04	0.98	0.66	0.99	-
Priestley	6	P	0.75	0.03	0.98	0.66	0.98	-
Priestley	6	N	0.75	0.03	0.98	0.66	0.98	-

DAMAGE STATE DS6 - FULLY-GROUTED RM SHEAR WALLS (Class B)

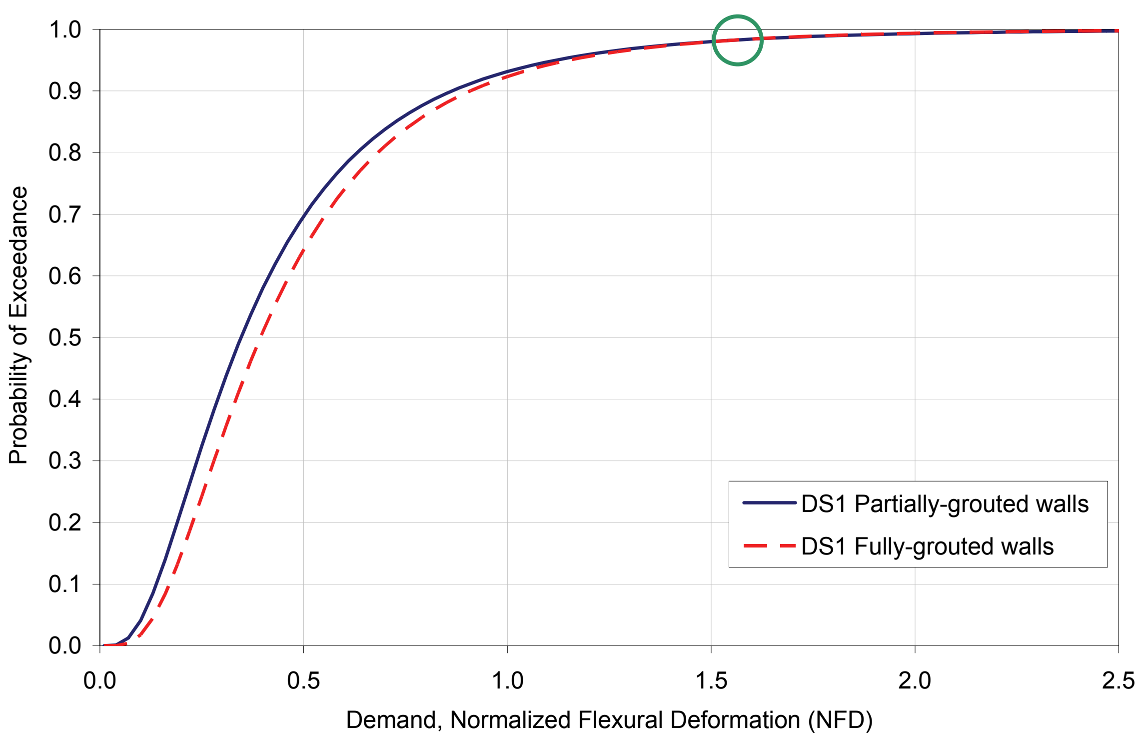
The fragility curve for this damage state cannot be developed using the actual demand data because of lack of relevant experimental data. Few test specimens have been found to have significant sliding. In addition, only qualitative information has been obtained in these cases. Therefore, it has not been possible to estimate the amount of sliding and the load level at which it occurred. Hence, it is analytically derived.

APPENDIX D. CLASS B FRAGILITY CURVE DATA FOR PARTIALLY-GROUTED WALLS

DAMAGE STATE DS1 - PARTIALLY-GROUTED RM SHEAR WALLS (Class B)

The fragility curve cannot be derived using the actual demand data because of the lack of experimental data. Instead, it is derived based on the authors' opinion.

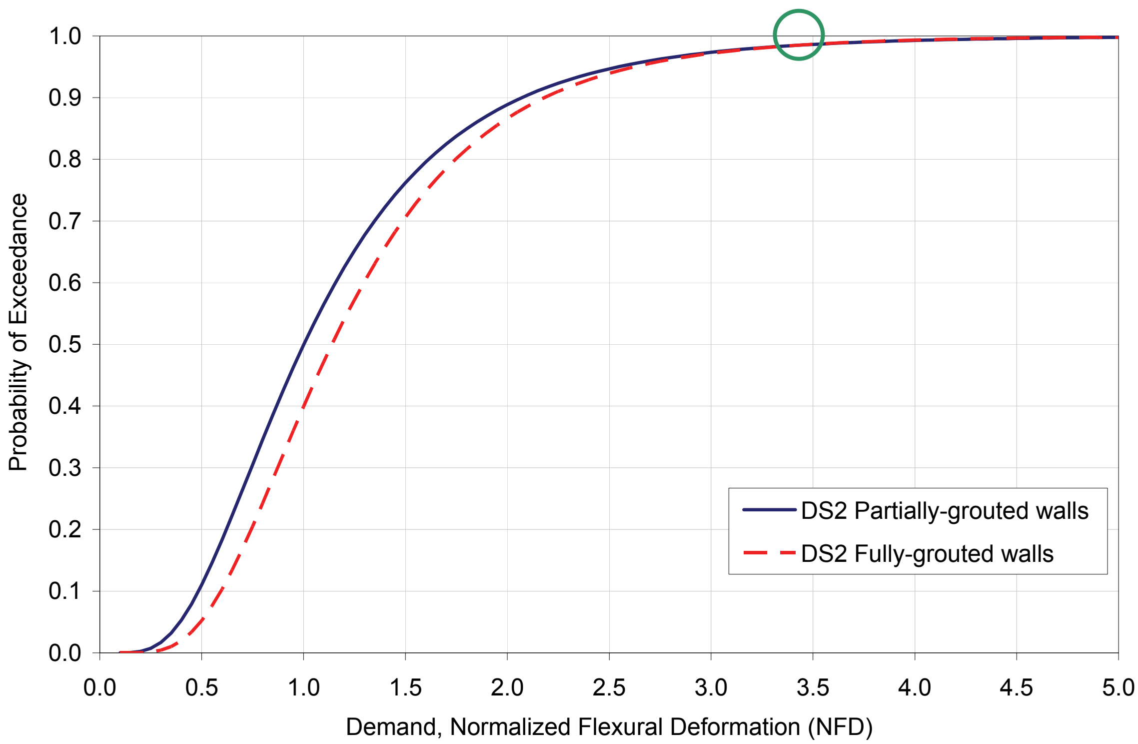
The θ value for fully-grouted walls is taken to be 88% of that of partially-grouted walls based on the data for DS5 as described in Chapter 7 of this report. The random dispersion β_r is initially increased by $\Delta\beta_{r,PG}$=0.18 based on that observed for DS5, which is derived using the actual demand data. The total dispersion is then reduced in such a way that the intersection of the curves for fully-grouted and partially-grouted walls is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



DAMAGE STATE DS2 - PARTIALLY-GROUTED RM SHEAR WALLS (Class B)

The fragility curve cannot be developed using the actual demand data because of the lack of experimental data. Instead, it is derived based on the authors' opinion.

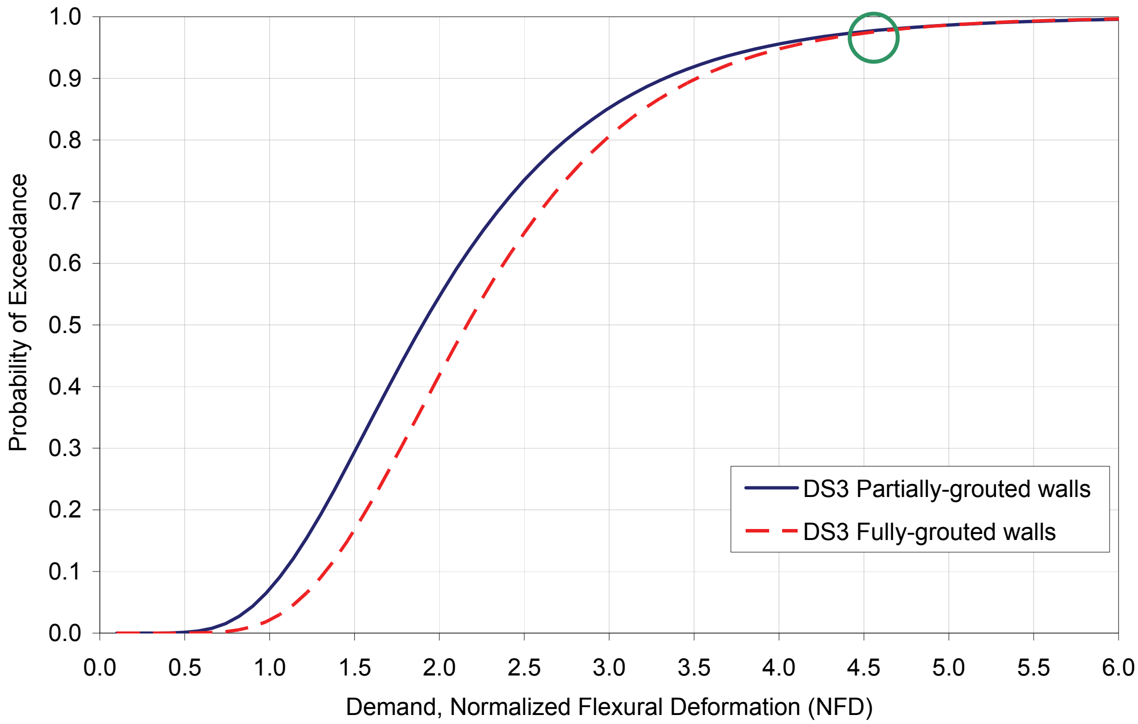
The θ value for partially-grouted walls is 88% of that for fully-grouted walls. The random dispersion is initially increased by $\Delta\beta_{r,PG}$=0.18. The total dispersion is then reduced in such a way that the intersection of the curves for fully-grouted and partially-grouted walls is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



DAMAGE STATE DS3 - PARTIALLY-GROUTED RM SHEAR WALLS (Class B)

The fragility curve cannot be developed using the actual demand data because of the lack of experimental data. Instead, it is derived based on the authors' opinion.

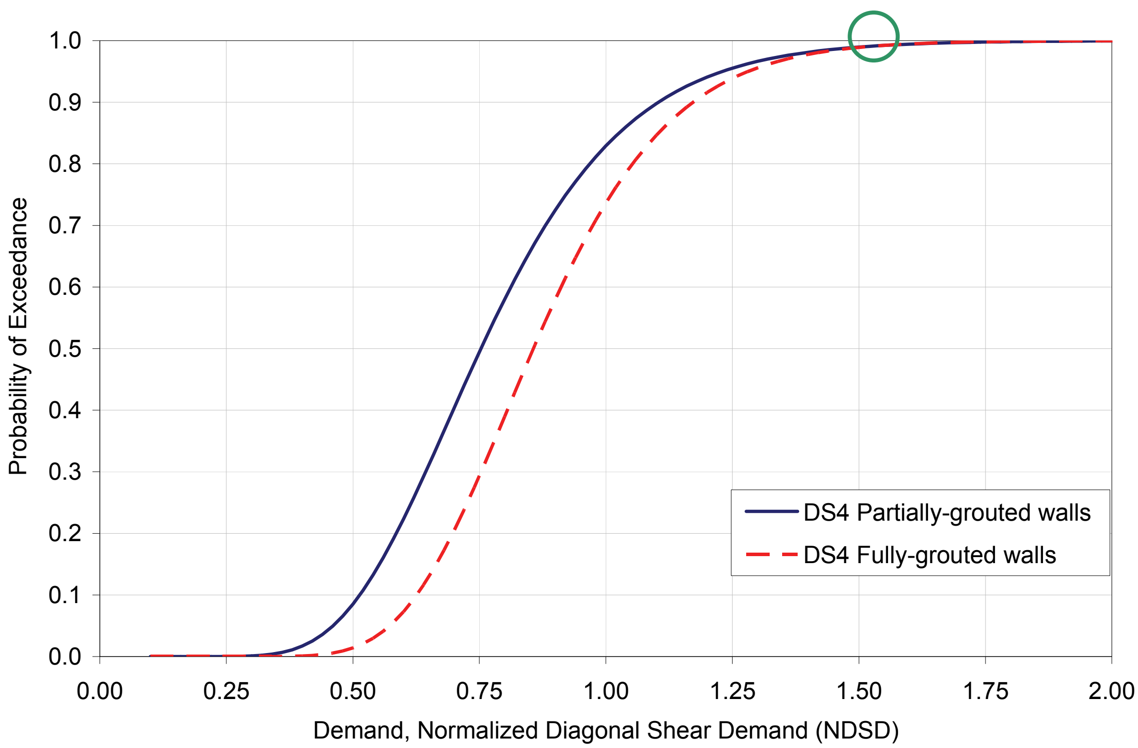
The θ value for partially-grouted walls is 88% of that for fully-grouted walls. The random dispersion is initially increased by $\Delta\beta_{r,PG}$ =0.18. The total dispersion is then reduced in such a way that the intersection of the curves for fully-grouted and partially-grouted walls is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



DAMAGE STATE DS4 - PARTIALLY-GROUTED RM SHEAR WALLS (Class B)

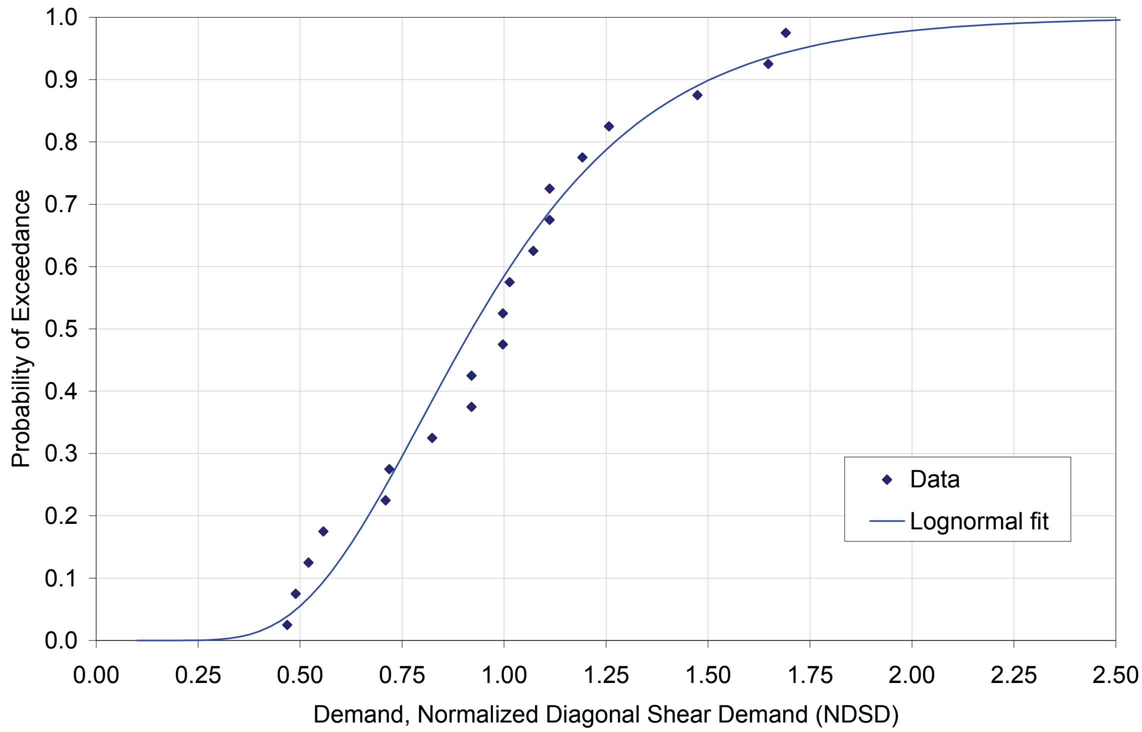
The fragility curve cannot be developed using the actual demand data because of the lack of experimental data. Instead, it is derived based on the authors' opinion.

The θ value for partially-grouted walls is 88% of that for fully-grouted walls. The random dispersion is initially increased by $\Delta\beta_{r,PG}$ =0.18. The total dispersion is then reduced in such a way that the intersection of the curves for fully-grouted and partially-grouted walls is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



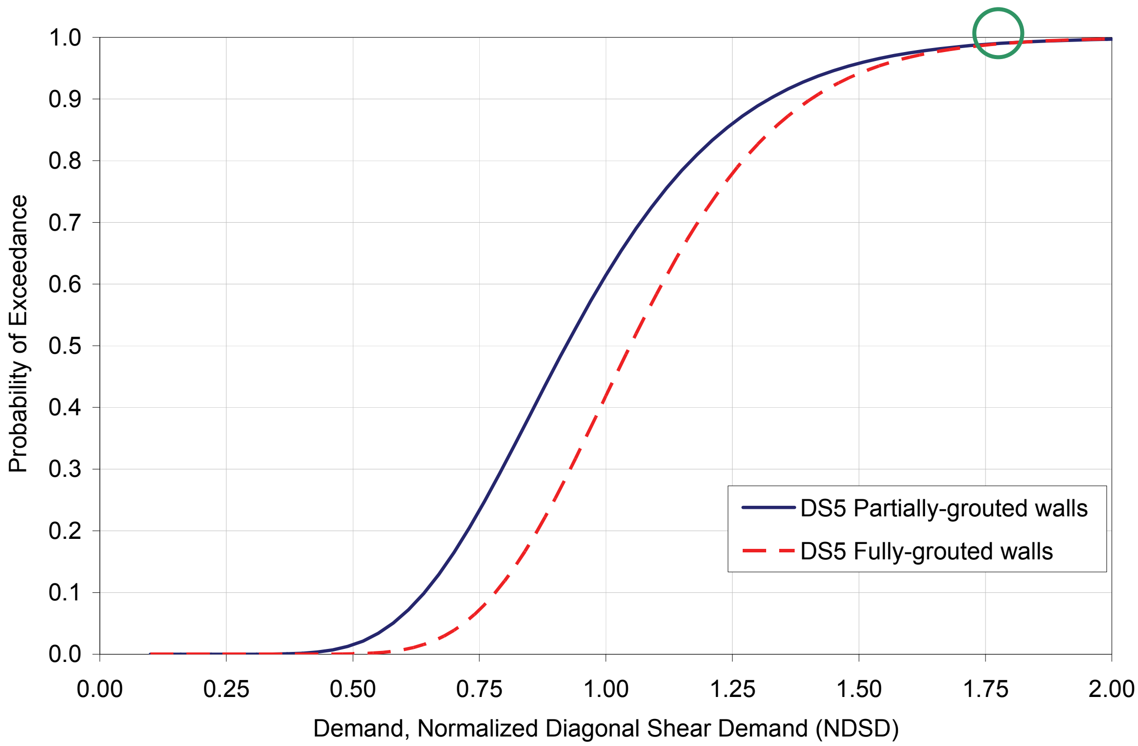
DAMAGE STATE DS5 - PARTIALLY-GROUTED RM SHEAR WALLS (Class B)

Median θ	Random Dispersion β_r
0.92	0.38



Passes Lilliefors test:
D= 0.1241 < D_{crit} = 0.1923

The curve is first generated with the actual demand data. Its comparison with the test data is shown above. The total dispersion β is then reduced from 0.40 to 0.28 to ensure that the intersection of the fragility curves for fully-grouted and partially-grouted curves is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.

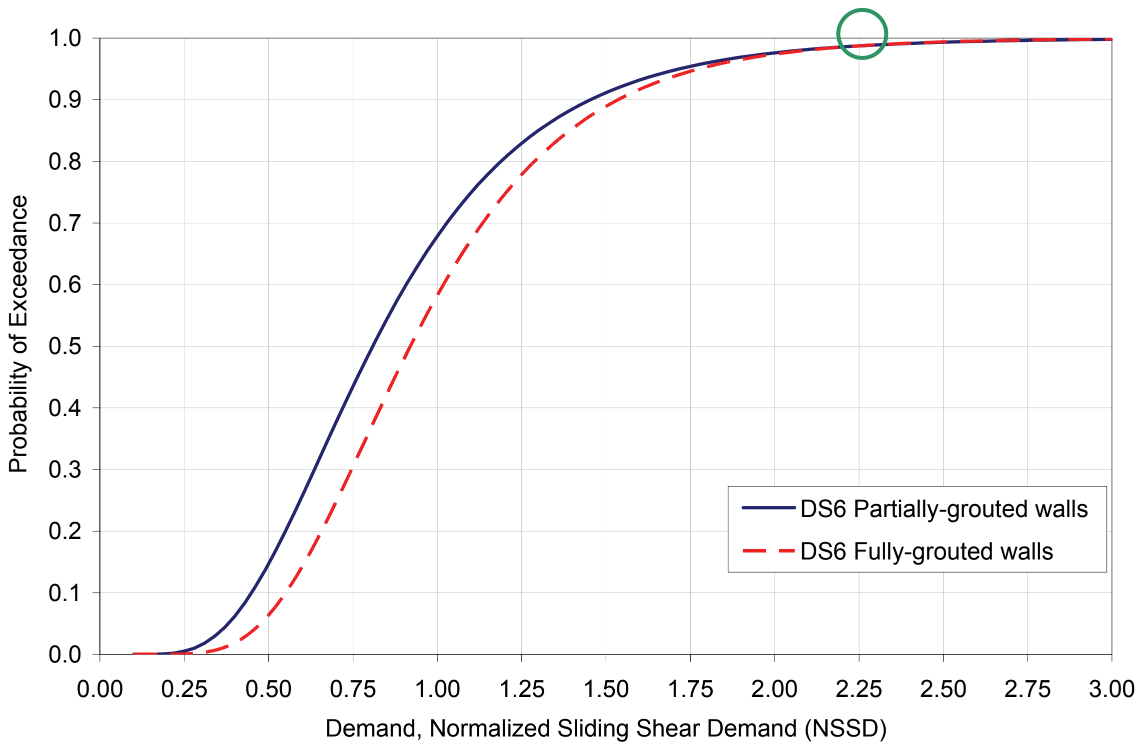


Summary of Test Data for Shear-dominated Partially-grouted Walls

Reference	Specimen	Direction	Aspect Ratio (*H*/*L*)	$P/(A_n f'_m)$	ρ_h (%)	ρ_v (%)	***NDSD* for DS5**
Voon and Ingham	5	0	1.00	0.00	0.00	1.45	1.65
Voon and Ingham	6	0	1.00	0.00	0.00	0.87	1.07
Ingham et al.	2	P	0.92	0.00	0.00	0.20	0.71
Ingham et al.	2	N	0.92	0.00	0.00	0.20	0.56
Ingham et al.	5	P	3.00	0.00	0.00	0.94	0.49
Ingham et al.	5	N	3.00	0.00	0.00	0.94	0.47
Ingham et al.	6	P	1.33	0.00	0.00	0.42	0.72
Ingham et al.	7	P	0.92	0.00	0.00	0.29	0.92
Ingham et al.	7	N	0.92	0.00	0.00	0.29	0.92
Ingham et al.	8	P	0.57	0.00	0.00	0.18	1.01
Ingham et al.	9	P	3.00	0.00	0.00	0.94	0.52
Ingham et al.	10	P	1.33	0.00	0.00	0.42	0.82
Ingham et al.	11	P	0.92	0.00	0.00	0.29	1.00
Ingham et al.	11	N	0.92	0.00	0.00	0.29	1.00
Ingham et al.	12	P	0.57	0.00	0.00	0.18	1.11
Ingham et al.	12	N	0.57	0.00	0.00	0.18	1.11
Ghanem et al.	2	0	1.00	0.04	0.36	0.36	1.26
Ghanem et al.	3	0	1.00	0.09	0.36	0.36	1.69
Ghanem et al.	1	0	1.00	0.04	0.34	0.34	1.19
Ghanem et al.	2	0	1.00	0.04	0.36	0.36	1.47

DAMAGE STATE DS6 - PARTIALLY-GROUTED RM SHEAR WALLS (Class B)

The θ value for partially-grouted walls is 88% of that for fully-grouted walls. The fragility curve for fully-grouted walls is derived based on the authors' opinion because of the lack of experimental data. The dispersion is initially increased by $\Delta\beta_{PG}$ =0.18, but it is then reduced in such a way that the intersection of the curves for fully-grouted and partially-grouted walls is obtained at a demand value that is equal to the mean plus three times the standard deviation of the curve for fully-grouted walls as shown in the graph below.



APPENDIX E. SUPPLEMENTAL INFORMATION ON SCOPE OF REPAIR

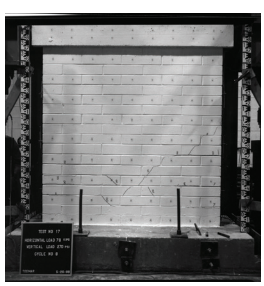
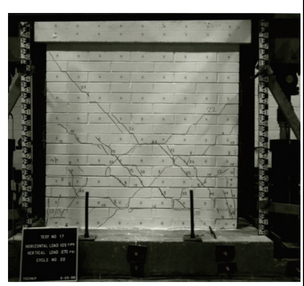
When a wall component has reached damage state DS3, DS5, or DS6, total replacement of the wall component is recommended. The replacement cost should include the costs for shoring the structure, the demolition of the damaged wall component, and the construction of a new wall. For damage state DS1, repair is cosmetic, mainly involving patching the cracks and painting the wall. For damage states DS2 and DS4, repair mainly involves epoxy or grout injection into cracks; and, sometimes, DS2 may require removal of spalled masonry and patching the void with a non-shrink grout. For partially-grouted walls, crack repair may require the grouting of the cavities. Hence, to help the estimation of repair costs and effort for these damage states, information on the extent of anticipated damage in terms of the total crack length and spalled area per unit wall area is gathered and presented in this appendix. This information is gathered from pictures of damaged walls tested by Shing et al. (1991). All the walls were single-story cantilever walls and were fully-grouted. Such information is not available in the other references. Only one specimen in Shing's tests had light toe crushing in damage state DS2. For this reason, this is not reported here considering that such damage is unlikely in DS2. The crack lengths measured for DS1, DS2, and DS4 include both flexural and shear cracks which often occurred together regardless of the final failure mode. The following table shows the crack density calculated by dividing the total crack length measured on one face of a wall by the total wall area. However, it should be mentioned that for the single-story walls considered here, flexural cracks in DS1 and DS2 were mainly concentrated in the lower half of the a wall over a height that is approximately twice the effective plastic-hinge length. Hence, the numbers in the table may under-estimate the density of flexural cracks for cases where the plastic-hinge region covers a larger portion of a story-high wall component. For example, for walls with heights of two stories or more, two times the plastic-hinge length will cover the entire bottom story.

Crack Density Data from Tests by Shing et al.

Specimen	Crack Density (ft./ft.^{2})		
	DS1 (Slight flexural damage)	DS2 (Moderate flexural damage)	DS4 (Moderate shear damage)
1	0.50	0.53	
2	0.14	0.60	
3			0.62
4			0.63
5			0.65
7			1.30
8			Incomplete information
9			0.86
10	0.25	0.46	
11			0.50
12	0.30	0.61	
13			0.75
14			0.65
15	0.36	1.19	
16			0.38
17	0.21	0.94	
18	Incomplete information		
19	0.29	0.63	
20	0.25	0.63	
21			0.88
22			0.78
23			Incomplete information
24			0.59
Mean	**0.29**	**0.70**	**0.66**
Median	**0.27**	**0.62**	**0.65**
Standard Dev.	**0.11**	**0.24**	**0.30**
Coef. Variation	**0.38**	**0.35**	**0.45**

APPENDIX F. FRAGILITY SPECIFICATION (CLASS A) FOR FULLY-GROUTED WALLS

Fragility Specification RM Wall Panel (flexurally controlled)—B1051					
Developer and Date:	Juan Murcia-Delso and P. Benson Shing, December, 2009				
NISTIR Classification:	B1051.RM-3a				
Description (Basic Composition):	Reinforced Masonry Bearing Walls				
Construction Quality: (1)	Good				
Seismic Installation Conditions:					
Normative Quantity (unit):	1				
Demand Parameter:	Story-Drift Ratio				
Number of Damage States:	3				
Type of Damage States:	X	ordered		mutually exclusive		simultaneous

Damage States	**DS1**	**DS2**	**DS3**
Description:	• A few flexural and shear cracks with hardly noticeable residual crack width • Slight yielding of extreme vertical reinforcement • No spalling • No fracture or buckling of reinforcement • Not structurally significant	• Numerous flexural and shear cracks • Mild toe crushing with vertical cracks or light spalling at wall toes • No fracture or buckling of reinforcement • Small residual deformation • Repairable	• Severe flexural cracks • Significant toe crushing and spalling • Fracture or buckling of some reinforcement • Significant residual deformation • Not repairable
Illustrations:			
Probability: (2)			

(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave "Probability" blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in "Probability." For simultaneous damage states, ensure that the probabilities add to at least 1.0.

RM Wall Panel (flexurally controlled)—B1051			
Fragility Parameters	**DS1**	**DS2**	**DS3**
Median Demand, θ: (3)	0.31%	0.87%	1.51%
Data dispersion, β_d: (4)	0.40	0.27	0.20
Uncertainty, β_u: (5)	0.25	0.25	0.25
Total Dispersion, β: (6)	0.45	0.35	0.30
Correlation:			
Quality Ratings			
Data Quality:	none	none	none
	marginal	marginal	marginal
	average	average	average
	superior	superior	superior
Data Relevance:	none	none	none
	marginal	marginal	marginal
	average	average	average
	superior	superior	superior
Documentation Quality:	marginal	marginal	marginal
	average	average	average
	superior	superior	superior
Rationality:	marginal	marginal	marginal
	average	average	average
	superior	superior	superior
	N/A	N/A	N/A

Extrapolation (7)							
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**	**θ**	**β**	**θ**	**β**
Good							
Fair							
Poor							
Average or unknown							
Explain basis for extrapolation. What factors affect θ and β?							

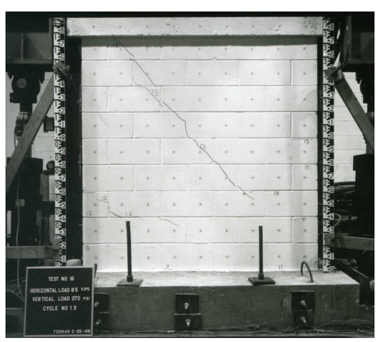
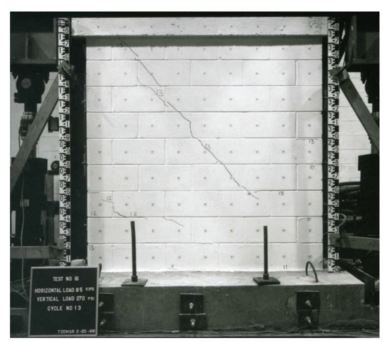
(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

RM Wall Panel (flexurally controlled)—B1051									
Consequence Functions	**DS1**			**DS2**			**DS3**		
Repair Description:	• Cosmetic repair			• Epoxy injection to repair cracks • Remove loose masonry • Patch spalls with NS grout • Paint each side			• Shore • Demo existing wall • Replace		
Repair Costs:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:									
Min. consequence over upper quantity:									
Assumed distribution:	☐ normal			☐ normal			☐ normal		
	☐ lognormal			☐ lognormal			☐ lognormal		
Repair Time:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:									
Min. consequence over upper quantity:									
Assumed distribution:	☐ normal			☐ normal			☐ normal		
	☐ lognormal			☐ lognormal			☐ lognormal		
LifeSafety Hazard:	☐ yes			☐ yes			☐ yes		
	☐ no			☐ no			☐ no		
Casualty-affected Planar Area (sf) per Normative Unit:									
Casualty Rate in Affected Planar Area:									
Post-event Tagging Flag:									
Total Damage Quantity (red tag trigger):									
Comments:									

Fragility Specification

RM Wall Panel (shear controlled)—B1051

<table>
<tr><td>Developer and Date:</td><td colspan="6">Juan Murcia-Delso and P. Benson Shing, November, 2009</td></tr>
<tr><td>NISTIR Classification:</td><td colspan="6">B1051.RM-1b</td></tr>
<tr><td>Description (Basic Composition):</td><td colspan="6">Reinforced Masonry Bearing Walls</td></tr>
<tr><td>Construction Quality: (1)</td><td colspan="6">Good</td></tr>
<tr><td>Seismic Installation Conditions:</td><td colspan="6"></td></tr>
<tr><td>Normative Quantity (unit):</td><td colspan="6">1</td></tr>
<tr><td>Demand Parameter:</td><td colspan="6">Story-Drift Ratio</td></tr>
<tr><td>Number of Damage States:</td><td colspan="6">2</td></tr>
<tr><td>Type of Damage States:</td><td>X</td><td>ordered</td><td></td><td>mutually exclusive</td><td></td><td>simultaneous</td></tr>
</table>

Damage States	**DS4**	**DS5**
Description:	• First occurrence of major diagonal cracks • Cracks remain closed after load removal • Repairable	• Wide diagonal cracks with typically one or two cracks in each direction • Crushing or spalling at wall toes • Not repairable
Illustrations:		
Probability: (2)		

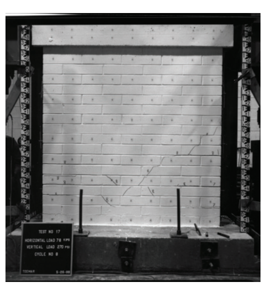
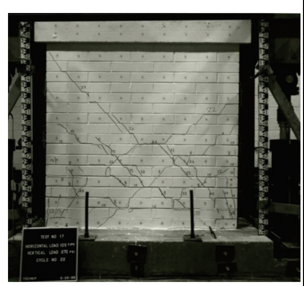
(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave "Probability" blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in "Probability." For simultaneous damage states, ensure that the probabilities add to at least 1.0.

RM Wall Panel (shear controlled)—B1051					
Fragility Parameters		**DS4**		**DS5**	
Median Demand, θ: (3)		0.36%		0.59%	
Data dispersion, β_d: (4)		0.54		0.44	
Uncertainty, β_u: (5)		0.25		0.25	
Total Dispersion, β: (6)		0.60		0.50	
Correlation:					
Quality Ratings					
Data Quality:		none		none	
		marginal		marginal	
		average		average	
		superior		superior	
Data Relevance:		none		none	
		marginal		marginal	
		average		average	
		superior		superior	
Documentation Quality:		marginal		marginal	
		average		average	
		superior		superior	
Rationality:		marginal		marginal	
		average		average	
		superior		superior	
		N/A		N/A	
Extrapolation (7)					
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**	**θ**	**β**
Good					
Fair					
Poor					
Average or unknown					
Explain basis for extrapolation. What factors affect θ and β?					

(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

<table>
<tr><th colspan="7">RM Wall Panel (shear controlled)—B1051</th></tr>
<tr><td>Consequence Functions</td><td colspan="3">DS4</td><td colspan="3">DS5</td></tr>
<tr><td>Repair Description:</td><td colspan="3">• Epoxy injection to repair cracks
• Paint each side</td><td colspan="3">• Shore
• Demo existing wall
• Replace</td></tr>
<tr><td>Repair Costs:</td><td>P_{10}</td><td>P_{50}</td><td>P_{90}</td><td>P_{10}</td><td>P_{50}</td><td>P_{90}</td></tr>
<tr><td>Max. consequence up to lower quantity:</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Min. consequence over upper quantity:</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Assumed distribution:</td><td colspan="3">☐ normal</td><td colspan="3">☐ normal</td></tr>
<tr><td colspan="3">☐ lognormal</td><td colspan="3">☐ lognormal</td></tr>
<tr><td>Repair Time:</td><td>P_{10}</td><td>P_{50}</td><td>P_{90}</td><td>P_{10}</td><td>P_{50}</td><td>P_{90}</td></tr>
<tr><td>Max. consequence up to lower quantity:</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Min. consequence over upper quantity:</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Assumed distribution:</td><td colspan="3">☐ normal</td><td colspan="3">☐ normal</td></tr>
<tr><td colspan="3">☐ lognormal</td><td colspan="3">☐ lognormal</td></tr>
<tr><td rowspan="2">LifeSafety Hazard:</td><td colspan="3">☐ yes</td><td colspan="3">☐ yes</td></tr>
<tr><td colspan="3">☐ no</td><td colspan="3">☐ no</td></tr>
<tr><td>Casualty-affected Planar Area (sf) per Normative Unit:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Casualty Rate in Affected Planar Area:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Post-event Tagging Flag:</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Total Damage Quantity (red tag trigger):</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Comments:</td><td colspan="3"></td><td colspan="3"></td></tr>
</table>

APPENDIX G. FRAGILITY SPECIFICATION (CLASS A) FOR PARTIALLY-GROUTED WALLS

Fragility Specification RM Wall Panel (flexurally controlled)—B1051			
Developer and Date:	Juan Murcia-Delso and P. Benson Shing, November, 2009		
NISTIR Classification:	B1051.RM-2a		
Description (Basic Composition):	Reinforced Masonry Bearing Walls		
Construction Quality: (1)	Good		
Seismic Installation Conditions:			
Normative Quantity (unit):	1		
Demand Parameter:	Story-Drift Ratio		
Number of Damage States:	3		
Type of Damage States:	X ordered	mutually exclusive	simultaneous
Damage States	**DS1**	**DS2**	**DS3**
Description:	• A few flexural and shear cracks with hardly noticeable residual crack width • Slight yielding of extreme vertical reinforcement • No spalling • No fracture or buckling of reinforcement • Not structurally significant	• Numerous flexural and shear cracks • Mild toe crushing with vertical cracks or light spalling at wall toes • No fracture or buckling of reinforcement • Small residual deformation • Repairable	• Severe flexural cracks • Significant toe crushing and spalling • Fracture or buckling of some reinforcement • Significant residual deformation • Not repairable
Illustrations:			
Probability: (2)			

(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave “Probability” blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in “Probability.” For simultaneous damage states, ensure that the probabilities add to at least 1.0.

RM Wall Panel (flexurally controlled)—B1051			
Fragility Parameters	**DS1**	**DS2**	**DS3**
Median Demand, θ: (3)	0.18%	0.51%	0.86%
Data dispersion, β_d: (4)	-	-	-
Uncertainty, β_u: (5)	-	-	-
Total Dispersion, β: (6)	0.75	0.60	0.55
Correlation:			
Quality Ratings			
Data Quality:	☐ none ☐ marginal ☐ average ☐ superior	☐ none ☐ marginal ☐ average ☐ superior	☐ none ☐ marginal ☐ average ☐ superior
Data Relevance:	☐ none ☐ marginal ☐ average ☐ superior	☐ none ☐ marginal ☐ average ☐ superior	☐ none ☐ marginal ☐ average ☐ superior
Documentation Quality:	☐ marginal ☐ average ☐ superior	☐ marginal ☐ average ☐ superior	☐ marginal ☐ average ☐ superior
Rationality:	☐ marginal ☐ average ☐ superior ☐ N/A	☐ marginal ☐ average ☐ superior ☐ N/A	☐ marginal ☐ average ☐ superior ☐ N/A

Extrapolation(7)							
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**	**θ**	**β**	**θ**	**β**
Good							
Fair							
Poor							
Average or unknown							
Explain basis for extrapolation. What factors affect θ and β?							

(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

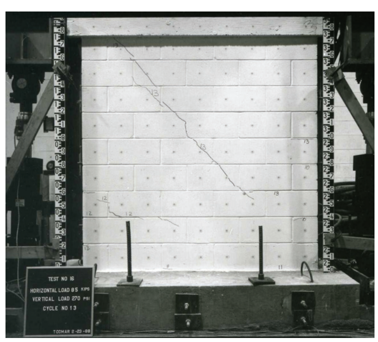
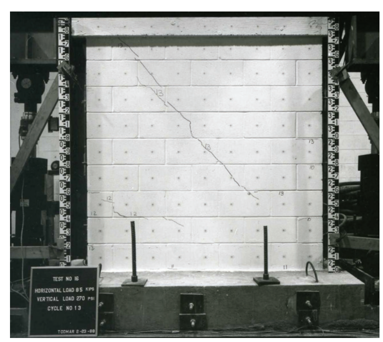
RM Wall Panel (flexurally controlled)—B1051									
Consequence Functions	**DS1**			**DS2**			**DS3**		
Repair Description:	• Cosmetic repair			• Grout wall cavities • Grout injection to repair cracks • Remove loose masonry • Patch spalls with NS grout • Paint each side			• Shore • Demo existing wall • Replace		
Repair Costs:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:									
Min. consequence over upper quantity:									
Assumed distribution:	☐ normal ☐ lognormal			☐ normal ☐ lognormal			☐ normal ☐ lognormal		
Repair Time:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:									
Min. consequence over upper quantity:									
Assumed distribution:	☐ normal ☐ lognormal			☐ normal ☐ lognormal			☐ normal ☐ lognormal		
LifeSafety Hazard:	☐ yes ☐ no			☐ yes ☐ no			☐ yes ☐ no		
Casualty-affected Planar Area (sf) per Normative Unit:									
Casualty Rate in Affected Planar Area:									
Post-event Tagging Flag:									
Total Damage Quantity (red tag trigger):									
Comments:									

Fragility Specification

RM Wall Panel (shear controlled)—B1051

Developer and Date:	Juan Murcia-Delso and P. Benson Shing, November, 2009
NISTIR Classification:	B1051.RM-1a
Description (Basic Composition):	Reinforced Masonry Bearing Walls
Construction Quality: (1)	Good
Seismic Installation Conditions:	
Normative Quantity (unit):	1
Demand Parameter:	Story-Drift Ratio
Number of Damage States:	2

Type of Damage States:	X	ordered		mutually exclusive		simultaneous

Damage States	**DS4**	**DS5**
Description:	• First occurrence of major diagonal cracks • Cracks remain closed after load removal • Repairable	• Wide diagonal cracks with typically one or two cracks in each direction • Crushing or spalling at wall toes • Not repairable
Illustrations:		
Probability: (2)		

(1) If possible, describe in terms of relevant code or standard.

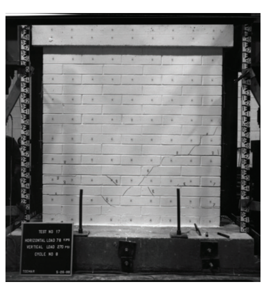
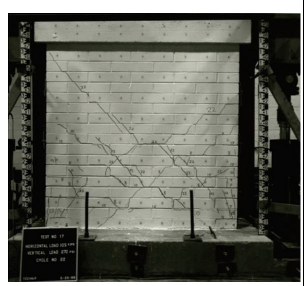
(2) For ordered damage states, leave "Probability" blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in "Probability." For simultaneous damage states, ensure that the probabilities add to at least 1.0.

RM Wall Panel (shear controlled)—B1051					
Fragility Parameters		**DS4**		**DS5**	
Median Demand, θ: (3)		0.20%		0.33%	
Data dispersion, β_d: (4)		-		0.74	
Uncertainty, β_u: (5)		-		0.25	
Total Dispersion, β: (6)		0.85		0.75	
Correlation:					
Quality Ratings					
Data Quality:		none		none	
		marginal		marginal	
		average		average	
		superior		superior	
Data Relevance:		none		none	
		marginal		marginal	
		average		average	
		superior		superior	
Documentation Quality:		marginal		marginal	
		average		average	
		superior		superior	
Rationality:		marginal		marginal	
		average		average	
		superior		superior	
		N/A		N/A	
Extrapolation(7)					
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**	**θ**	**β**
Good					
Fair					
Poor					
Average or unknown					
Explain basis for extrapolation. What factors affect θ and β?					

(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

RM Wall Panel (shear controlled)—B1051						
Consequence Functions	**DS4**			**DS5**		
Repair Description:	• Grout wall cavities • Grout injection to repair cracks • Paint each side			• Shore • Demo existing wall • Replace		
Repair Costs:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:						
Min. consequence over upper quantity:						
Assumed distribution:	☐ normal ☐ lognormal			☐ normal ☐ lognormal		
Repair Time:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:						
Min. consequence over upper quantity:						
Assumed distribution:	☐ normal ☐ lognormal			☐ normal ☐ lognormal		
LifeSafety Hazard:	☐ yes ☐ no			☐ yes ☐ no		
Casualty-affected Planar Area (sf) per Normative Unit:						
Casualty Rate in Affected Planar Area:						
Post-event Tagging Flag:						
Total Damage Quantity (red tag trigger):						
Comments:						

APPENDIX H. FRAGILITY SPECIFICATION (CLASS B) FOR FULLY-GROUTED WALLS

Fragility Specification RM Wall Panel (flexurally controlled)—B1051			
Developer and Date:	Juan Murcia-Delso and P. Benson Shing, November, 2009		
NISTIR Classification:	B1051.RM-3a		
Description (Basic Composition):	Reinforced Masonry Bearing Walls		
Construction Quality: (1)	Good		
Seismic Installation Conditions:			
Normative Quantity (unit):	1		
Demand Parameter:	Normalized Flexural Deformation (NFD)		
Number of Damage States:	3		
Type of Damage States:	X ordered	mutually exclusive	simultaneous
Damage States	**DS1**	**DS2**	**DS3**
Description:	• A few flexural and shear cracks with hardly noticeable residual crack width • Slight yielding of extreme vertical reinforcement • No spalling • No fracture or buckling of reinforcement • Not structurally significant	• Numerous flexural and shear cracks • Mild toe crushing with vertical cracks or light spalling at wall toes • No fracture or buckling of reinforcement • Small residual deformation • Repairable	• Severe flexural cracks • Significant toe crushing and spalling • Fracture or buckling of some reinforcement • Significant residual deformation • Not repairable
Illustrations:			
Probability: (2)			

(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave "Probability" blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in "Probability." For simultaneous damage states, ensure that the probabilities add to at least 1.0.

RM Wall Panel (flexurally controlled)—B1051			
Fragility Parameters	**DS1**	**DS2**	**DS3**
Median Demand, θ: (3)	0.39	1.14	2.16
Data dispersion, β_d: (4)	0.64	0.50	0.37
Uncertainty, β_u: (5)	0.10	0.10	0.10
Total Dispersion, β: (6)	0.65	0.50	0.40
Correlation:			

Quality Ratings	DS1		DS2		DS3	
Data Quality:		none		none		none
		marginal		marginal		marginal
		average		average		average
		superior		superior		superior
Data Relevance:		none		none		none
		marginal		marginal		marginal
		average		average		average
		superior		superior		superior
Documentation Quality:		marginal		marginal		marginal
		average		average		average
		superior		superior		superior
Rationality:		marginal		marginal		marginal
		average		average		average
		superior		superior		superior
		N/A		N/A		N/A

Extrapolation(7)		DS1		DS2		DS3	
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**	**θ**	**β**	**θ**	**β**
Good							
Fair							
Poor							
Average or unknown							
Explain basis for extrapolation. What factors affect θ and β?							

(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

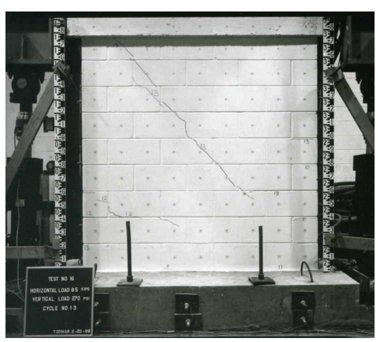
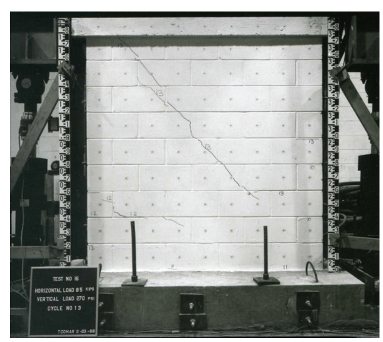
RM Wall Panel (flexurally controlled)—B1051									
Consequence Functions	**DS1**			**DS2**			**DS3**		
Repair Description:	• Cosmetic repair			• Epoxy injection to repair cracks • Remove loose masonry • Patch spalls with NS grout • Paint each side			• Shore • Demo existing wall • Replace		
Repair Costs:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:									
Min. consequence over upper quantity:									
Assumed distribution:	normal			normal			normal		
	lognormal			lognormal			lognormal		
Repair Time:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:									
Min. consequence over upper quantity:									
Assumed distribution:	normal			normal			normal		
	lognormal			lognormal			lognormal		
LifeSafety Hazard:	yes			yes			yes		
	no			no			no		
Casualty-affected Planar Area (sf) per Normative Unit:									
Casualty Rate in Affected Planar Area:									
Post-event Tagging Flag:									
Total Damage Quantity (red tag trigger):									
Comments:									

Fragility Specification

RM Wall Panel (shear controlled)—B1051

Developer and Date:	Juan Murcia-Delso and P. Benson Shing, November, 2009
NISTIR Classification:	B1051.RM-1b
Description (Basic Composition):	Reinforced Masonry Bearing Walls
Construction Quality: (1)	Good
Seismic Installation Conditions:	
Normative Quantity (unit):	1
Demand Parameter:	Normalized Diagonal Shear Demand (NDSD)
Number of Damage States:	2

Type of Damage States:	X	ordered		mutually exclusive		simultaneous

Damage States	**DS4**	**DS5**
Description:	• First occurrence of major diagonal cracks • Cracks remain closed after load removal • Repairable	• Wide diagonal cracks with typically one or two cracks in each direction • Crushing or spalling at wall toes • Not repairable
Illustrations:		
Probability: (2)		

(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave “Probability” blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in “Probability.” For simultaneous damage states, ensure that the probabilities add to at least 1.0.

RM Wall Panel (shear controlled)—B1051					
Fragility Parameters		**DS4**		**DS5**	
Median Demand, θ: (3)		0.86		1.05	
Data dispersion, β_d: (4)		0.22		0.21	
Uncertainty, β_u: (5)		0.10		0.10	
Total Dispersion, β: (6)		0.25		0.25	
Correlation:					
Quality Ratings					
Data Quality:		none		none	
		marginal		marginal	
		average		average	
		superior		superior	
Data Relevance:		none		none	
		marginal		marginal	
		average		average	
		superior		superior	
Documentation Quality:		marginal		marginal	
		average		average	
		superior		superior	
Rationality:		marginal		marginal	
		average		average	
		superior		superior	
		N/A		N/A	
Extrapolation(7)					
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**	**θ**	**β**
Good					
Fair					
Poor					
Average or unknown					
Explain basis for extrapolation. What factors affect θ and β?					

(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

RM Wall Panel (shear controlled)—B1051						
Consequence Functions	**DS4**			**DS5**		
Repair Description:	• Epoxy injection to repair cracks • Paint each side			• Shore • Demo existing wall • Replace		
Repair Costs:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:						
Min. consequence over upper quantity:						
Assumed distribution:	normal			normal		
	lognormal			lognormal		
Repair Time:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:						
Min. consequence over upper quantity:						
Assumed distribution:	normal			normal		
	lognormal			lognormal		
LifeSafety Hazard:	yes			yes		
	no			no		
Casualty-affected Planar Area (sf) per Normative Unit:						
Casualty Rate in Affected Planar Area:						
Post-event Tagging Flag:						
Total Damage Quantity (red tag trigger):						
Comments:						

Fragility Specification RM Wall Panel (sliding)—B1051						
Developer and Date:	Juan Murcia-Delso and P. Benson Shing, November, 2009					
NISTIR Classification:	B1051.RM-1b					
Description (Basic Composition):	Reinforced Masonry Bearing Walls					
Construction Quality: (1)	Good					
Seismic Installation Conditions:						
Normative Quantity (unit):	1					
Demand Parameter:	Normalized Sliding Shear Demand (NSSD)					
Number of Damage States:	1					
Type of Damage States:	X	ordered		mutually exclusive		simultaneous
Damage States	**DS6**					
Description:	• Large permanent wall offset • Spalling and crushing at the base • Severe bending or shear fracture of vertical reinforcement or dowels at the base • Not repairable					
Illustrations:						
Probability: (2)						

(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave “Probability” blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in “Probability.” For simultaneous damage states, ensure that the probabilities add to at least 1.0.

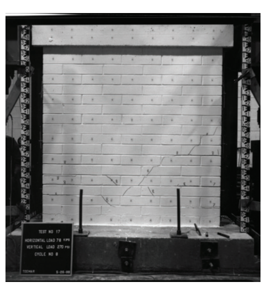
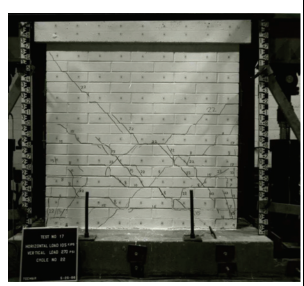
RM Wall Panel (sliding)—B1051			
Fragility Parameters		**DS6**	
Median Demand, θ: (3)		0.92	
Data dispersion, β_d: (4)		-	
Uncertainty, β_u: (5)		-	
Total Dispersion, β: (6)		0.40	
Correlation:			
Quality Ratings			
Data Quality:		none marginal average superior	
Data Relevance:		none marginal average superior	
Documentation Quality:		marginal average superior	
Rationality:		marginal average superior N/A	
Extrapolation(7)			
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**
Good			
Fair			
Poor			
Average or unknown			
Explain basis for extrapolation. What factors affect θ and β?			

(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

RM Wall Panel (sliding)—B1051			
Consequence Functions	**DS6**		
Repair Description:	• Shore • Demo existing wall • Replace		
Repair Costs:	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:			
Min. consequence over upper quantity:			
Assumed distribution:	normal		
	lognormal		
Repair Time:	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:			
Min. consequence over upper quantity:			
Assumed distribution:	normal		
	lognormal		
LifeSafety Hazard:	yes		
	no		
Casualty-affected Planar Area (sf) per Normative Unit:			
Casualty Rate in Affected Planar Area:			
Post-event Tagging Flag:			
Total Damage Quantity (red tag trigger):			
Comments:			

APPENDIX I. FRAGILITY SPECIFICATION (CLASS B) FOR PARTIALLY-GROUTED

Fragility Specification RM Wall Panel (flexurally controlled)—B1051						
Developer and Date:	Juan Murcia-Delso and P. Benson Shing, November, 2009					
NISTIR Classification:	B1051.RM-2a					
Description (Basic Composition):	Reinforced Masonry Bearing Walls					
Construction Quality: (1)	Good					
Seismic Installation Conditions:						
Normative Quantity (unit):	1					
Demand Parameter:	Story-Drift Ratio					
Number of Damage States:	3					
Type of Damage States:	X	ordered		mutually exclusive		simultaneous

Damage States	**DS1**	**DS2**	**DS3**
Description:	• A few flexural and shear cracks with hardly noticeable residual crack width • Slight yielding of extreme vertical reinforcement • No spalling • No fracture or buckling of reinforcement • Not structurally significant	• Numerous flexural and shear cracks • Mild toe crushing with vertical cracks or light spalling at wall toes • No fracture or buckling of reinforcement • Small residual deformation • Repairable	• Severe flexural cracks • Significant toe crushing and spalling • Fracture or buckling of some reinforcement • Significant residual deformation • Not repairable
Illustrations:			
Probability: (2)			

(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave "Probability" blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in "Probability." For simultaneous damage states, ensure that the probabilities add to at least 1.0.

RM Wall Panel (flexurally controlled)—B1051			
Fragility Parameters	**DS1**	**DS2**	**DS3**
Median Demand, θ: (3)	0.35	1.00	1.90
Data dispersion, β_d: (4)	-	-	-
Uncertainty, β_u: (5)	-	-	-
Total Dispersion, β: (6)	0.70	0.55	0.45
Correlation:			

Quality Ratings		DS1		DS2		DS3
Data Quality:		none		none		none
		marginal		marginal		marginal
		average		average		average
		superior		superior		superior
Data Relevance:		none		none		none
		marginal		marginal		marginal
		average		average		average
		superior		superior		superior
Documentation Quality:		marginal		marginal		marginal
		average		average		average
		superior		superior		superior
Rationality:		marginal		marginal		marginal
		average		average		average
		superior		superior		superior
		N/A		N/A		N/A

Extrapolation(7)		DS1		DS2		DS3	
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**	**θ**	**β**	**θ**	**β**
Good							
Fair							
Poor							
Average or unknown							
Explain basis for extrapolation. What factors affect θ and β?							

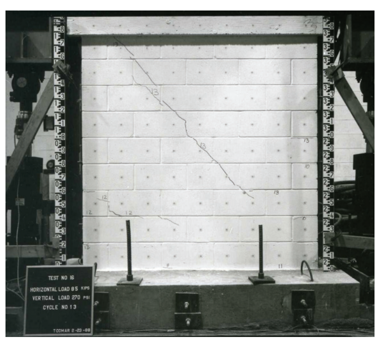
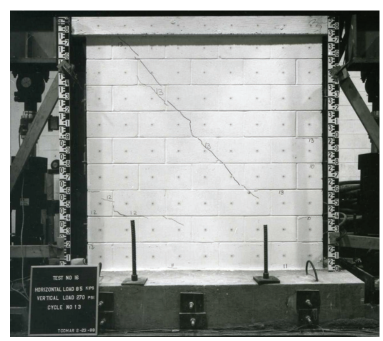
(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

RM Wall Panel (flexurally controlled)—B1051									
Consequence Functions	**DS1**			**DS2**			**DS3**		
Repair Description:	• Cosmetic repair			• Grout wall cavities • Grout injection to repair cracks • Remove loose masonry • Patch spalls with NS grout • Paint each side			• Shore • Demo existing wall • Replace		
Repair Costs:	P_{10}	P_{50}	P_{90}	P_{10}	P_{50}	P_{90}	P_{10}	P_{50}	P_{90}
Max. consequence up to lower quantity:									
Min. consequence over upper quantity:									
Assumed distribution:	normal			normal			normal		
	lognormal			lognormal			lognormal		
Repair Time:	P_{10}	P_{50}	P_{90}	P_{10}	P_{50}	P_{90}	P_{10}	P_{50}	P_{90}
Max. consequence up to lower quantity:									
Min. consequence over upper quantity:									
Assumed distribution:	normal			normal			normal		
	lognormal			lognormal			lognormal		
LifeSafety Hazard:	yes			yes			yes		
	no			no			no		
Casualty-affected Planar Area (sf) per Normative Unit:									
Casualty Rate in Affected Planar Area:									
Post-event Tagging Flag:									
Total Damage Quantity (red tag trigger):									
Comments:									

Fragility Specification

RM Wall Panel (shear controlled)—B1051

Developer and Date:	Juan Murcia-Delso and P. Benson Shing, November, 2009
NISTIR Classification:	B1051.RM-1a
Description (Basic Composition):	Reinforced Masonry Bearing Walls
Construction Quality: (1)	Good
Seismic Installation Conditions:	
Normative Quantity (unit):	1
Demand Parameter:	Normalized Diagonal Shear Demand (NDSD)
Number of Damage States:	2
Type of Damage States:	X ordered; ☐ mutually exclusive; ☐ simultaneous

Damage States	**DS4**	**DS5**
Description:	• First occurrence of major diagonal cracks • Cracks remain closed after load removal • Repairable	• Wide diagonal cracks with typically one or two cracks in each direction • Crushing or spalling at wall toes • Not repairable
Illustrations:		
Probability: (2)		

(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave "Probability" blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in "Probability." For simultaneous damage states, ensure that the probabilities add to at least 1.0.

<table>
<tr><th colspan="5">RM Wall Panel (shear controlled)—B1051</th></tr>
<tr><td colspan="1">Fragility Parameters</td><td colspan="2">DS4</td><td colspan="2">DS5</td></tr>
<tr><td>Median Demand, θ: (3)</td><td colspan="2">0.75</td><td colspan="2">0.92</td></tr>
<tr><td>Data dispersion, β_d: (4)</td><td colspan="2">-</td><td colspan="2">0.32</td></tr>
<tr><td>Uncertainty, β_u: (5)</td><td colspan="2">-</td><td colspan="2">0.10</td></tr>
<tr><td>Total Dispersion, β: (6)</td><td colspan="2">0.30</td><td colspan="2">0.30</td></tr>
<tr><td>Correlation:</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Quality Ratings</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td rowspan="4">Data Quality:</td><td></td><td>none</td><td></td><td>none</td></tr>
<tr><td></td><td>marginal</td><td></td><td>marginal</td></tr>
<tr><td></td><td>average</td><td></td><td>average</td></tr>
<tr><td></td><td>superior</td><td></td><td>superior</td></tr>
<tr><td rowspan="4">Data Relevance:</td><td></td><td>none</td><td></td><td>none</td></tr>
<tr><td></td><td>marginal</td><td></td><td>marginal</td></tr>
<tr><td></td><td>average</td><td></td><td>average</td></tr>
<tr><td></td><td>superior</td><td></td><td>superior</td></tr>
<tr><td rowspan="3">Documentation Quality:</td><td></td><td>marginal</td><td></td><td>marginal</td></tr>
<tr><td></td><td>average</td><td></td><td>average</td></tr>
<tr><td></td><td>superior</td><td></td><td>superior</td></tr>
<tr><td rowspan="4">Rationality:</td><td></td><td>marginal</td><td></td><td>marginal</td></tr>
<tr><td></td><td>average</td><td></td><td>average</td></tr>
<tr><td></td><td>superior</td><td></td><td>superior</td></tr>
<tr><td></td><td>N/A</td><td></td><td>N/A</td></tr>
</table>

<table>
<tr><th colspan="2">Extrapolation (7)</th><th colspan="2"></th><th colspan="2"></th></tr>
<tr><td>Seismic Installation Condition</td><td>Included in data? (Y/N)</td><td>θ</td><td>β</td><td>θ</td><td>β</td></tr>
<tr><td>Good</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Fair</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Poor</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average or unknown</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Explain basis for extrapolation. What factors affect θ and β?</td><td colspan="4"></td></tr>
</table>

(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

RM Wall Panel (shear controlled)—B1051						
Consequence Functions	**DS4**			**DS5**		
Repair Description:	• Grout wall cavities • Grout injection to repair cracks • Paint each side			• Shore • Demo existing wall • Replace		
Repair Costs:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:						
Min. consequence over upper quantity:						
Assumed distribution:	normal			normal		
	lognormal			lognormal		
Repair Time:	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Max. consequence up to lower quantity:						
Min. consequence over upper quantity:						
Assumed distribution:	normal			normal		
	lognormal			lognormal		
LifeSafety Hazard:	yes			yes		
	no			no		
Casualty-affected Planar Area (sf) per Normative Unit:						
Casualty Rate in Affected Planar Area:						
Post-event Tagging Flag:						
Total Damage Quantity (red tag trigger):						
Comments:						

Fragility Specification RM Wall Panel (sliding)—B1051						
Developer and Date:	Juan Murcia-Delso and P. Benson Shing, November, 2009					
NISTIR Classification:	B1051.RM-1a					
Description (Basic Composition):	Reinforced Masonry Bearing Walls					
Construction Quality: (1)	Good					
Seismic Installation Conditions:						
Normative Quantity (unit):	1					
Demand Parameter:	Normalized Sliding Shear Demand (NSSD)					
Number of Damage States:	1					
Type of Damage States:	X	ordered		mutually exclusive		simultaneous
Damage States	**DS6**					
Description:	• Large permanent wall offset • Spalling and crushing at the base • Severe bending or shear fracture of vertical reinforcement or dowels at the base • Not repairable					
Illustrations:						
Probability: (2)						

(1) If possible, describe in terms of relevant code or standard.
(2) For ordered damage states, leave "Probability" blank and provide fragility parameters for each damage state. For mutually exclusive or simultaneous damage states, provide fragility parameters in DS1 column only, and state probabilities of each damage state in "Probability." For simultaneous damage states, ensure that the probabilities add to at least 1.0.

RM Wall Panel (sliding)—B1051			
Fragility Parameters		**DS6**	
Median Demand, θ: (3)		0.81	
Data dispersion, β_d: (4)		-	
Uncertainty, β_u: (5)		-	
Total Dispersion, β: (6)		0.45	
Correlation:			
Quality Ratings			
Data Quality:		none	
		marginal	
		average	
		superior	
Data Relevance:		none	
		marginal	
		average	
		superior	
Documentation Quality:		marginal	
		average	
		superior	
Rationality:		marginal	
		average	
		superior	
		N/A	
Extrapolation(7)			
Seismic Installation Condition	**Included in data? (Y/N)**	**θ**	**β**
Good			
Fair			
Poor			
Average or unknown			
Explain basis for extrapolation. What factors affect θ and β?			

(3) Round *θ* to 2 significant figures and *β* to nearest 0.05.
(4) β_d – random variability observed in test data, if available
(5) β_u – uncertainty that tests represent actual conditions of installation and loading
(6) β – SRSS combination of β_d and β_u when test data are available, or total estimated uncertainty when data are not available
(7) Identify the seismic installation conditions represented by the data set, and extrapolate fragility parameters θ and β for other seismic installation conditions.

<table>
<tr><th colspan="4">RM Wall Panel (sliding)—B1051</th></tr>
<tr><td>Consequence Functions</td><td colspan="3">DS6</td></tr>
<tr><td>Repair Description:</td><td colspan="3">Shore
Demo existing wall
Replace</td></tr>
<tr><td>Repair Costs:</td><td>P_{10}</td><td>P_{50}</td><td>P_{90}</td></tr>
<tr><td>Max. consequence up to lower quantity:</td><td></td><td></td><td></td></tr>
<tr><td>Min. consequence over upper quantity:</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Assumed distribution:</td><td colspan="3">☐ normal</td></tr>
<tr><td colspan="3">☐ lognormal</td></tr>
<tr><td>Repair Time:</td><td>P_{10}</td><td>P_{50}</td><td>P_{90}</td></tr>
<tr><td>Max. consequence up to lower quantity:</td><td></td><td></td><td></td></tr>
<tr><td>Min. consequence over upper quantity:</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Assumed distribution:</td><td colspan="3">☐ normal</td></tr>
<tr><td colspan="3">☐ lognormal</td></tr>
<tr><td rowspan="2">LifeSafety Hazard:</td><td colspan="3">☐ yes</td></tr>
<tr><td colspan="3">☐ no</td></tr>
<tr><td>Casualty-affected Planar Area (sf) per Normative Unit:</td><td></td><td colspan="2"></td></tr>
<tr><td>Casualty Rate in Affected Planar Area:</td><td></td><td colspan="2"></td></tr>
<tr><td>Post-event Tagging Flag:</td><td></td><td colspan="2"></td></tr>
<tr><td>Total Damage Quantity (red tag trigger):</td><td></td><td colspan="2"></td></tr>
<tr><td>Comments:</td><td></td><td colspan="2"></td></tr>
</table>