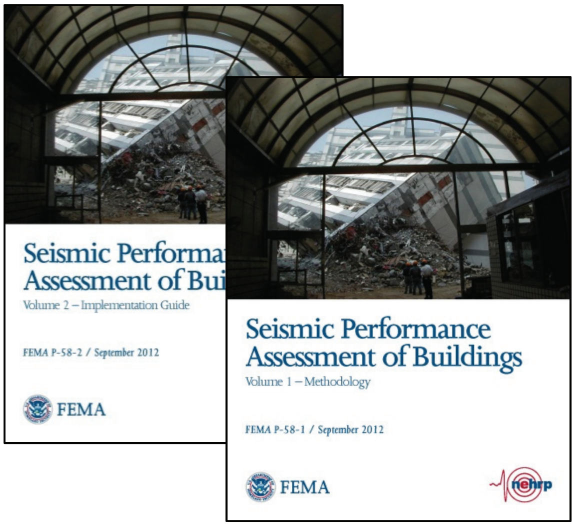

Background Document

FEMA P-58/BD-3.9.6

Seismic Fragility of Standard Building Stairs

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March 11, 2011

FEMA

Background Documentation

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

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

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contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology.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

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*.

SEISMIC FRAGILITY OF STANDARD BUILDING STAIRS

prepared for ATC 58 by
Christopher Higgins, Ph.D.

Introduction

The objective of this document is to summarize the development of fragility functions for standard building stairs commonly specified by architects. These stair systems include: steel stair assemblies with steel tread, steel stair assemblies with concrete infill steel pans, precast concrete stairs, cast-in-place concrete stairs, and hybrid combinations of these types.

Stairs serve as a primary means of egress from buildings after an earthquake and thus their role in achieving life-safety performance for a building system is critical. Many different types of stair systems are specified by architects. These include steel, concrete, and hybrid systems. Some general terminology is required to describe the various stair components discussed in this document. The salient stair components are shown in Fig. 1a. As seen here, common stair systems include lower, intermediate, and upper landings connected by flights of stairs. Stairs are generally considered to span as simple or continuous beams while others are built integral with a core wall area whereby the stair runs are continuously edge supported (commonly cast-in-place concrete), suspended between floors and landings (vertical support provided at intermediate landing), or span directly between floors (vertical support at top and bottom landing only). Many stairways are placed in stair shafts and connected only at the top and bottom landing locations to the structural concrete floor slab. Standard stair geometries considered in this document are shown in Fig. 1b.

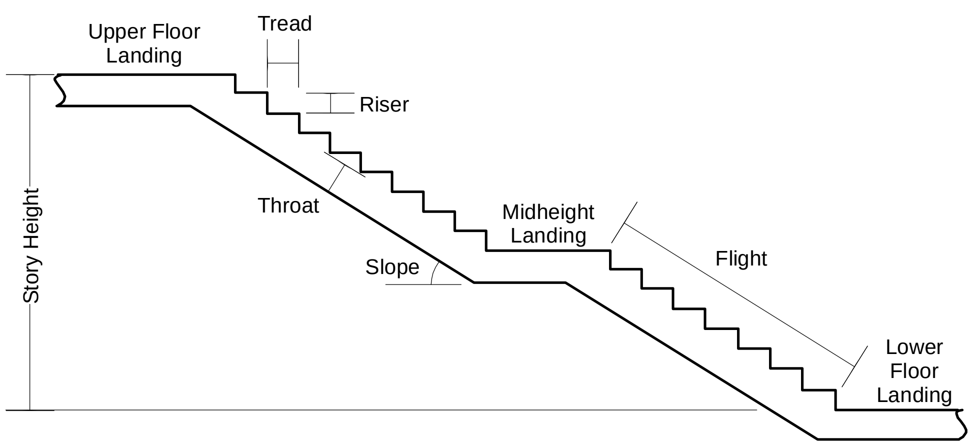


Fig. 1a – Common stair components.

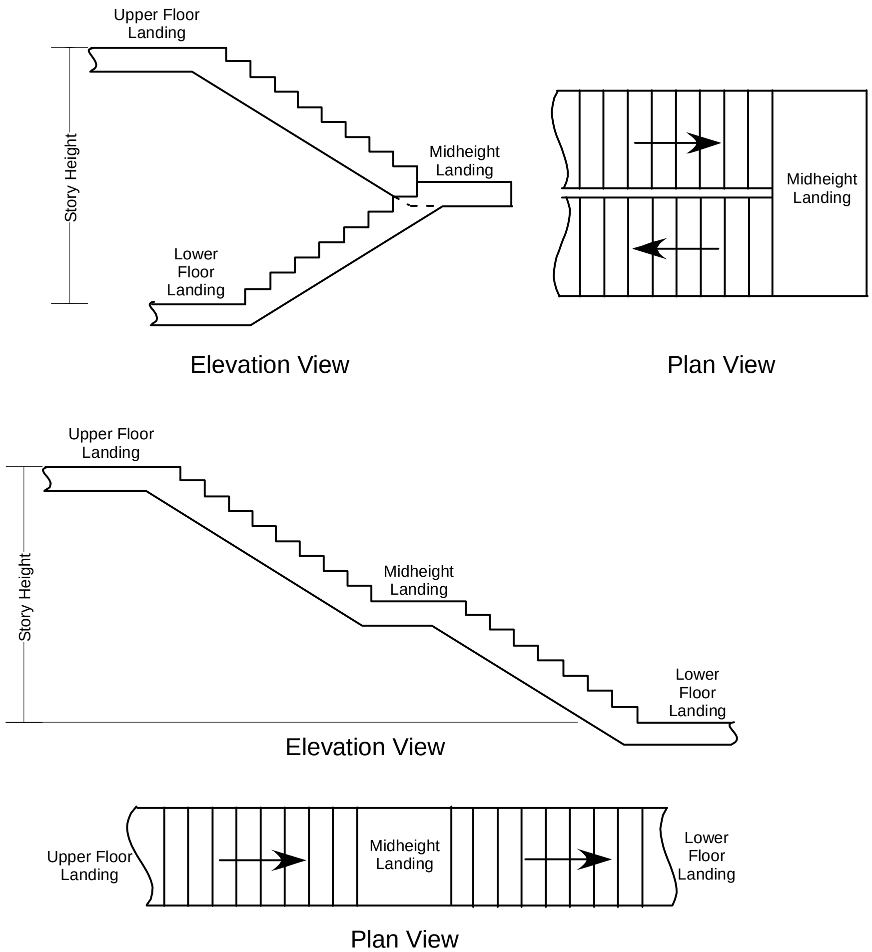


Fig 1b – Common stair geometries.

Stair systems must satisfy prescribed functional (e.g. rise/run, slip resistance, markings, railing) and structural requirements (e.g. strength, serviceability). Depending on the selected materials, structural designs are commonly performed according to either the American Institute of Steel Construction (AISC) provisions or American Concrete Institute (ACI) requirements (AISC, 2003; ACI 2008) for consideration of limit states, load combinations, and proportioning stair elements, connections, and detailing. For concrete stairs, the throat of the flight is typically designed to carry loads as a simple supported or continuous beam between landings. For most stairs, the treads transfer loads to the stringers which are designed as simply supported spans between landings. Different stair systems interact with the landings in different ways. Precast concrete and prefabricated steel stairs typically have only vertical support at landings while cast-in-place stairs may have moment transfer (continuity effects) at the landing locations. For hybrid steel-concrete and some precast concrete stairs, individual treads are commonly used. The stair treads on some prefabricated steel and concrete stairs are continuous with each other and form a diaphragm between the supporting stringers to resist lateral loading.

During earthquake induced motions, stairs are compliant with the structural drifts of the building and are thus subjected to relative motions between the upper and lower landing.

These relative motions can be transverse- or parallel-to-stair-run, as illustrated in Fig. 2, or combinations of these directions. Stairs must accommodate the imposed building interstory drift demands as well as any induced dynamic response of the stair assemblies themselves. Stairs are considered as architectural components for determining lateral design forces and deformability within the NEHRP Provisions (BSSC 2001a; BSSC 2001b; BSSC 2004a; BSSC 2004b). Stairs were formerly listed in the 2000 *Provisions*, but are now classified within the category of “Other Components” in Chapter 6 of the 2003 *Provisions*. As such an architectural component, stairs are to be designed for both strength and flexibility, however little commentary is provided to aid designers in the treatment of stairs.

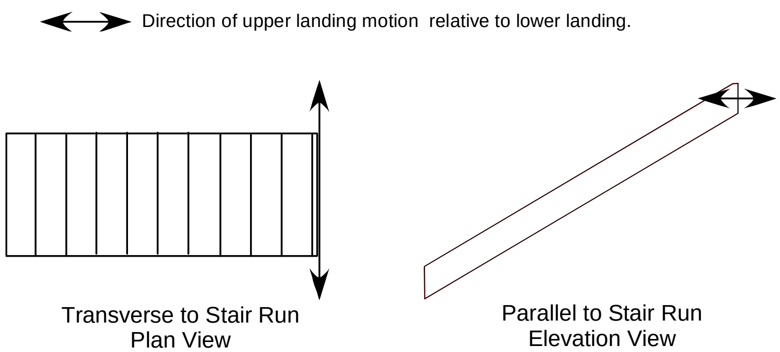


Fig. 2 – Definitions of relative motions induced at stair landings.

Some stair systems are designed and detailed with seismic separation gaps at the ends of the stair runs to preclude them from loads induced by interstory drift. Proper sizing and maintenance of seismic gaps is needed to ensure this performance. In cases where the stairs are rigidly connected to the upper and lower landings, the stairs can act as an inclined brace and large lateral forces can be produced.

Because stairs are often placed within stair shafts, the shafts must be able to accommodate earthquake induced stair deformations without becoming intermediate points of contact. Interaction of the stairs with the shaft walls can induce unintended loads into the stair system and walls. Damage to the shaft walls, produced either autogenously or by stair-shaft wall interaction during an earthquake may result in debris that can block or hinder stairway access as seen in Fig. 3.

Fig. 3 - Stairway in the Banco Central Building, Managua, Nicaragua (1972 Managua Earthquake). Debris on stairs from the failure of the hollow tile partitions surrounding the stairs (Photo from PEER Godden Collection, No. J94).

Background

Relatively little information is available in the literature on stair performance under seismic loading conditions. Field experience during past earthquakes has indicated some performance issues for different stair assemblies. Post-earthquake reconnaissance has documented damage at the treads, landings, and to stair shafts (Simmons 2000).

Very few laboratory studies of stair systems have been performed internationally. Only three systems have available test data: prefabricated steel (United States), precast concrete (New Zealand), and hybrid concrete-steel stairs (Japan). The available test data have been collected from isolated stair assemblies under pseudo-static loading conditions. The tests have been performed considering simulated seismic interstory drift deformations applied parallel to the stair run (prefabricated steel and precast concrete) and transverse to stair run (prefabricated steel and hybrid). No test data are available for deformations involving combined parallel and transverse orientations applied simultaneously.

Developments of a hybrid stair system including seismic performance aspects are reported in Japanese by Seki et al. (1999), Tada et al. (1999), Toyonaga et al. (1999), Hukazawa et al. (1999); Osamu et al. (2000), Mitsunobu et al. (2000), Tada et al.

(2001), Yanagisawa et al. (2001), Asakura et al. (2001), Fukazawa et al. (2001), Hanano et al. (2001), and Mochizuki et al. (2001). The hybrid stair system used steel stringers to support individual precast concrete stair treads. Each precast concrete stair tread was L-shaped and join to the stringer with fasteners that were anchored into inserts located within the tread. A number of different tests were conducted on the stair system including gravity load tests and lateral load tests. Lateral load tests reported by Yanagisawa et al. (2001) were conducted using a specimen consisting of a single flight of stairs as seen in Fig. 4a. Two different stairway widths were investigated: 1200 mm (47 in.) and 900 mm (35.5 in.) wide stair runs. The stair rise was 1.45 m and the span was 2.14 m (slope = 34.1 degrees, pitch = rise/run = 0.678). The assemblies consisted of seven individual treads. Stair assemblies were held at the upper landing and reversed cyclic lateral deformations were imposed at the lower landing. Deformations were applied transverse-to-stair-run. Two complete cycles were completed for each prescribed drift. The imposed drift angles were: 0.003, 0.0074, 0.0148, 0.0224, 0.0295, 0.0492, and 0.0738 rad. as shown in Fig. 4b. Note the originally reported drift angles were for bottom landing deformation relative to the stair run dimension. These drift angles were converted to upper story drift relative to the story height to be consistent with reported results from other tests. Cracking and localized crushing due to bending and debonding was observed in the treads at 0.0148 drift angle for both specimens. At drift angles of 0.0295 rad. substantial crushing was observed on the stair treads and the overall response showed stiffness degradation. Maximum loads were achieved at drifts of approximately 0.065 for the 1200 mm (47 in.) wide specimen and 0.060 for the 900 mm wide specimen. No data were provided on the live load capacity of the stair systems after lateral load tests. The different stairway widths had similar failure modes.

Hukazawa et al. (1999) reported lateral load tests of a single specimen consisting of two stair flights with upper, lower, and intermediate landings as shown in Fig. 4c. The intermediate landing represented the landing connection to the building floor slab. The upper and lower landings were subjected to lateral deformations oriented transverse to stair run. A cyclic loading protocol was used that did not apply reversals as seen in Fig. 4d. Only two cycles were applied at the target amplitudes. The specified target amplitudes were based on the dead weight of the stair segment and testing was performed in load control until maximum strength was achieved. After this point, displacement control was used. The reported findings of these tests were similar those of the individual stair flights reported by Yanagisawa et al. (1999). Initial cracking and local crushing of the treads were observed at drifts similar to those reported previously (0.0148 rad.). Significant crushing of the treads and corresponding change in overall stiffness was observed at drift angles of 0.0248 and 0.0234 for the upper and lower flights, respectively. Maximum loads were obtained at drift angles of 0.0507 for the lower flight and 0.0517 for the upper flight.

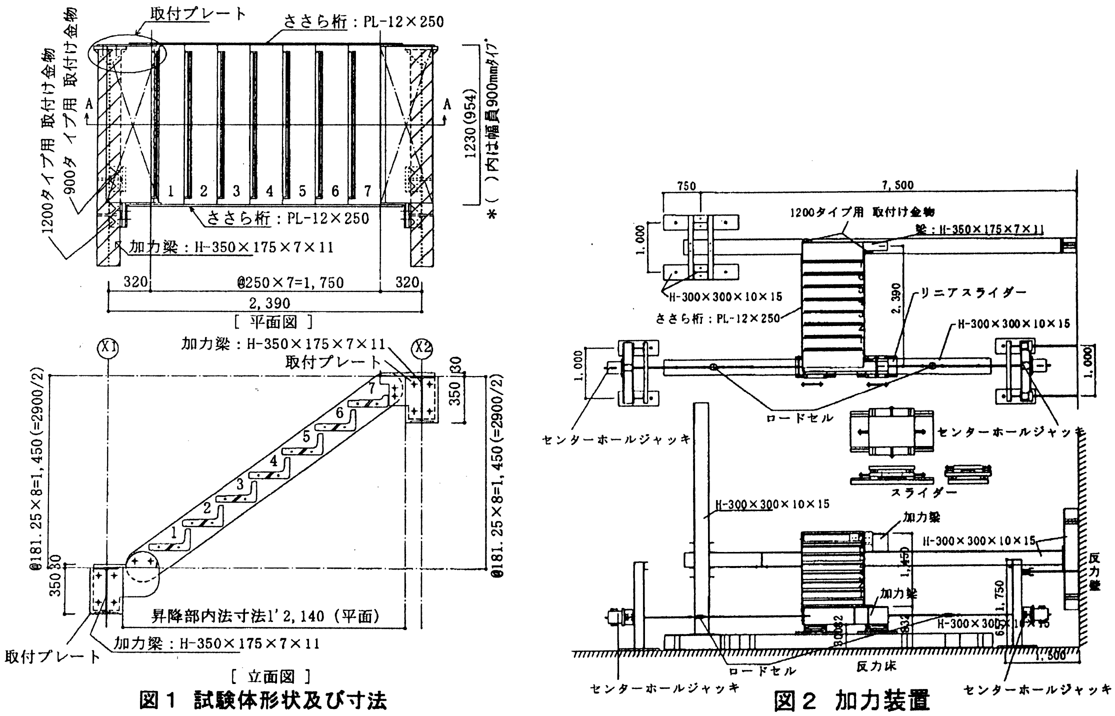


Fig. 4a – Hybrid (steel and concrete) stair single flight tests (Yanagisawa et al. 1999).

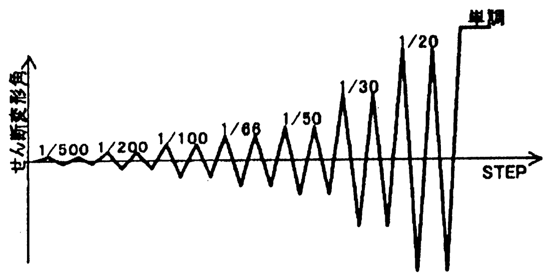


Fig. 4b - Typical hybrid stair test loading protocol for single flight tests (Yanagisawa et al. 1999)

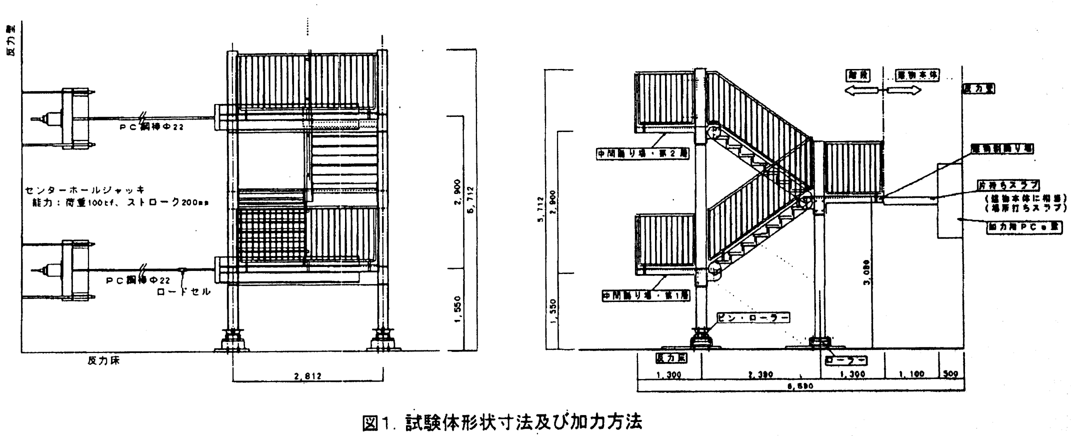


Fig. 4c – Hybrid (steel and concrete) stair system test specimen (Toyonaga et al. 1999).

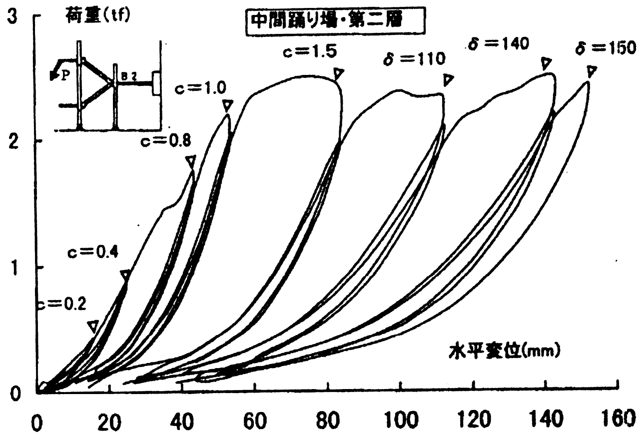


Fig. 4d - Hybrid (steel and concrete) stair load-deformation response for system tests.

Precast reinforced concrete stairs were tested by Simmons (2000) in New Zealand. The tests were intended to characterize performance of the stairs if the seismic gap failed and the bottom landing was prevented from sliding as intended. The laboratory specimens were full size representations of typical designs but were only half of the stair width. The specimens consisted to two stair flights and an intermediate landing as shown in Fig. 5a. The stairs were straight-run with an intermediate landing located midway between the upper and lower flights. The slope of the stairs was 32.5 degrees (pitch = rise/run =0.64). The landing width was 1170 mm (3 ft 10 in.) and the story height was 3.14 m (10 ft 3.8 in.).The bottom landing was pinned to simulate failure of the seismic gap and lateral displacements were applied at the top landing in the parallel-to-stair-run direction. Rollers were used at the top landing to constrain the top landing displacements. Three stair specimens were tested. Each had similar overall geometry (span, slope, landings, etc.) but had different reinforcing or throat dimensions. The specimens were subjected to cyclic compression loading followed by unloading and then application of relatively small tensile reversals as seen in Fig. 5b. Only single cycles were applied at each load step. A maximum drift of approximately 2% was applied and after achieving the 2% drift amplitude, lead weights were applied to the treads to achieve a service level live load magnitude of 5.7 kPa (120 psf).

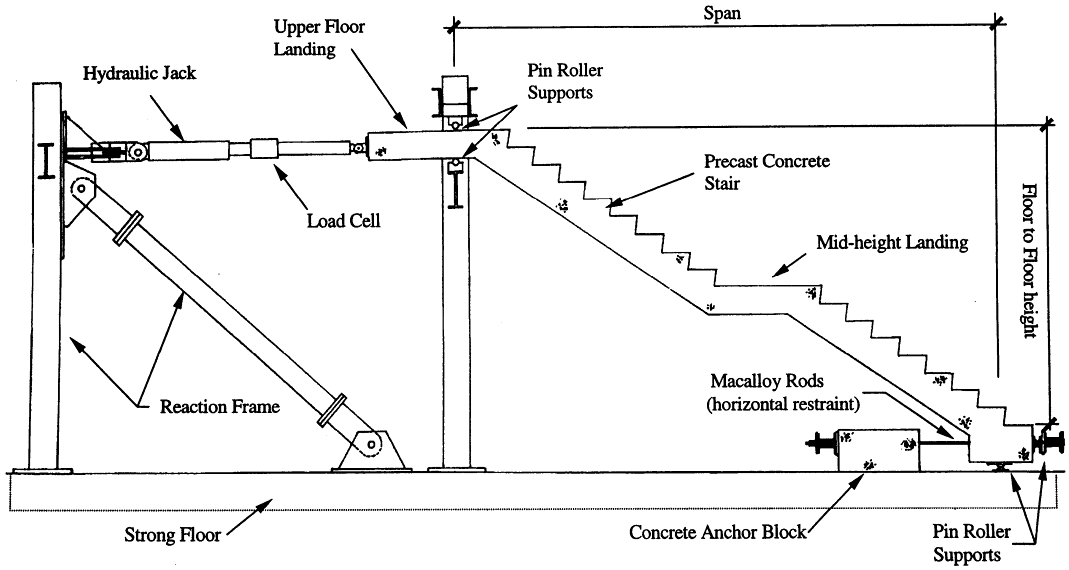


Fig. 5a – Precast concrete stair test specimen and setup (Simmons 2000).

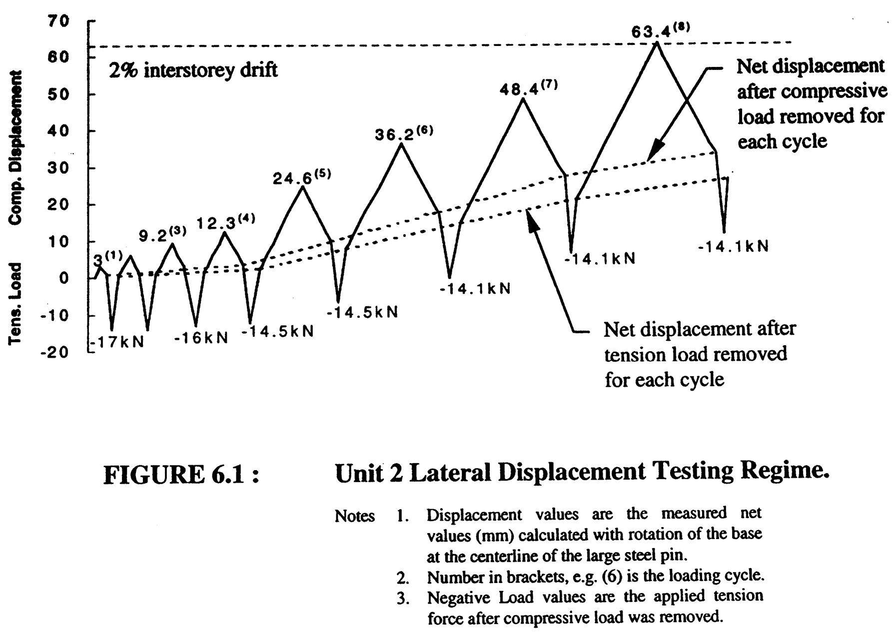


Fig. 5b – Example concrete stair test loading protocol (Simmons 2000).

Higgins (2009) conducted tests to assess the seismic performance of prefabricated steel stair assemblies. Two different production-run stair units were tested: checker plate (also called diamond plate) and concrete filled pan stair treads. The stair assemblies included two flights attached to a 1.2 m (4 ft) wide intermediate landing. The stair flights reverse at the landing and each flight has 11 treads 279 mm (11 in.) wide with 166 mm (6.55 in.) high risers (slope = 33 degrees, pitch = rise/run = 0.65). The overall stair specimen is shown in Fig. 6a. The test samples were subjected to simultaneously applied factored gravity loads and lateral displacements simulating seismic interstory drifts. Peak lateral displacements on the stair assemblies, shown in Fig. 6b, were based on a maximum average interstory drift angle of +/-2.5%, representative of a steel frame building with 3.6 m (12 ft) story heights. Drift displacements were imposed to the stair assemblies at the top landing location in each direction in sequence (parallel-to-stair-run followed by transverse-to-stair-run). The testing apparatus constrained the top landing displacements to the plane of loading considered, thereby imposing deformations and stresses consistent with in-situ building conditions. Both stair assemblies completed the testing protocol by demonstrating full factored live load capability (7.7 kPa (160 psf)) after undergoing lateral displacements in both orthogonal directions and there were no appreciable differences between the performance of the two different stair assemblies. Parallel loading produced single curvature in the stair runs and produced the highest deformation demand in the bottom landing connection. Transverse loading produced double curvature in the stair runs and produced the highest deformation demands in the top stair to landing connection. Stringers were subject to combined stringer bending (both strong-axis from seismic and weak-axis from gravity load) and axial force from seismic loading. Significant out-of-plane motions are produced at the intermediate stair landing during parallel to stair loading and stair shaft wall designs may need to accommodate these motions. Stair performance is dependent on the landing connections and welds joining the connection plates to the stringers. Connection details provided adequate cyclic deformability and endurance so that full factored design live load was sustained after application of the lateral deformation history.

Fig. 6a – Prefabricated steel stair tests (Higgins 2009).

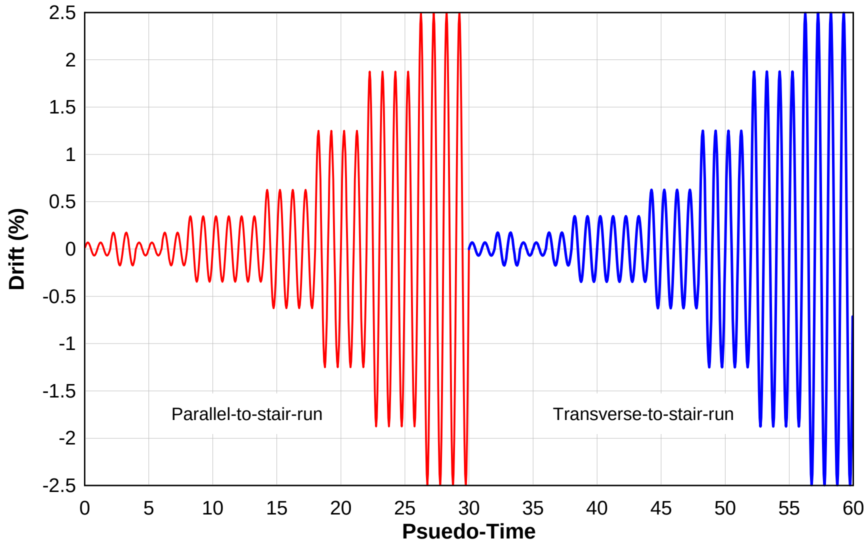


Fig. 6b – Loading protocol used for prefabricated steel stairs. Sequence of loading reversed for second specimen (Higgins 2009).

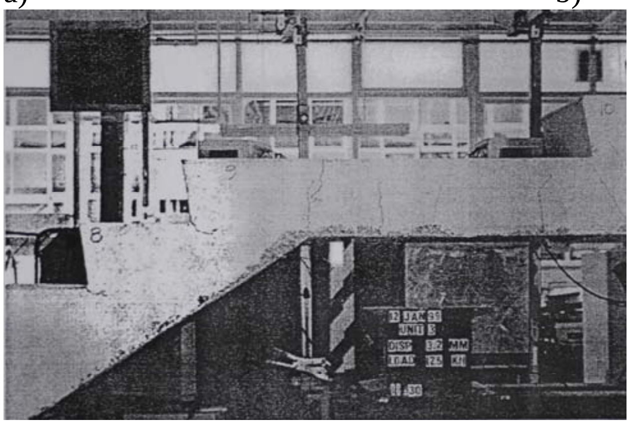
Damage States

Three damage states were selected for development of fragility functions. Damage states were selected with regard to the relative ease and cost of repair methods for the different types of damage observed as well as relative to functional performance.

The first damage state, DS1, consists of nonstructural or minor damage that can be repaired by patching, epoxy injection, painting, or applying a topping or fill material. This type of damage includes local concrete cracking, localized steel yielding, and localized spalling. Examples of these types of damages are shown in Fig. 7 for different stair systems.

a)

b)



c)

Fig. 7 – Examples of damage state DS1 for stairs a) Yielding around bolted connection (photo by C. Higgins), b) Yielding and paint flaking at stair tread-riser bend (photo by C. Higgins), c) Minor concrete cracking (Simmons 2000).

The second damage state, DS2, consists of structural damage such as extensive concrete cracking, concrete crushing, buckling of steel, and weld cracking. Repair of this damage would likely require removal of damaged elements, sections, or materials or extensive field repair. While the repair work required may be extensive, the stairs maintain the ability to carry full design live load. Examples of this type of damage are shown in Fig. 8.

a)

b)

c)

d)

Fig. 8 – Examples of damage state DS2 for stairs: a) Weld cracking on steel stair (photo by C. Higgins), b) spalling of concrete stair (La Union, stair damage, Los Palos Grande District, Caracas, Venezuela, (The Earthquake Engineering Online Archive, Karl V. Steinbrugge Collection: S2170S3558), c) concrete crushing and spalling on upper story stair landing after Anchorage, Alaska earthquake, (The Earthquake Engineering Online Archive, Karl V. Steinbrugge Collection: S2170), d) Concrete crushing, spalling, and significant cracking (Simmons 2000) .

The third damage state, DS3, consists of severe damage to the stair system such that it could not support factored live loads and permit egress from the building. The stair system would have to be completely replaced and would have failed the functional design objectives. Examples of this type of damage are shown in Fig. 9.

a) b)

Fig. 9 – Examples of damage state DS3 for stairs; a) Staircase between first and second floors of a two-story RC frame structure building in Dujiangyan, China after 2008 Wenchuan Earthquake. (Photo by Feng Yuan, Earthquake Engineering and Engineering Vibration (2009)), b) Hybrid stairway damaged in 1994 Northridge, California earthquake (FEMA 74, 1994 (image inverted at source location)).

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Fragility Functions

Fragility functions were developed based on the available laboratory test data for different stair systems. Data are available for stair systems with slopes ranging between 32 to 34 degrees (pitch = rise/run = 0.64 and 0.68), supported at the top and bottom landings, attached to intermediate landings with widths of approximately 1.2 m (4 ft), and of the configurations shown in Fig. 1b. Thus the subsequent fragility functions are limited to these common stair geometries. The stair damage states were related to the commonly used definition of interstory drift ratio (relative displacements of the upper and lower floor divided by story height). To apply these relationships, stairs must have geometric properties within the range considered here to ensure that the interstory drift is characteristic of the damage imposed on stairs. From the literature, the reported magnitude of lateral deformation imposed on the different stair systems at each of the above damage levels was identified. The drift-damage observations from tests in the literature are summarized in Table 1. None of the available tests were conducted to the stage at which live load capacity was documented to be lost. Thus for damage state three, DS3, Table 1 reports the maximum applied drift after which live load capacity was demonstrated experimentally. Because different stair systems produce different damages at different magnitudes of interstory drift, ideally different fragilities would be developed for each type of stair system (precast concrete, prefabricated steel, etc.). However, as seen in Table 1, there is sparse data and reported drifts for the damage states for many of the different stairs system types occur at essentially the same drift values, thus variability within a given system becomes zero. In addition, widely disparate test methodologies were employed to develop the data. As a result, insufficient data exists to statistically characterize any specific stair system. In order to produce fragility curves for stairs generally, all the stair types were combined to make some use the very limited available data. This obviously does not adequately characterize any of the stair systems (benefitting some, while penalizing others). To retain the particular stair system as a reference in the confounded fragility curves, different symbols are used to represent the stair type.

The data for each damage state were sorted in ascending order using Hazen's plotting location. Without sufficient data to establish the distribution type that best fits stairs, lognormal probability distributions were fitted to the available data. The geometric mean was taken as the median and the logarithmic standard deviation as the dispersion. The empirical cumulative distribution functions for DS1, DS2, and DS3 are shown in Figs. 10, 11, and 12, respectively. The parameters for the fitted logarithmic fragility functions are shown in Table 2. Because of the large differences between the different test methods, no modifications were made to account for end of cycle reporting of the identified damage.

To account for additional uncertainty based on the small sample size, the logarithmic variance was increased by the square of the standard error for each of the damage states. The resulting parameters for the fragility functions are shown in Table 3 and the lognormal distributions for all damage states are shown in Fig. 13. Due to the very limited sample size and resulting lumping of stair system types, this population uncertainty is confounded. An attempt was made to better distinguish between the different stair types below.

As an alternative formulation and following the NEHRP *Provisions* (2004a), the stair systems were classified as rigid or flexible. For the three stair types where data are available, the precast concrete stairs would be considered rigid, while the hybrid and prefabricated steel stairs would be considered flexible. It is important to consider that the classification of stairs as either rigid or flexible will be dependent on the design and detailing of the particular stair assembly. This can be difficult to ascertain for many practical stair systems. Using the distinction provided by the *Provisions*, it was possible to develop some fragility functions for flexible stairs. For the flexible stairs, the same methodology was used to develop fragility functions for two of the three damage states as seen in Figs. 15 and 16, with the resulting recommended fragility parameters shown in Table 4. For DS3 there was no variability in the reported data and only two (2) tests are available, thus this function is not available. For the rigid stairs, no variability is found in the reported data (three tests) and fragility functions were not developed.

Based on the results of this study, it is clear that additional data are needed to characterize fragility of stair systems. Ideally, data must be developed for individual stair types rather than combining systems with disparate damage-drift responses or damage types.

Table 1 – Experimentally identified damage states for stairs.

Test ID	Loading Direction	Load Type	DS1 Interstory Drift Ratio	DS2 Interstory Drift Ratio	DS3 Interstory Drift Ratio
Prefab. Steel Plate[1]	Transverse[a]	Reversed Cyclic	0.006	0.025	0.05[b]
Prefab. Steel with Concrete Filled Pans[1]	Parallel[a]	Reversed Cyclic	0.006	0.025	0.05[b]
Precast Concrete Unit#1 [2]	Parallel	Cyclic No Reversals	0.001	0.006	0.02
Precast Concrete Unit #2 [2]	Parallel	Cyclic No Reversals	0.001	0.0107	0.02
Precast Concrete Unit #3 [2]	Parallel	Cyclic No Reversals	0.001	0.0075	0.02
Hybrid 900 mm [3]	Transverse	Reversed Cyclic	0.015	0.029	-
Hybrid 1200 mm [3]	Transverse	Reversed Cyclic	0.015	0.029	-
Hybrid Upper Flight 4	Transverse	Cyclic No Reversals	0.015	0.024	-
Hybrid Lower Flight [4]	Transverse	Cyclic No Reversals	0.015	0.023	-

[1] Higgins, 2009; [2] Simmons, 2000; [3] Yanagisawa et al. 1999; [4] Hukazawa et al. 1999.
[a] Each specimen was tested in both loading directions (Fig. 6b). Damage state reported here is for first loading direction.
[b] DS3 is predicted using equivalent damage rule after each specimen was tested in both the transverse and parallel to stair run directions.

Table 2 – Parameters for lognormal distributions fitted to data in Table 1.

Damage State	Description	Median Interstory Drift Ratio	Dispersion
DS1	Local concrete cracking, localized steel yielding, and localized spalling	0.005	1.26
DS2	Extensive concrete cracking, concrete crushing, buckling of steel, and weld cracking	0.017	0.62
DS3	Loss of live load capacity	0.028	0.50

Table 3 – Recommended parameters for fragility functions combining all stairs.

Damage State	**Description**	**Median Interstory Drift Ratio**	**Dispersion**
DS1	Local concrete cracking, localized steel yielding, and localized spalling	0.005	1.18
DS2	Extensive concrete cracking, concrete crushing, buckling of steel, and weld cracking	0.017	0.58
DS3	Loss of live load capacity	0.028	0.45

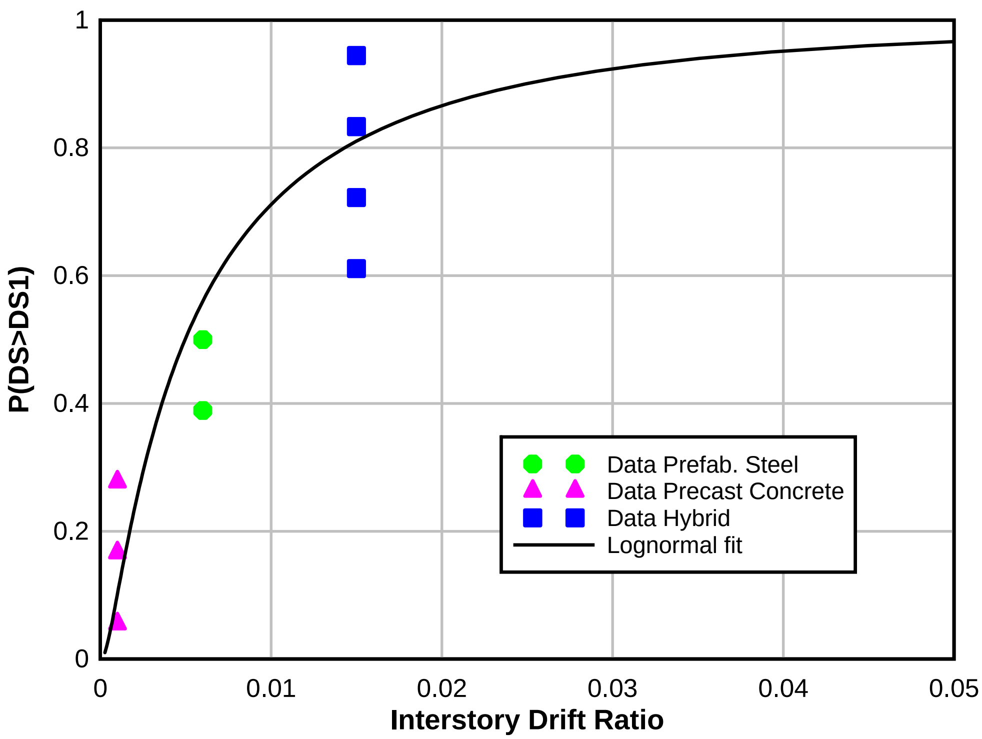

Fig. 10 – Cumulative distribution function for damage state 1 (DS1) considering all stairs.

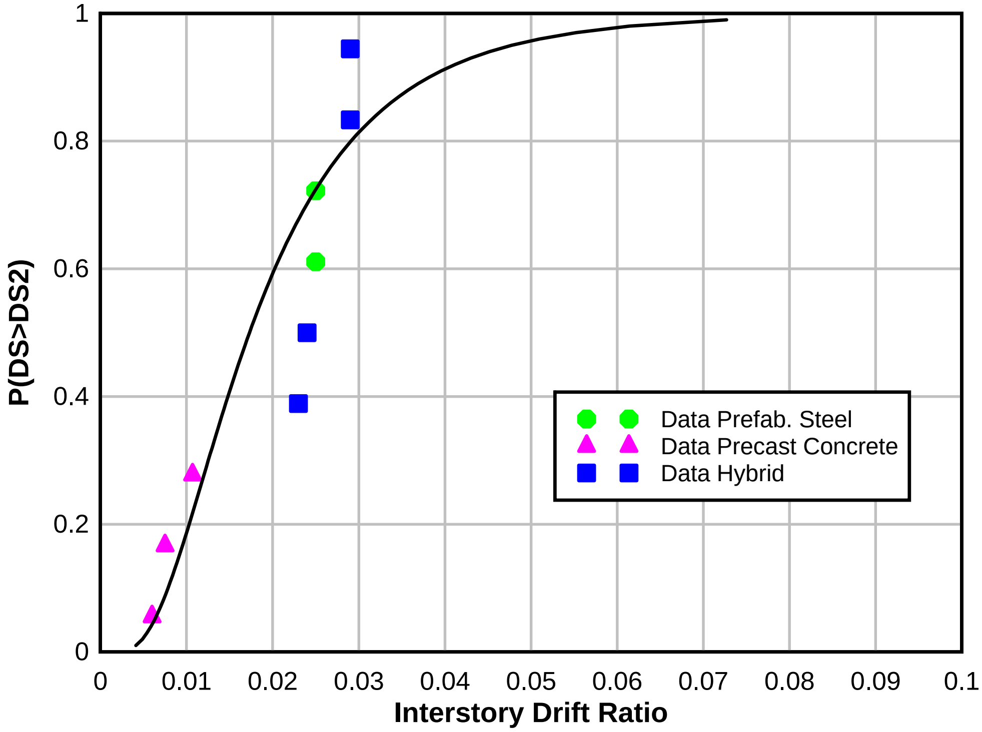

Fig. 11 – Cumulative distribution function for damage state 2 (DS2) considering all stairs.

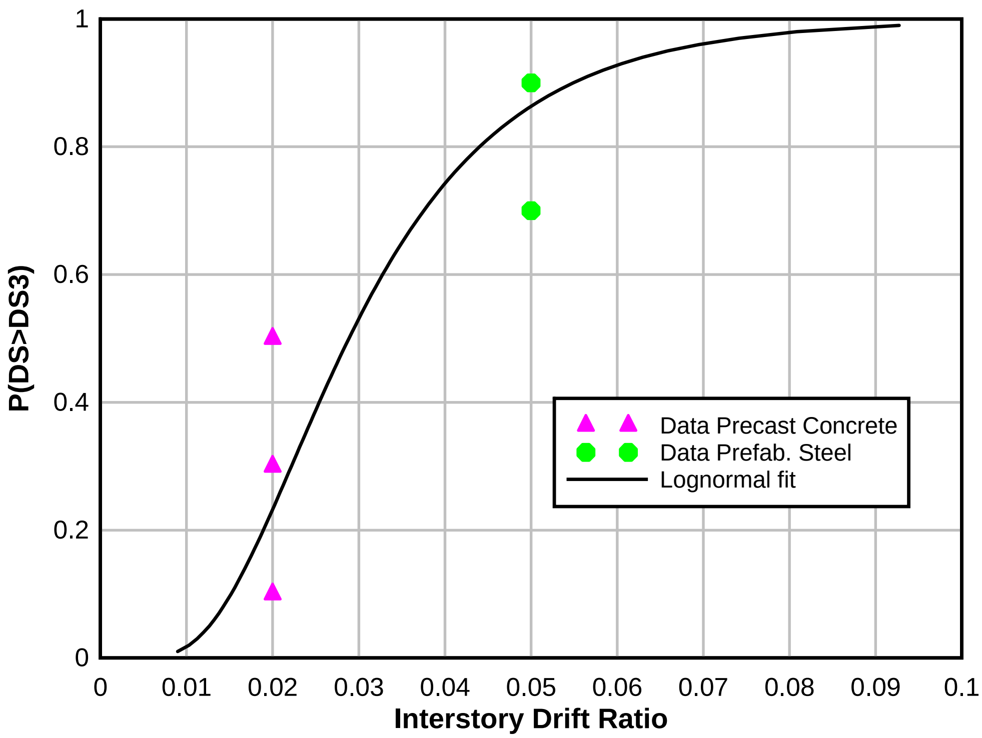

Fig. 12 – Cumulative distribution function for damage state 3 (DS3) considering all stairs.

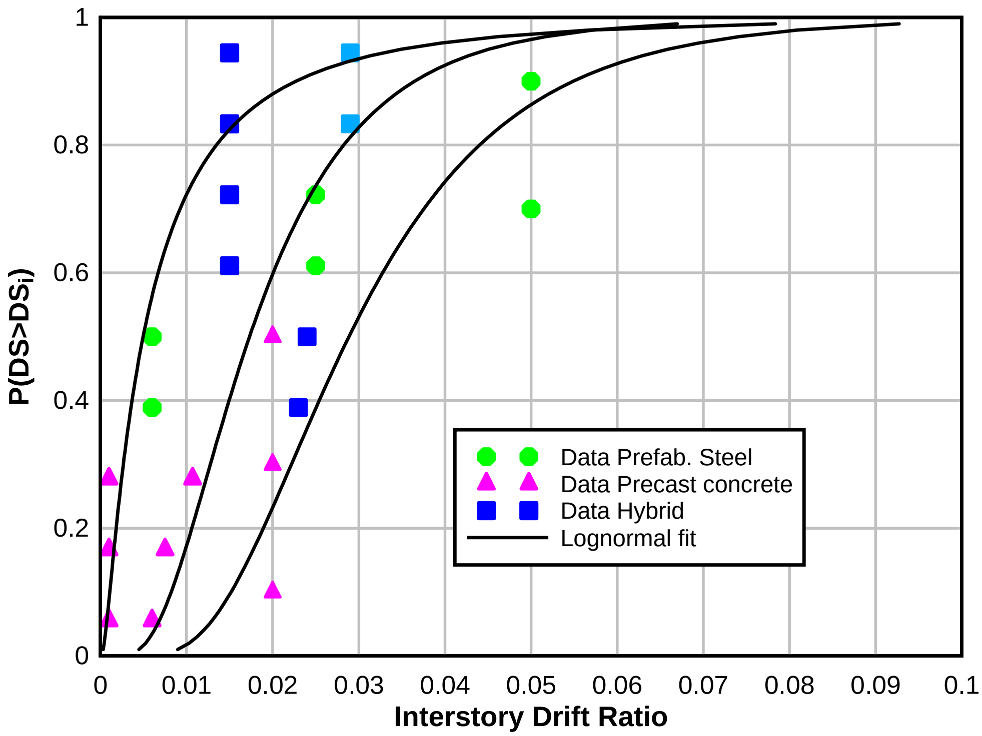

Fig. 13 – Empirical cumulative distribution functions and lognormal distributions for all damage states.

Table 4 – Recommended parameters for fragility functions considering flexible stairs.

Damage State	**Description**	**Median Interstory Drift Ratio**	**Dispersion**
DS1	Local concrete cracking, localized steel yielding, and localized spalling	0.011	0.43
DS2	Extensive concrete cracking, concrete crushing, buckling of steel, and weld cracking	0.026	0.08
DS3	Loss of live load capacity	0.050	-

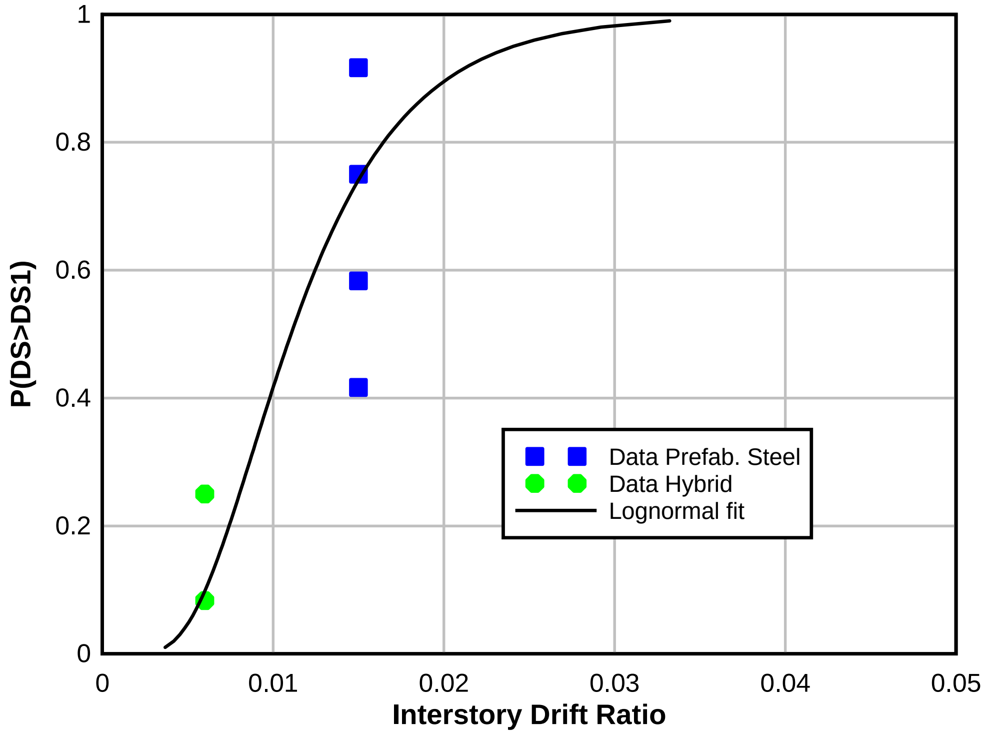

Fig. 14 – Cumulative distribution function for flexible stair damage state 1 (DS1).

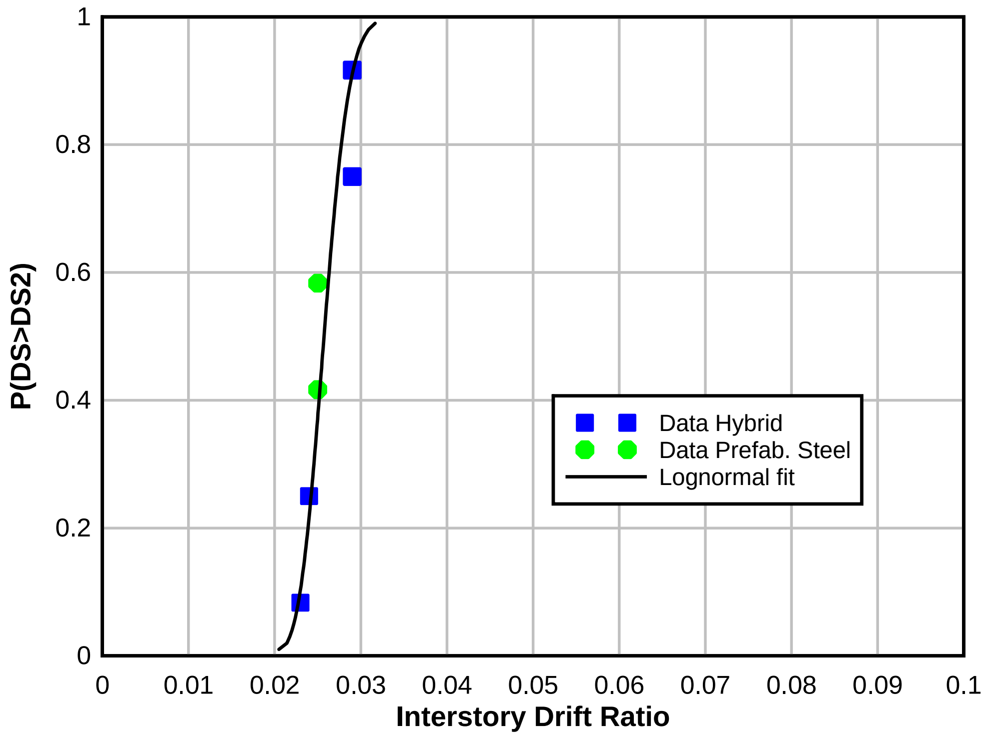

Fig. 15 – Cumulative distribution function for flexible stair damage state 2 (DS2).

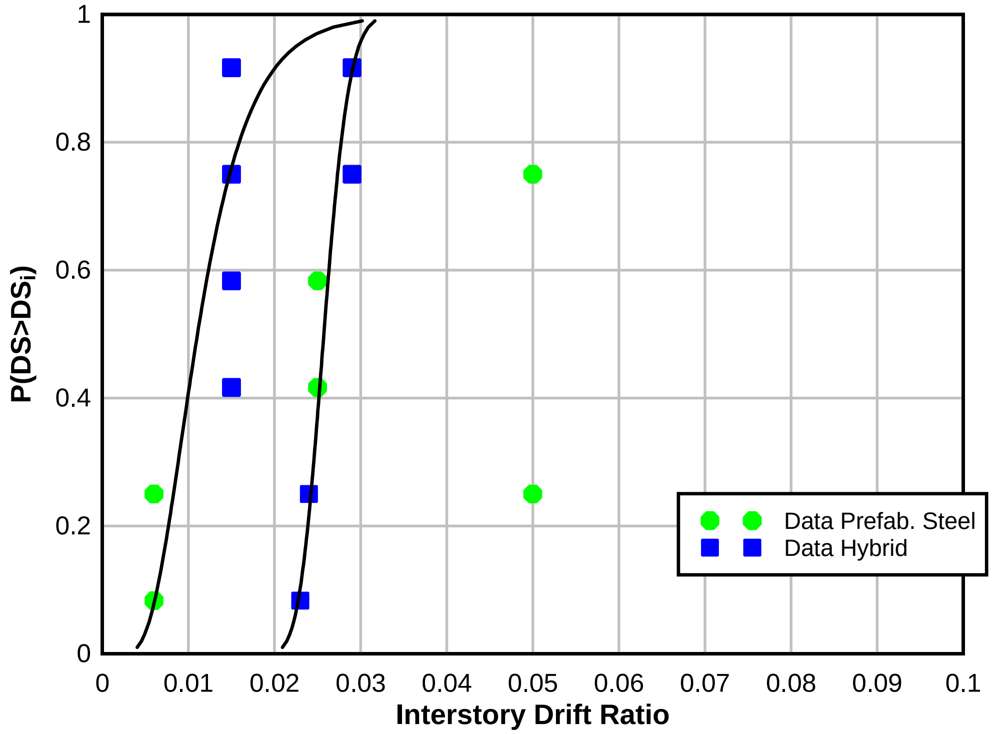

Fig. 16 – Empirical cumulative distribution functions and lognormal distributions for all damage states for flexible stairs (for DS3, dispersion from reported test results is zero).

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