Drift-Based Functional Fragility Framework for Fire-Rated Doors in Post-Earthquake Fires

Serdar Selamet[1] and Masahiro Kurata[2]

[1] Exponent Inc.
149 Commonwealth Dr. Menlo Park, CA 94025 USA
e-mail: sselamet@exponent.com
[2] Disaster Prevention Research Institute, Kyoto University
Kyoto, Japan
e-mail: kurata@dpri.kyoto-u.ac.jp

Abstract. This study evaluates the expected post-earthquake fire performance of fire-rated door assemblies by integrating structural drift demands from full-scale seismic testing with fire door fragility characterization. A fragility curve for 90-minute-rated fire doors is first developed based on the experiments of Calayir et al. [2022], in which doors were subjected to quasi-static cyclic loading followed by standard fire resistance tests. The resulting curve relates inter-story drift ratio (IDR) to the probability of fire rating loss, indicating reductions of approximately 70% at drift levels around 2%. The fragility curve is then applied to the partition walls in a steel-moment-resisting frame specimen reported by Huang et al. [2022], where a full-scale, four-story steel moment-resisting frame was subjected to increasing ground motions. Recorded IDRs reached approximately 1.45% at the second story. By mapping these drift demands to the fragility curve, the likely degradation in fire performance of hypothetical fire door sets is inferred for each story. This approach constitutes the first quantitative method to express the functional degradation of fire doors as a function of seismic deformation, enabling integration of fire compartmentation reliability into multi-hazard fragility assessments and informing code provisions for seismic qualification and post-earthquake inspection of fire-rated doors. Results suggest that, within the tested door configuration, drift levels of 1% and 2% caused approximately 30% and 40% reductions in fire-resistance rating, respectively, based on the integrated fragility model.

Keywords: fire-rated doors, post-earthquake fire, functional loss, fragility curves, non-structural components.

1. INTRODUCTION

Modern building performance under multi-hazard scenarios, particularly earthquakes followed by fire, has become a major focus in structural and fire safety engineering. Past earthquakes have shown that even when the primary structure remains stable, nonstructural damage can severely compromise compartmentation and fire containment. Following the 1995 Kobe (Hanshin-Awaji) earthquake, post-event inspections reported that approximately 30 % of fire-rated door sets were damaged, threatening the integrity of fire compartments [Nishino, 2023]. Fire doors are critical passive fire-protection elements; when distorted or misaligned by seismic drift, their ability to restrict smoke and flame spread diminishes sharply creating pathways for post-earthquake fires (PEFs).

Recent work has begun to quantify the seismic fragility of fire-rated assemblies and other passive fire-protection systems. Calayir et. al [2022] conducted the first full-scale study on fire-door performance under in-plane cyclic drift, demonstrating that even moderate inter-story drifts cause door-frame rotation, hinge distress, and seal degradation. When doors were subsequently tested to EN 1634-1 under the ISO 834 standard curve, fire-resistance durations decreased by as much as 70 % once inter-story drift ratios (IDR) approached 2.0–2.3 %, primarily due to 8 mm door–frame gaps and crushed or dislodged intumescent seals. Similar experimental observations were reported by Collier [2005] and Bartlett [2022] for racked wall-door assemblies, where small separations reduced rated fire resistance by 50 % or more. Mulligan et al. [2020] also found that plasterboard partitions with door openings experienced early cracking and detachment at only 0.8–1.0 % drift, reinforcing that ordinary office partitions cannot sustain design-level deformation without affecting attached fire doors.

Complementary research has addressed the system-level implications of such local failures. Dashti et al. [2025] highlighted that compartmentation loss in passive fire-protection components remains one of the least-quantified uncertainties in PEF modeling. Covi et al. [2024] developed fragility functions for fires-following-earthquakes (FFE), showing that even minor drift-induced misalignments in doors, windows, and partitions can drastically increase predicted fire-spread probabilities. Nishino [2023] proposed a probabilistic framework linking seismic damage states of passive systems—door frames and gypsum wall assemblies—to their expected reduction in fire endurance. These studies converge on the conclusion that door and partition fragilities dominate early fire-spread pathways in multistory buildings subjected to design-level earthquakes.

This paper reports the expected post-earthquake fire performance of fire-rated door assemblies, evaluated by integrating structural drift demands from full-scale seismic testing with fire door fragility characterization. A fragility curve for 90-minute-rated fire doors is first developed based on previously reported experiment dataset, in which doors were subjected to quasi-static cyclic loading followed by standard fire resistance tests. The resulting curve relates inter-story drift ratio (IDR) to the probability of fire rating loss, indicating reductions of approximately70% at drift levels around 2%. The fragility curve is then applied to the partition walls in a full-scale shaking table test. By mapping the drift demands to the fragility curve, the likely degradation in fire performance of hypothetical fire door sets is inferred for each story.

2. POST-EARTHQUAKE FIRE-DOOR EXPERIMENTS

The first author and colleagues from Turkey investigated the post-earthquake performance of fire-rated steel door assemblies [Calayir et. al., 2022]. The objective was to quantify how in-plane cyclic deformation influences the fire-resistance rating (FRR) of a compartmentation element. The test specimens were standard single-leaf steel fire door sets (as seen in Figure 1) rated for 90 minutes of fire endurance (insulation criterion) and 120 minutes integrity. According to EN 1634-1 [CEN, 2014], fire integrity E failure occurs when excessive deformation or clearance between the door leaf and frame allows sustained flaming or hot gases to pass to the unexposed side. It is characterized by visible cracks or fissures, continuous flaming for more than 10 s, or ignition of a cotton pad placed on the unexposed surface. Fire insulation (I_2) failure, on the other hand, is defined by excessive heat transfer through the door: when thermocouples positioned at least 100 mm from the edges record a temperature rise exceeding 180 °C at any point, 360 °C at the frame, or an average increase of 140 °C across the central area, indicating that the door no longer provides adequate thermal protection.

2.1 EXPERIMENTAL PROGRAM

Each door frame was mounted in a stiff timber loading frame and cyclic lateral displacements were applied at the top of the door frame to impose racking deformations. The loading protocols followed standardized approaches to incrementally increase drift demands up to a target level around 2.3% IDR, representing a design-level earthquake for a tall building. Three identical door sets (Door 2–4) were each loaded to this drift level, while a fourth door set (Door 1) was tested quasi-statically up to 3% drift to examine ultimate failure modes. After the lateral loading, the damaged door specimens were subjected to standard fire resistance tests to determine their remaining fire endurance.

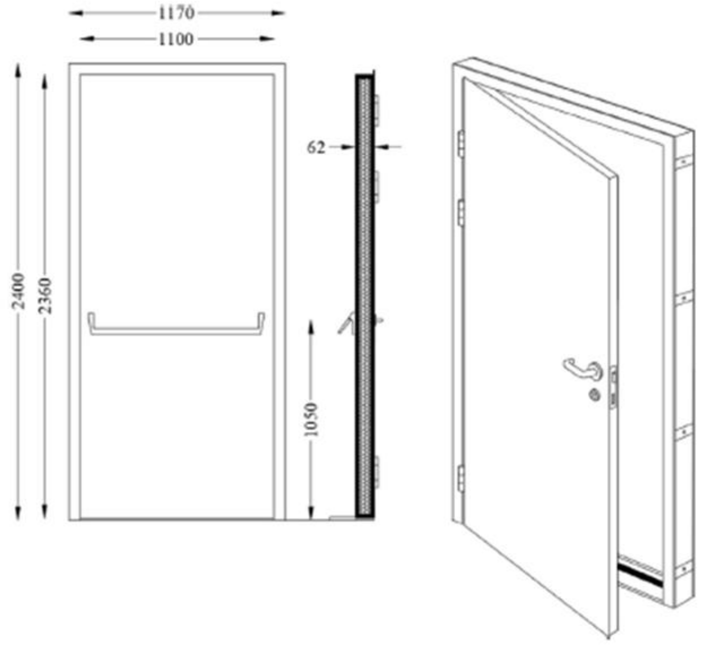

Figure 1. Construction details and dimensions (mm) of the tested fire door set [Calayir et. al. 2022]

2.2 DAMAGE OBSERVATIONS

During the cyclic drift tests, the fire door sets sustained progressively worsening damage with increasing story drift. Initial drifts (~0.5%) caused minor visible gaps and distortions. As drifts exceeded ~1%, the steel door frames bent and separated notably from the door panels at the top corners. By around 2% IDR, all tested door sets had developed large permanent set, the door frames were visibly racked (parallelogram-shaped) and the door panels jammed in place due to frame narrowing at one corner. Figure 2 a–c [Calayir et al. 2022] shows the distorted shape of three door specimens at their peak drift: each exhibits a significant gap opening at the upper latch-side corner, along with localized tearing or cracking of the frame steel near the lock area. The doors at this point could not be operated (they were stuck in the deformed frame) and had residual offsets. Additional damage included loosened hinge attachments and compressed/crushed intumescent seals along the edges (especially where the door edge bore against the frame). One specimen showed a crack through the frame corner weld at 1.9% drift, and another had tearing around the latch bolt by 2.3% drift.

Table 1. Summary of quasi-statically loaded fire door test results [Calayir et al., 2022]

Door Specimen	Peak Cyclic Drift (IDR)	Notable Seismic Damage	Residual Fire Resistance (min)	Fire Rating Loss
Door Set No.2	2.3%	Frame tearing at lock; large top gap (~8mm)	36 min	69%
Door Set No.3	1.9%	Frame cracked at top corner; door jammed	38 min	67%
Door Set No.4	2.3%	Severe frame distortion; hinges loosened	37 min	68%

The fire exposure tests revealed drastic reductions in fire endurance for the earthquake-damaged doors. All three door sets that underwent seismic loading failed to achieve even half of the original 90-minute rating. Table 1 and Figure 3 summarize the outcomes. While an undamaged control door easily survived the full 90-min (and indeed had no integrity or insulation failure even at 2 hours, demonstrating some safety margin), the drifted specimens failed between about 30 and 40 minutes under the same fire test. The mode of fire failure for the damaged doors was integrity failure: due to the quake-induced gaps, hot gases and flames penetrated the door-frame interface well before 90 minutes. In Calayir et al. [2022] tests, flaming was observed around the warped frame edges after roughly 30–40 minutes of fire exposure, leading to the cotton pad ignition criterion being met (i.e. fire breaching). Additionally, thermocouples on the frame registered rapid temperature rise – one door exceeded the 360 °C frame temperature limit at around 40 min. All damaged doors thus failed the integrity criterion by 40 min, versus the control door which maintained integrity past 120 min. The insulation criterion (average door temperature rise) was satisfied for the damaged doors up to their failure time, meaning the door panels themselves did not overheat; it was the through-gap hot gas leakage that caused failure. This highlights that gaps and distortions, not panel burn-through, were the critical weakness in the post-quake fire performance. With only three data points, Calayir et al. [2022] did not demonstrate fitting a specific probability distribution; however, the implication is that the fragility function for fire door failure (loss of rating) is steep – likely a lognormal curve. The authors succinctly stated: "The fire performance of 90-min rated door sets reduced approximately70% in terms of insulation and integrity failure." They recommend that post-earthquake inspections measure door frame gaps, and if gaps exceed ~8 mm (which corresponded to ~2% IDR in their tests), the door should be considered compromised.

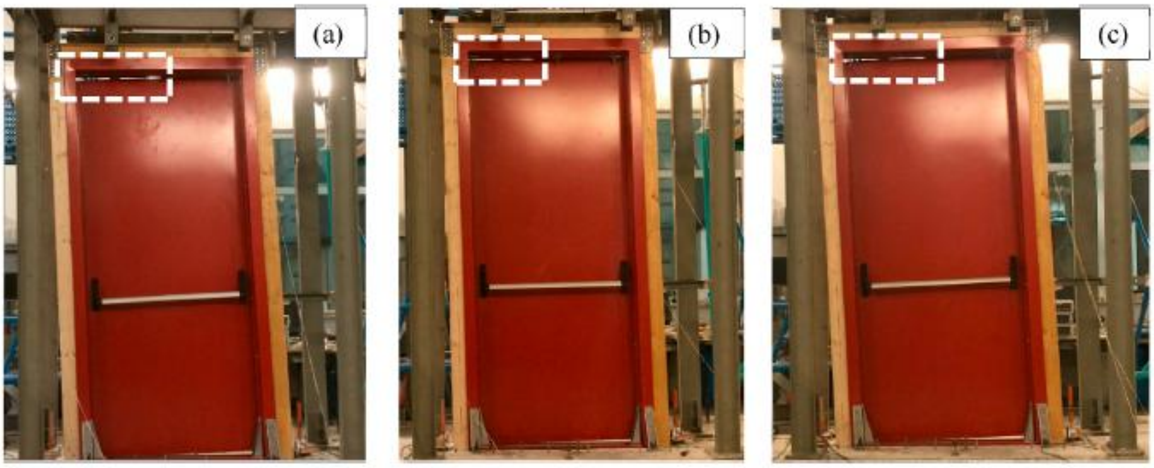

Figure 2. Observed damage to fire door sets under lateral drift [Calayir et al., 2022]: (a–c) Permanent distortion of three 90-min fire door specimens at their failure inter-story drifts (~1.9–2.3% IDR) – note large gap openings at top corners and tearing near the locks

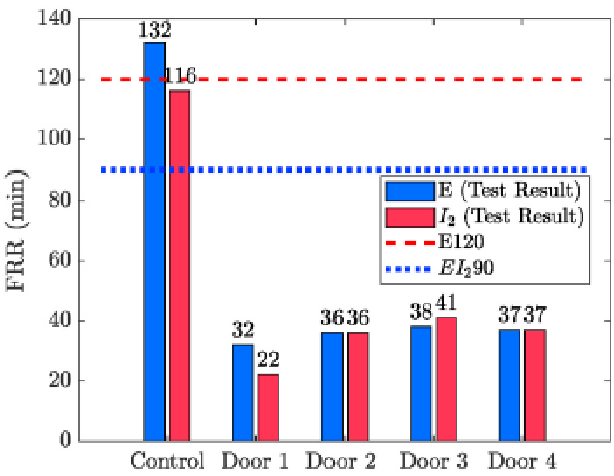

Figure 3. Residual fire resistance of 90-min rated fire doors versus inter-story drift ratio, based on data from Calayir et al. [2022]. Higher seismic drifts lead to drastic reductions in fire endurance (approximately 70% loss at 2.3 % IDR)

3.PARTITION WALL FRAGILITY

To investigate realistic drift demands on non-structural walls and door frames, the second author and colleagues from Japan conducted full-scale shake-table tests on a four-story steel moment-resisting frame with non-structural components and medical equipment. The experiment took place at the E-Defense facility in Japan. Huang et al. [2022] reported the summary for cold-formed steel (CFS) gypsum partition wall behaviours, highlighting the influence of the vertical boundary conditions on the wall damages.

3.1 EXPERIMENTAL CONFIGURATION

The steel frame building measured 4 stories tall (approximately 3.8 m per story, 15.2 m total height) and was designed to modern code standards. A total of sixteen non-structural drywall partition panels were installed on each floor, in typical office layout configurations, including some with door openings and others spanning between columns. Some partition walls included door frame segments though the doors themselves were not installed, the framing and opening were present. This means that these test results can shed light on door frame deformations. The frame was subjected to a sequence of six earthquake input cases of increasing intensity. These included scaled versions of the 1995 Kobe (JMA Kobe) ground motion and a long-duration long-period design ground motion (the Nankai Trough earthquake of Mw 9.0 scenario) at Osaka soft-soil site, applied in both horizontal directions to simulate a variety of seismic demands. Throughout these tests, extensive instrumentation measured structural and non-structural responses, including inter-story drift ratios (via string potentiometers) at each floor and detailed observation of partition wall damage progression.

After each test, the partition walls were inspected and damage was catalogued in detail (cracks, gaps, screw failures, etc.). Huang et al. [2022] reported that all partition walls containing door frames suffered damage type of panel detachment at door-frame connections and type of board cracking by the end of the tests. This indicates that the presence of a door opening created a weak point where seismic drift concentrated damage, consistent with expectations.

The maximum IDR recorded was approximately 1.5% at the second floor. The first story and third story experienced slightly lower peak drifts, and the top story was the most rigid. The second floor with ~1.45% IDR, and the first/third floors with ~1.0–1.2% IDR exceed the drift at which Calayir et al. [2022] observed major fire door damage (~1–2% IDR). In other words, a realistic design-level earthquake caused drifts in this mid-rise building that likely would compromise 90-min fire doors.

3.2 DAMAGE OBSERVATIONS

The damage observed for representing partition walls without door frames are summarized in Table 2. The GA and GB configurations represent strong-strong boundary condition and weak-weak/strong boundary condition, , respectively and -N represents walls without door. The walls exhibited median story drift ratios of 0.5 %, 0.7 %, and 1.6 % for DS1–DS3, respectively. Here, DS1–DS3 correspond to superficial, minor and severe damage, respectively. Although actual door leaves were not present in the test, it can be inferred that if a fire door had been installed within those frames, it would have experienced similar in-plane racking to that observed in the quasi-static fire door experiments by Calayir et al. [2022].

The observed partition wall damage around the boundary frame indicates that the surrounding frame members likely deformed several millimeters out of square under drift demands of approximately 1–2%. Huang et al. [2022] did not directly measure door gap widening (as no door leaf was installed), but visible cracking and separations of 5–10 mm around the panel boundaries suggest that a hypothetical fire door would have experienced comparable corner misalignments. This is consistent with Calayir et al. [2022], where an 8 mm top gap corresponded to a 2% drift ratio. Therefore, for second-story drift levels near 1.4–1.5%, a door installed within the same boundary condition could be expected to exhibit 5–6 mm corner gaps.

Table 2. Summary of partition wall test results [Huang et al., 2022]

Boundary Type	Specimens	Boundary Description	Median IDR (DS1 / DS 2 /DS 3) [%]	Seismic Damage
GA-N / GB-D	P1, P2, P8, P10, P13, P14, P4, P6, P7, P11, P15	Strong–strong external boundaries, no door frame	0.5 / 0.7 / 1.6	Edge crumpling and screw failures near both vertical boundaries; diagonal cracking; plaster spalling concentrated at corners,
		At least one weak (panel or stud) external boundary, no door frame		Cracking and crushing along weak boundary; localized panel separation; limited overall deformation

Huang's fragility framework explicitly quantifies the influence of boundary stiffness on the seismic vulnerability of non-structural walls. The GA-D configuration representing a door frame embedded between two stiff vertical supports serves as a direct analogue to the boundary condition of a fire-rated door assembly, forming the structural basis for the functional fragility relationships developed in the next section. The fragility function in Huang et al. [2002] follows a lognormal cumulative distribution where m_i is the median drift, β = 0.25 is the logarithmic standard deviation [FEMA P-58, 2018], and Φ is the standard normal cumulative distribution.

$$P(DS \geq i \mid IDR) = \Phi((\ln(IDR) - \ln(m_i))/\beta \ ) \tag{1}$$

4. INTEGRATION OF SEISMIC DAMAGE AND FIRE FUNCTIONALITY FRAGILITIES

To evaluate post-earthquake fire performance of door assemblies, the drift-based fragility framework established by Huang et al. [2022] was adapted to represent fire-resistance loss. The inter-story drift ratio (IDR) was used as the engineering demand parameter (EDP) for both datasets, where IDR = Δ/h describes the relative story deformation imposed on the door–frame system. Three functional loss states (LS1–LS3) were defined to characterize the degradation of fire-resistance rating (FRR).

Table 3. Functional limit states for fire-rated doors

Limit state	Representative FRR loss	Median IDR (m_i)	Source	Physical interpretation
LS1 (DS1)	20 %	0.5 %	Huang [2022]	Onset of distortion; minor seal separation
LS2 (DS2)	50 %	0.7 %	Huang [2022]	≈ 5 mm gap; partial loss of seal continuity
LS3 (DS3)	70 %	2.3 %	Calayir et. al. [2022]	≈ 8 mm gap; loss of fire integrity and insulation

The first two median drifts were adopted from the GA-D configuration in Huang et al. [2022], representing strong–strong boundaries with a door frame, which most closely resemble the boundary conditions of a fire-rated door assembly installed within a rigid structural frame. The third median, 2.3 %, corresponds to the measured approximately 70 % reduction in FRR observed in the Calayir et al. [2022] door experiments, where full integrity failure occurred between 2.0–2.3 % drift. Relative to the 132-minute integrity performance of the control door, the drifted specimens achieved only 32, 36, 38, and 37 minutes of fire endurance, corresponding to reductions of 76%, 73%, 71%, and 72%, respectively. Because LS3 is based on only three fire-tested specimens of identical construction, its statistical basis is limited. The LS3 parameters should therefore be interpreted as an engineering estimate anchored to the observed failure mechanism rather than a statistically robust distribution. Each limit state was modeled as a lognormal fragility function, consistent with Huang et al. [2022] and FEMA P-58 conventions:

$$P(LS \geq i \mid IDR) = \Phi((\ln(IDR) - \ln(m_i \ ))/\beta \ ) \tag{2}$$

where m_i is the median drift, β = 0.4 is the logarithmic standard deviation [Miranda et al. 2003] for interior doors), and Φ is the standard normal cumulative distribution.

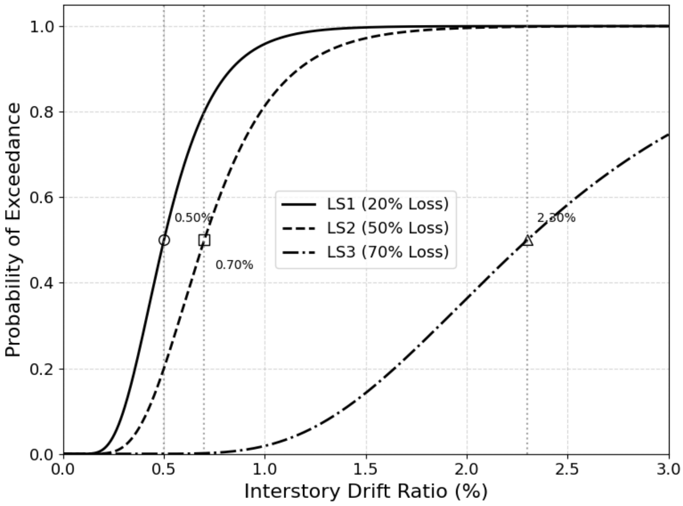

Figure 4. Drift-based fragility curves for fire-rated door assemblies showing probability of exceedance for three functional loss states (LS1–LS3) as a function of interstory drift ratio.

The three fragility curves describe the probability of exceeding each loss state as a function of drift (Figure 4). To relate these exceedance probabilities to residual fire performance, an expected functionality curve was derived as seen in Figure 5, expressing the mean retained FRR at each drift level:

$$E[L(IDR)] = L_1^*(F_1 - F_2) + L_2^*(F_2 - F_3) + L_3^* F_3 \tag{3}$$

where $F_i = P(LS \geq i)$ and L_i^* are representative loss values for each interval as $L_1^* = 0.10,\ L_2^* = 0.35,$ $L_3^* = 0.60$. The expected retained functionality is then:

$$E[R_f(IDR)\ ] = 1 - E[L(IDR)] \tag{4}$$

This curve transitions from E [R_f] = 1.0 and E [R_f] = 0.3 at 2.0-2.5 % IDR reflecting the progressive degradation of fire-door performance with increasing seismic deformation.

The combined model bridges the structural fragility of partition walls and the functional degradation of fire-rated doors:

- Huang [2022] data define the early deformation thresholds (0.5–0.7 % IDR) where gaps initiate and seals begin to fail.

- Calayir et al. [2022] results establish the severe-damage threshold (≈ 2.3 % IDR) corresponding to full seal failure and a 70 % FRR loss.

- The adopted dispersion β=0.4 captures installation variability typical of interior door systems and provides a conservative envelope compared with Huang's β ≈ 0.25–0.30 for laboratory partitions.

The resulting functionality model quantitatively connects earthquake-induced drift to loss of fire compartmentation, enabling integration of fire-safety metrics within seismic fragility analyses.

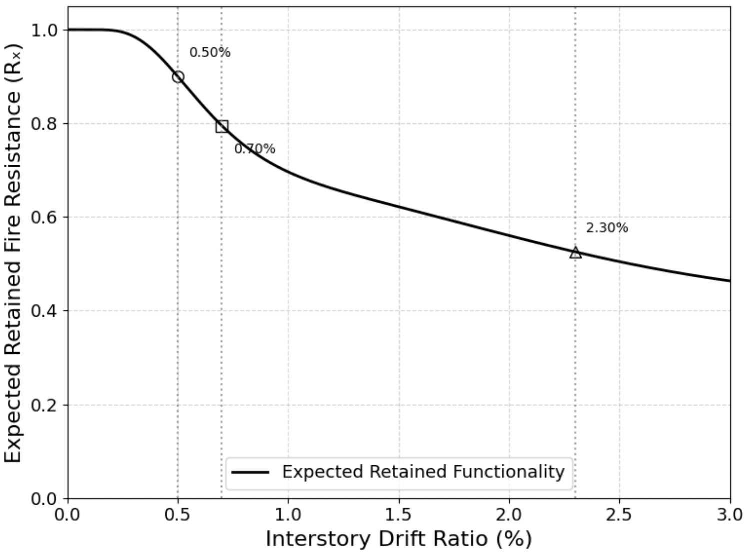

Figure 5. Functional loss curve of the fire-rated door showing retained FRR with increasing drift

5.CONCLUSIONS

This study evaluates the post-earthquake performance of fire-rated door assemblies by integrating the authors' prior experimental fragility data [Calayir et al., 2022] with full-scale structural response measurements from Huang et al. [2022]. Calayir et al. [2022] demonstrated that drift-induced distortion can significantly impair the performance of fire-rated doors. Quasi-static testing of 90-minute fire-rated steel door assemblies showed that moderate interstory drifts (1–2%) cause significant frame distortion, hinge loosening, and seal damage. Under subsequent standard fire exposure, the fire-resistance rating decreased by approximately ~70%, with integrity failure observed after 30 minutes instead of the nominal 90 minutes. The results confirm that drift ratio is a reliable predictor of fire performance loss. In the four-story steel moment frame tested by Huang et al. [2022], peak story drifts during design-level shaking reached ~1.0–1.5%. Partition walls with door openings on the most drifted floor exhibited severe boundary damage.

The main findings are as follows:

- Applying the fire-door fragility model to the measured story drifts in the four-story steel moment frame indicated that the probability of door failure (FRR < 90 min) was approximately 50–60% on the maximum observed IDR.

- While based on a limited case study, the analysis indicates that compartmentation for fire safety can be substantially impaired following a design-level earthquake. A fire igniting on a story with drift-damaged doors could spread beyond the room of origin due to premature leakage or flame passage through frame gaps. A practical post-earthquake inspection criterion is the door-frame gap width: observed separations of >6–8 mm should be considered indicative of compromised fire resistance.

- The expected retained fire resistance decreases from nearly 100% at low drift to about 80% at 0.7 % IDR and 60% at 1.5% IDR, the latter corresponding to design-level story drifts observed in Huang et al. [2022]. The functional loss curve thus provides the first quantitative method to relate seismic drift directly to fire-door performance degradation, enabling consistent assessment of compartmentation reliability in multi-hazard design.

In summary, this work identifies a critical linkage between seismic deformation and fire-safety performance. Fire doors designed to provide 90 minutes of protection may offer only 55 minutes of resistance following moderate structural drift. Quantifying this reduction enables realistic assessment of fire spread potential after earthquakes. The findings support consideration of seismic qualification and post-event inspection provisions for fire-rated doors in future editions of ASCE 7 and NFPA 80, ensuring that both structural and compartmentation systems retain functionality under multi-hazard conditions.

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