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INFLUENCE OF IRREPARABILITY FRAGILITY ON SEISMIC VULNERABILITY ASSESSMENT OF BUILDINGS

Amir Safiey[1], Ershad Ziaei[2], Mengzhe Gu[3], Weichiang Pang[4], Keivan Rokneddin[5] and Mohammad Javanbarg[6]

ABSTRACT

The probability that a building is sanctioned to demolition following an earthquake depends on several geotechnical, structural, strategic and financial decision variables. This paper explores the literature on post-earthquake reparability assessment of buildings focusing on structural characteristics and evaluates their approaches for four midrise code-compliant structural systems, namely, steel moment frame, reinforced concrete moment frame, light frame wood, and steel braced frame. The structural responses are estimated using incremental dynamics analysis (IDA) in accordance with FEMA P-695 provisions and the IDA results are relayed to a building-specific loss assessment framework to estimate their seismic vulnerability in terms of monetary losses. To estimate the impact of irreparability fragility, the loss assessment framework evaluates the vulnerability for each reference model at four levels of irreparability thresholds as well as for a case which excludes irreparability. The results show that the projected losses for these reference models are very sensitive to the assumptions for irreparability fragility. The impact of irreparability fragility on the final loss estimates, while varying by reference model, is relatively limited at lower levels of shaking intensity and tends to grow when incrementing toward higher levels of shaking. The paper also discusses a potential numerical issue with the framework to include irreparability

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in loss estimation, called ‘irreparability anomaly’, which arises from merely linking irreparability to peak residual drift. The observations emphasize the significance of the underlying assumptions for irreparability fragility in seismic vulnerability and loss assessment of building and call for further studies to establish more robust procedures.

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Introduction

A study of earthquakes occurred within the United States over the past century reveals how development and enforcement of building codes has contributed to reducing fatality rate due to earthquakes. On the other hand, financial losses have been on the rise over the past century [1]. Catastrophe loss modeling has been in use to project losses due to damages to properties exposed to the earthquake peril. Catastrophe loss modeling is "a probabilistic model that estimates losses based on risk and vulnerability of exposure units for a foreseeable set of events" [2]. Vulnerability assessment plays a central role in catastrophe loss modeling by estimating the distribution of financial losses from any given event. While empirical vulnerability functions (also known as loss functions) may be developed by fitting statistical models to historical loss data –if sufficient data is available– analytically derived functions are also viable alternatives. Following the introduction of FEMA P-58 [3], component-based (assembly-based) vulnerability function development has been gaining momentum against inventory-based (a.k.a. class-based) vulnerability functions which are used in HAZUS-MH [4].

In addition to the building characteristics and local site conditions, the vulnerability of a building depends on post-earthquake decision-making variables. Following a series of destructive earthquakes and aftershocks in Christchurch, New Zealand in 2010 and 2011, a study on a group of reinforced concrete buildings in the Central Business District of the city that 'survived' the Christchurch earthquakes revealed that more than half of these buildings were eventually demolished [5]. However, a similar study in the United States for the 1989 Loma Prieta and 1994 Northridge earthquakes on a group of affected light-frame wood buildings suggests much lower rate of building demolishment [6]. Although no concrete conclusion can be drawn by comparing these two studies, however, it can be implied that the demolishment rate can vary from region to region in accordance with a set of variables, which decide if a building has become 'irreparable'. Irreparability in accordance with FEMA P-58 can be defined as making determination as to whether or not repair of a damaged building is impractical [3]. In the context of this paper, irreparability refers to the state of a structure being either unsafe or more expensive to repair than re-build. Whether a building is deemed irreparable is often determined by the adjuster working on behalf of the insurance carrier. The adjusters consider a few factors such as the clause in the policy which defines indemnity in terms of actual cash value or replacement cost, and, particularly for commercial buildings, the time element coverage. Since the time to repair a property can be longer than re-building, the business interruption costs can surpass those of the structural losses.

Kim *et al.* argued that irreparability is controlled by two types of major factors as follows: 1) 'building features' which includes structure specific characteristics such as height, structural system, etc. and 2) 'contextual factors' which includes parameters dealing with socio-economic environment of the building site, e.g. insurance policy, legislation, etc. [5]. Adopting a proper irreparability model in the vulnerability assessment framework contributes significantly to reliable loss estimations.

This study is conducted to shed light on the influence of irreparability on vulnerability assessment of building. First, different methods to predict irreparability of a specific building property is reviewed. Thereafter, four different midrise code-complying building reference models with different structural systems are studied for vulnerability function development with respective irreparability thresholds. The study focuses on code-compliant buildings, as the collapse prevention concept in seismic design codes highlights the influence of irreparability assumptions on the aggregated loss estimates. Next, an unintended consequence of the irreparability evaluation methodology introduced by employment of FEMA P-58 [3] in conjunction with FEMA P-695 [7] for developing vulnerability functions is examined, which is called 'irreparability anomaly'.

Review of Irreparability Models

A literature review of models for irreparability assessment of buildings shows three different main approaches, as follows:

The FEMA P-58 Approach

The FEMA P-58 approach proposes a global generic fragility function to assess irreparability, which utilizes the residual inter-story drift as a predictor for irreparability. It proposes that the irreparability fragility function follow lognormal distribution with a median residual inter-story drift of 1.0% and a dispersion (logarithmic standard deviation) of 0.3, regardless of the building features and contextual factors [3]. However, different researchers seemingly found this threshold to be too stringent (i.e. resulting in overestimation of losses), and proposed different values for parameters required for irreparability fragility function as summarized in Table 1.

Table 1. Summary of the view on the parameters of the irreparability fragility function.

Source	**Distribution**	**Median**	**Dispersion**	**Justification**
FEMA P-58 [3]	Lognormal	1.0%	0.3	Not provided.
Ramirez and Miranda [8]	Lognormal	1.5%	0.3	Expert opinion and field observation.
Reinforced Concrete Moment Frame by Jayaram *et al.* [9]	Lognormal	1.5%	0.39	Inclusion of epistemic dispersion in Ramirez and Miranda model.
Steel Moment Frame by Jayaram *et al.* [9]	Lognormal	1.85%	0.39	Inclusion of epistemic dispersion and relaxing the median in Ramirez and Miranda model.

The HAZUS-MH Approach

The HAZUS-MH [4] methodology does not explicitly incorporate the concept of irreparability. However, it can be inferred that irreparability assessment is integrated in the proposed whole-building fragility functions. Each structural fragility function consists of four damage states, namely, 'slight', 'moderate', 'extensive' and 'complete'. Complete damage state is further divided into two parts: 'collapse' and 'non-collapse'. Non-collapse part of the complete damage state can be interpreted as irreparable in HAZUS-MH. The high-code light frame wood building (W1) is taken as an example as shown in Fig. 1. In this figure, the blue curve marked with DS4 denotes the fragility curve for 'complete' damage state. The red curve marked with DS4 ($1-P_c$) shows the fraction of buildings, in terms of square footage, that are deemed 'complete' damage without structural collapses. As can be seen, the contribution of structural collapse to 'complete' damage is relatively low (i.e. the yellow curve marked with DS4 P_c). In HAZUS-MH, 3% of the area in each building that enters the complete damage state is assumed to collapse.

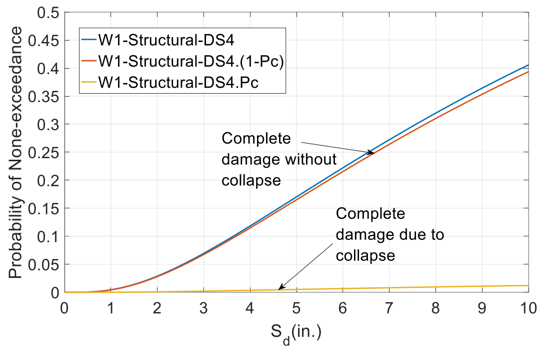


Figure 1. Decomposition of the complete damage fragility function in HAZUS' high-code light frame wood building (W1) to collapse and non-collapse (i.e., irreparability). P_c is the probability of collapse.

Field Data Driven Approaches

These approaches seek for a predictive model for irreparability based on observed reconnaissance data from past earthquake events. Two of such methods are briefly reviewed. The first approach relates irreparability to a concept called 'performance loss' (PL) of the building defined in terms of performance index (PI) [10]:

$$PL = 1 - \frac{PI'}{PI} \tag{1}$$

where, PL is defined as the ratio of the displacement capacity to displacement demand. PI is the performance index of the intact building, and PI' represents the performance index of the damaged building. Thereafter, repair cost (C_r) is described as a function of PL based on a regression conducted on the field data collected from the region shaken by the 2009 L'Aquila, Italy earthquake as follows:

$$C_r(PL) = 0.21 + 1.25.PL \tag{2}$$

The repair cost estimated by the above relationship can be used to make decision about reparability of a specific building asset [10]. It should be noted that the coefficients in Eqn. (2) are specific to the construction type of the region of interest. The second method relates irreparability to a series of parameters (predictors) based on a logistic regression model carried out on the field data obtained from the 2010 and 2011 Christchurch, New Zealand earthquakes [11]:

$$\ln\left(\frac{P}{1-P}\right) = -45.48 + 0.03x_2 - 1.65x_3 - 2.1x_6 - 0.2x_7 - 1.16x_{11} \tag{3}$$

where, P is the probability of reparability, $x_2$is construction year, x_3 is heritage status, x_6 is occupancy type, x_7 is number of floors and x_{11} is the damage ratio. More details on each of these parameters can be found elsewhere [11].

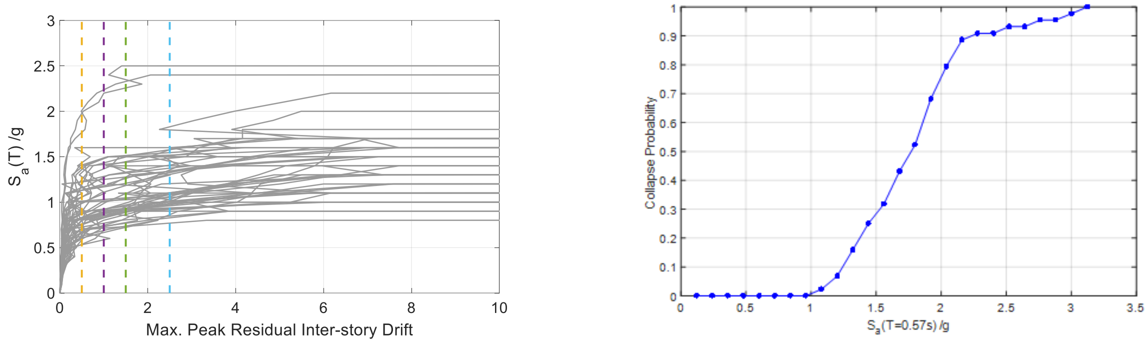
In general, the authors found the literature on irreparability models to be very limited. There is no experimental or analytical evidence to support the FEMA P-58 and HAZUS approaches. On the other hand, applicability of field data driven approaches are limited to a specific construction type and built environment. Field data driven methodologies with minor tweaks can be employed for seismic vulnerability assessment of buildings within the United States. However, adopted relationships in each framework needs to be recalibrated according to the United States construction practice. Particularly, there is not enough evidence to back the FEMA P-58 approach, which links irreparability solely to the peak inter-story residual drift. This approach will also result in a numerical stability issue during modeling, as explained later.

Vulnerability Assessment

This section reviews the vulnerability function development for four different reference models designed for seismic design category (SDC) of high seismic (D_{max}) as defined by FEMA P-695 [7] (S_s=1.5g and S_1=0.6g). Lateral load resisting systems considered in this study include light-frame wood shear walls, reinforced concrete moment frame, steel moment frame and steel concentric braced frame. Vulnerability function for each reference model is developed with different levels of median residual drift thresholds for irreparability to trace the influence of irreparability fragility on the predicted losses. The development of vulnerability function encompasses two main steps, namely, 'structural modeling' and 'performance modeling' as follows:

Structural Modeling

Incremental dynamic analysis (IDA) [12] using nonlinear response history procedure is employed to quantify the engineering demand parameters (EDPs) needed for performance modeling, i.e. peak inter-story drifts, peak floor accelerations and peak inter-story residual drifts of the building under different hazard levels. An ensemble of 22 pairs of bi-axial far-field ground motions developed as part of the FEMA P-695 project was utilized in this study [7]. This may limit the applicability of the results to loss assessment of buildings exposed to far-field ground motion. The IDA was carried out by scaling the median of the FEMA P-695 response spectrum at the fundamental period of the building to the target hazard levels. The time history analyses were performed on the computer clusters at Clemson University (Palmetto Cluster). The IDA results of light-frame wood reference model in terms of maximum peak inter-story residual drift versus the median scaled $S_a(T)$ are presented in Fig. 2(a). The corresponding collapse fragility curve is provided in Fig. 2(b). For the sake of brevity, IDA results of the rest of reference models are not presented here. Table 2 summarizes structural modeling of the studied reference models.



(a) (b)

Figure 2. Light frame wood IDA results: (a) IDA curves, and (b) collapse fragility curve.

Table 2. Summary of reference models.

Reference model lateral system	**Model dimension**	**Period (T_1)**	**Number of stories**	**Analysis Platform**	**Collapse simulation**	**Source**
Light-frame wood	3D	0.57s	4	Timber3D [14]	Simulated collapse	Based on [13]
Steel moment frame	2D	1.65s	4	OpenSees [15]	Non-simulated collapse	[16]
Steel concentric braced frame	2D	1.01s	6	OpenSees [15]	Non-simulated collapse	[16]
Reinforced concrete moment frame	2D	1.12s	4	OpenSees [15]	Simulated collapse	[17]

Performance Modeling

Structural modeling results are relayed to the performance model to predict different seismic performance metrics (i.e. downtime, repair cost or casualty) of the reference models. Vulnerability functions (a.k.a. damage functions according to insurance nomenclature) present the mean value of these performance metrics versus a given intensity measure. Vulnerability functions sought for in the present course of study describe the normalized repair cost or loss ratio –i.e., the mean damage ratio (MDR) – versus spectral acceleration at a given period of vibration (spectral acceleration) with a 5% damping. In this study, a MATLAB [18] toolbox is developed to conduct vulnerability assessments. The flowchart of the methodology adopted from FEAM P-58 [3] is presented in Fig. 3, schematically. The performance model consists of three Monte Carlo simulation (MCS) modules. In each realization of MCS, 'collapse state' is checked first followed by the 'reparability state' check. If neither of these states are materialized (i.e. the building is not collapsed and not deemed irreparable), a detailed loss estimation is conducted. The collapse state is checked using the raw collapse fragility curve obtained from IDA (see Fig. 2), which only accounts for record to record variability. Reparability is determined using a fragility curve conditioned on peak residual inter-story drift ratio, which assumes a lognormal distribution with a dispersion of 0.3. Four different median values for irreparability fragility functions are chosen (0.5%, 1.0%, 1.5% and 2.5%) to study the influence of this variable on the obtained vulnerability functions (Fig. 3). The first three median values are found in the literature [19, 3 and 8], respectively. The last one is a more liberal threshold (2.5%), which is being studied by the authors.

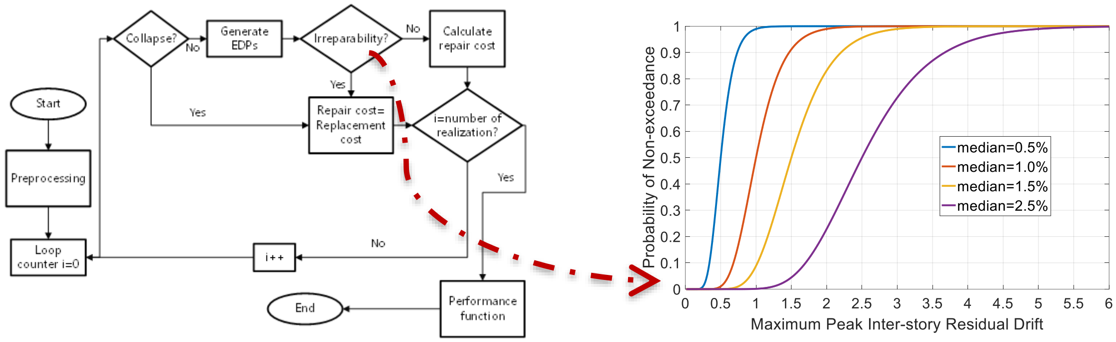


Figure 3. The flowchart of performance-based loss assessment procedure including four levels of irreparability fragility chosen for this study.

In performance modeling, a building is thought of as an assembly of components, either 'vulnerable' or 'rugged'. In order to assess the losses, components vulnerable to ground motions within the building envelope needs to be identified. Vulnerable components are chosen for commercial occupancy in accordance with FEMA P-58 accompanying clearinghouse of component fragility and consequence functions. Quantity of nonstructural components are obtained based on FEMA P-58 Volume 1 Appendix F normative quantities. Quantity of structural components are chosen based on details of each reference model.

Influence of Irreparability on Vulnerability Functions

Vulnerability function of each reference model is derived for four assumed median values of residual drift for irreparability assessment, and presented along with the corresponding collapse fragilities in Fig. 4. As an illustrative example, the four reference model buildings are assumed to be located in Seattle, WA (47.6207° N,122.3493° W). The MCE_R (risk-targeted maximum considered earthquake) spectral acceleration value for each reference model for the selected site is acquired from the USGS website [20], and presented along with vulnerability functions.

A quick examination of Fig. 4 reveals the significance of irreparability assumptions in the loss projection. The influence of irreparability on the vulnerability function can apparently surpass that of collapse. For the light-frame wood reference model, irreparability has insignificant influence on the loss within lower levels of shaking intensity. Comparison of losses estimated for the reinforced concrete reference model at different levels of irreparability shows it has the highest sensitivity to the irreparability assumption among the studied reference models.

Irreparability Anomaly

The described framework in Fig. 3 adopts the FEMA P-58 recommendation for irreparability assessment in conjunction with FEMA P-695 for structural analysis. For some reference models, this setup results in an anomaly in the developed vulnerability function. This anomaly arises from tying in irreparability solely with residual drift. One expects that the estimated loss ratios increase monotonically with increase in spectral accelerations. The vulnerability functions presented in Fig. 4 are developed by imposing the monotonic increase in vulnerability; however, the original light-frame wood reference model vulnerability function is presented in Fig. 5(a). In this figure, the vulnerability function without irreparability check is monotonically increasing. However, the rest of vulnerability functions considered irreparability, regardless of the adopted median residual drift, exhibit an unexpected drop between hazard levels of S_a = 1.7g and 1.8g. Fig. 5(b) presents the mean of non-collapse peak inter-story residual drifts obtained from IDA at all considered intensity levels. This figure shows a critical drop in the mean of the peak residual drifts between the above-mentioned two hazard levels (i.e. 1.7g and 1.8g), which resulted in redistribution of residual drifts and on average lower probability of irreparability. The occurrence of non-monotonic vulnerability functions is caused by the reduction of the number of non-collapse earthquake records or survival cases at high hazard levels (> 1.7g). The reduction of survival cases in turn resulted in loss of IDA records with large peak residual inter-story drifts as shown on Fig. 5(c). Fig. 5(d) presents loss distribution or performance function corresponding to hazard levels from 1.5g to 1.9g. Evidently, the loss distribution corresponding to 1.7g compared with that of 1.8g provides lower probability of non-exceedance for a given loss, contrary to expectations.

The authors surmise that many other factors can also contribute to irreparability anomaly as discussed above including, the number of considered ground motion records, increments of spectral acceleration and maintaining the same number of records resulting in building survival for all levels of shaking.

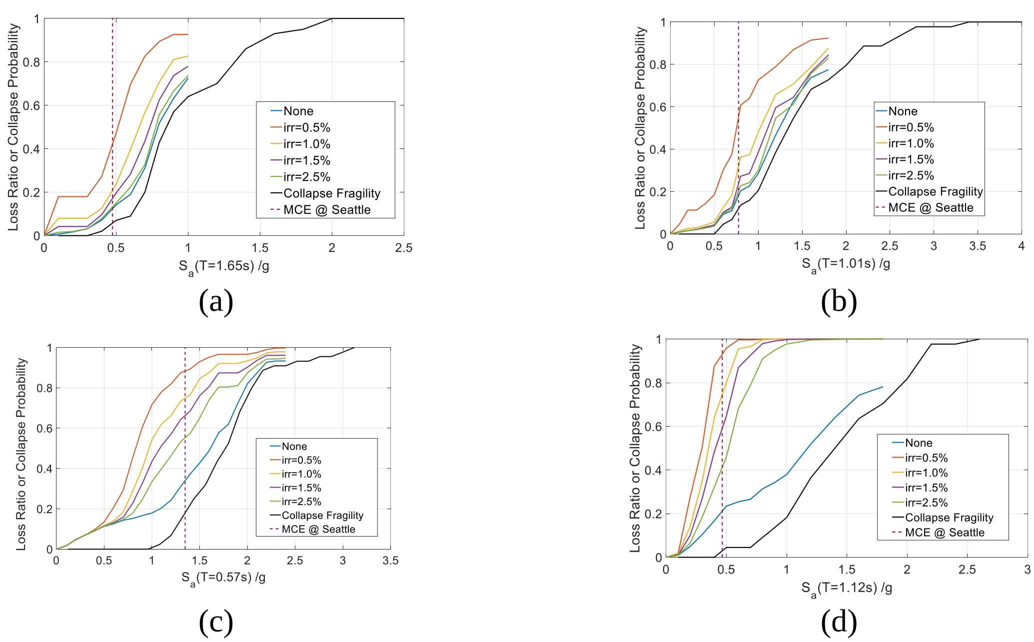


Figure 4. Vulnerability functions: (a) Steel moment resisting frame, (b) Steel concentric braced frame (c) Light frame wood and (d) Reinforced concrete moment frame.

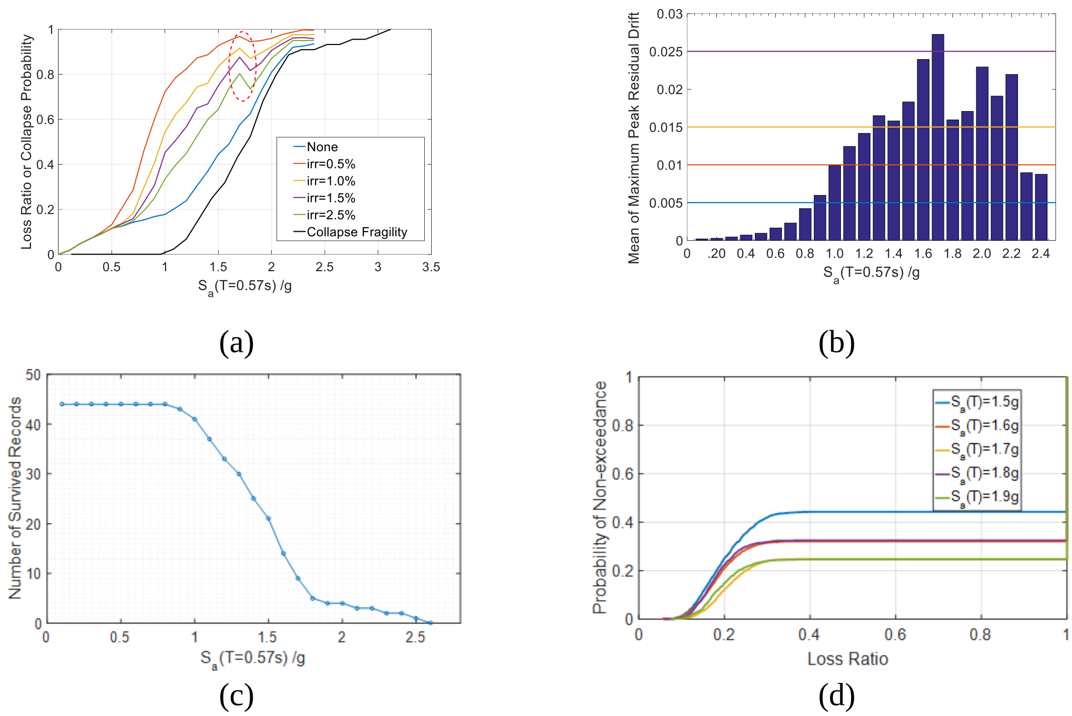


Figure 5. (a) Light frame wood reference model vulnerability function, (b) Mean residual drift versus spectral acceleration (c) Number of records resulting in survival versus spectral acceleration and (d) Performance functions for intensities in a range from 1.5g to 1.9g.

Conclusion

This paper discusses the significance of adopted irreparability assumptions in vulnerability function development. The following conclusion can be drawn from this study:

1. The pertinent literature on irreparability is relatively limited and can be categorized into three classes: FEMA P-58 approach, HAZUS-MH approach and field data driven approach.
2. Vulnerability functions for four midrise buildings with different structural systems are derived considering different levels of irreparability thresholds showing that the projected losses are highly sensitive to the assumptions of the median residual drift for irreparable.
3. Vulnerability functions developed for moment resisting systems is more sensitivity to irreparability possibly due to the inherent nature of moment resisting frame, which is designed to side sways in order to dissipate energy.
4. This study highlights a phenomenon called ‘irreparability anomaly’, which is caused by the result of incorporating residual drifts as the sole indicator of irreparability. This phenomenon violates the expectation that analytically-driven vulnerability functions are monotonically increasing with an increase in the ground motion intensity.

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