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Seismic Risk and Vulnerability Assessment of Mid-Rise Steel Building with Soft Story Effects

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ABSTRACT

Soft-story irregularity is one of the most critical forms of vertical structural irregularity that can significantly increase the seismic vulnerability of mid-rise steel buildings. This condition commonly occurs when the ground floor possesses substantially lower lateral stiffness than the upper stories due to certain architectural requirements such as open parking spaces, commercial areas, or reduced infill walls. During earthquake excitation, seismic demands tend to concentrate at the weaker story, resulting in excessive interstory drift, stiffness degradation, and potential collapse mechanisms. This study investigates the seismic performance and risk assessment using fragility towards a seven-story steel moment-resisting frame with a soft-story configuration in first floor subjected to seismic loading. A three-dimensional numerical model was developed in ETABS and analyzed using nonlinear static pushover analysis in both principal directions. Structural properties were defined according to Indonesian design code SNI 1729:2020, while seismic loading was applied based on the response spectrum specified in SNI 1726:2019 for Padang City. The resulting capacity curves were transformed into the Acceleration–Displacement Response Spectrum (ADRS) format to establish performance limit states corresponding to Slight, Moderate, Extensive, and Complete Damage. Fragility curves were subsequently developed using lognormal cumulative distribution functions and HAZUS value to quantify the probability of exceeding each damage state under increasing spectral displacement demands. The results indicate that seismic deformation is highly concentrated at the soft-story level, leading to rapid stiffness degradation and reduced post-yield capacity. The fragility assessment demonstrates a progressive increase in damage probability with increasing seismic demand, while the pushover results reveal significant directional differences in strength and ductility. These findings confirm that soft-story irregularity substantially influences the collapse potential of mid-rise steel buildings, highlighting the importance of performance-based seismic assessment for improving structural resilience in high-seismic regions.

1. Introduction

The rapid pace of urban development combined with limited land availability in high-seismic intensity regions of Indonesia has encouraged structural design in steel building to maximize floor space and clear out the groud floor. The consideration is aimed to accomodate open parking lots, commercial lobbies, or large retail spaces. While highly functional from an architectural perspective, ignoring structural mansory infill walls on the first level could possibly creates a structural vulnerability known as a soft-story irregularity. Furthermore, the steel members experience local buckling due to extreme distribution loads and inadequate stiffness. Columns and braces subjected to cyclic compression may experience local flange or web buckling due to repeated inelastic loading which result to structural instability[1], [2]. During strong earthquakes, structures experience an excessive interstory drift and seismic demand at the weak level, resulting in severe structural damage or partial collapse. The catastrophic vulnerability of soft story irregularity can be observed during global seismic events. In 2011, Christchurch, New Zealand experienced 6.2 magnitude earthquake that caused severe damage and sudden collapse to mid-rise reinforced concrete buildings. It was reported that vertical irregularity and inadequate lateral resistance contributed to column shear failure[3]. After 7.7 magnitude earthquake at Kahramanmaraş, Turkiye in 2023, statistical evidence identified soft-story irregularities as primary cause of catastrophic structural collapse under extreme seismic loading, accounting for a striking 82.7% of building failures[4]. This evidence proves that modern mid-rise structures suffer premature column failures when vertical stiffness is poorly distributed.

The hazardous of this structural configuration is recognized by the Indonesia seimic design code, SNI 1726:2019 which mean that the story's lateral stiffness is less than 70% of the story above. In terms of earthquake analysis, the presence of such a vertical irregularity disrupts the uniform distribution of lateral forces and displacements along the height of the structure[5]. Standard engineering practices typically evaluate these structural responses using dynamic linear methods, such as Response Spectrum Analysis (RSA) and Linear Time-History Analysis. Although the certain standard codes frequently rely on liniear elastic analysis due to design effectiveness, they are fundamentally inadequate for structures with severe vertical irregularities. Consequently, the actual seismic performance and collapse potential of these type of buildings are significantly underestimated, leading to unconservative assessments of structural safety and resilience. Therefore, this study implements a combination of Nonlinear Static Pushover Analysis and probabilistic fragility curves to quantify the structural capacity and damage probability of mid-rise steel buildings considering soft-story. By shifting conventional analysis to a performance-based and probabilistic framework, this research provides the risk assessments required to enhance the seismic resilience of irregular building for urban infrastructure in Indonesia.

2. Literature Review

2.1 The Mechanics of Soft-Story Failure

The soft-story phenomenon is concerned as the most critical vertical structural irregularities in modern earthquake engineering. By definition, a soft story occurs when the lateral stiffness of a particular building level is significantly lower than that of the floors above it. Structural design codes, including the Indonesian seismic provision SNI 1726:2019 calculate this irregularity when a story's lateral stiffness falls below 70% of the stiffness of the story immediately above, or less than 80% of the average stiffness of the three stories above.

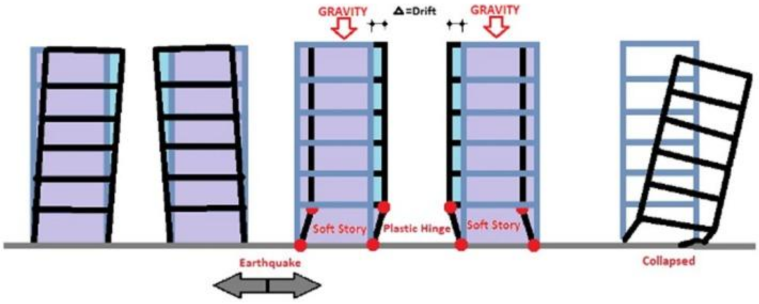

Figure 1. Soft-Story Mechanicsm in Multi-Story Building

Figure 1 illustrates how the collapse mechanism occur on soft-story building during a seismic event. An earthquake imparts dynamic lateral inertial forces distributed throughout the height of the building. In a regular, symmetrical structure, these lateral forces generate continuous shear stresses that transfer distributive force down to the foundation, causing the building to deflect uniformly. However, when a soft-story irregularity is introduced at the ground level, this continuous load path is abruptly severed. The upper stories experience slight relative interstory drift, moving essentially as a single, undeformed rigid body. This massive concentration of plastic demand forces the columns into extreme double-curvature bending, leading to the rapid and simultaneous formation of plastic hinges at both the top and bottom column joints[6]. Once these hinges form, the structure loses its static determinacy at the base, creating a classic story mechanism or sidesway collapse mechanism.

In structural steel buildings, such as moment-resisting or braced frames, the failure mechanics are governed by geometric instability due to particular steel sections are inherently determined either slender or non-compact, the extreme lateral drift concentrated at the soft story induces severe flexural yielding[7], [8]. Under the weight of the rigid upper floors, these yielded steel columns undergo rapid local flange buckling and global lateral-torsional buckling.

2.2 Nonlinear Static Pushover Analysis

Nonlinear Static Pushover Analysis (POA) is a performance-based structural engineering method used to evaluate the seismic capacity of a building. The lateral load is increased monotonically in small increments. As the displacement increase, the monitored points will inform which beams and columns crack or yield[9], [10]. The pushing continues until the building reaches a specified target displacement, the maximum expected drift during a design earthquake, or until the structure becomes unstable and collapses[5], [11]. The main result of a pushover analysis is the Capacity Curve, also known as the Pushover Curve. It plots the Base Shear (V) on the vertical axis against the Roof Displacement (Δ) on the horizontal axis.

2.3 Fragility Curves

Figure 2 shows the fragility curves that are commonly used to estimate the probability that a building will reach a certain level of damage under earthquake loading. The damage states represent the progression of structural deterioration from minor cracking to complete collapse which specifically describe in Table 2.1.

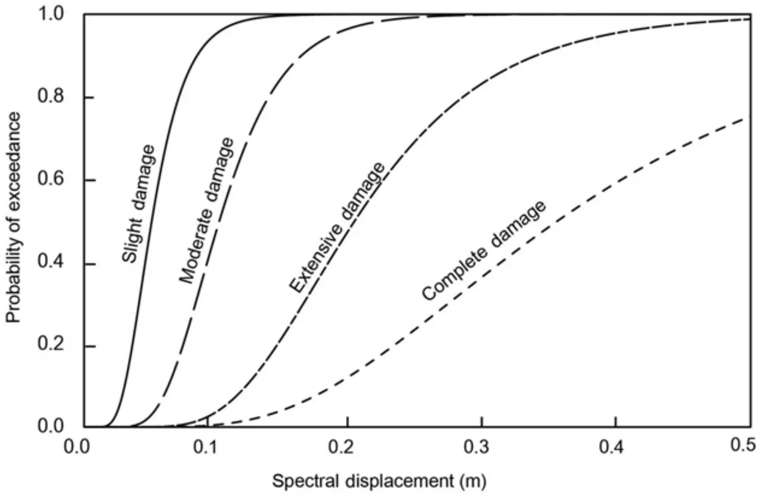

Figure 2. Fragility Curve

Table 2.1 Damage State Description

Damage	Description	Structural Condition
Slight Damage (DS1)	Minor cracks or initial yielding begin to appear in some structural components.	The building remains fully functional and safe to occupy. No significant loss of strength or stiffness occurs.
Moderate Damage (DS2)	Structural elements experience noticeable yielding and permanent deformation. Cracks become wider and some local damage develops.	The building remains stable but requires repair. Lateral stiffness begins to decrease, indicating the start of significant structural degradation.
Extensive Damage (DS3)	Severe damage develops in primary structural members, including heavy cracking, concrete spalling, reinforcement exposure, or local buckling of steel members.	Structural capacity is substantially reduced and the building approaches its collapse-prevention limit. Major rehabilitation is required before reuse.
Complete Damage (DS4)	Structural collapse mechanisms become active. Columns, beams, or bracing systems lose their ability to safely resist loads.	The building is considered near-collapse or collapsed and is generally beyond repair. Life safety can no longer be guaranteed.

3. Research Methodology

In general, the research methodology begins with the development of a representative mid-rise steel building model consisting of four stories and three bays using ETABS. The structural model incorporates a soft-story irregularity at the ground floor, representing a common building configuration where the first story is left open while the upper stories contain masonry infill walls. Material properties are defined using structural steel with a yield strength (fy) of 240 MPa, and seismic loading is assigned in accordance with SNI 1726:2019 using the design response spectrum Padang City ($SD_S = 0.93g$, $SD_1 = 0.68g$) with design seismic category D (high intensity). Nonlinear static pushover analysis (POA) is performed by applying a lateral load pattern proportional to the fundamental mode shape of the structure and incrementally increasing the load until the target displacement or structural collapse condition is reached. The resulting capacity curve is subsequently transformed into the Acceleration–Displacement Response Spectrum (ADRS) format to evaluate the seismic performance of the structure. Performance limit states are defined as Slight, Moderate, Extensive, and Complete Damage based on structural response parameters. Finally, fragility curves are developed using lognormal cumulative distribution functions to estimate the probability of exceeding each damage state under varying levels of earthquake intensity.

3.1 Structural Modelling

The structure shown in Figure 3 is a seven-story steel moment-resisting frame building with a regular plan configuration. This building is modeled using ETABS that consists of seven levels with a typical story height of 4.0 m, resulting in a total structural height 28 m. Each structural bay maintains a uniform span width of 4.0 m in both directions, establishing a squre plan 12.0 m x 12.0 m. The structural system is composed of steel columns and beams connected rigidly to resist dead and live loads. To potray the extreme condition of soft-story phenomenon, the first story possesses significant lower stiffness than the upper stories. In such cases, the upper stories become relatively stiff due to the presence of infill walls, while the first story remain flexible.

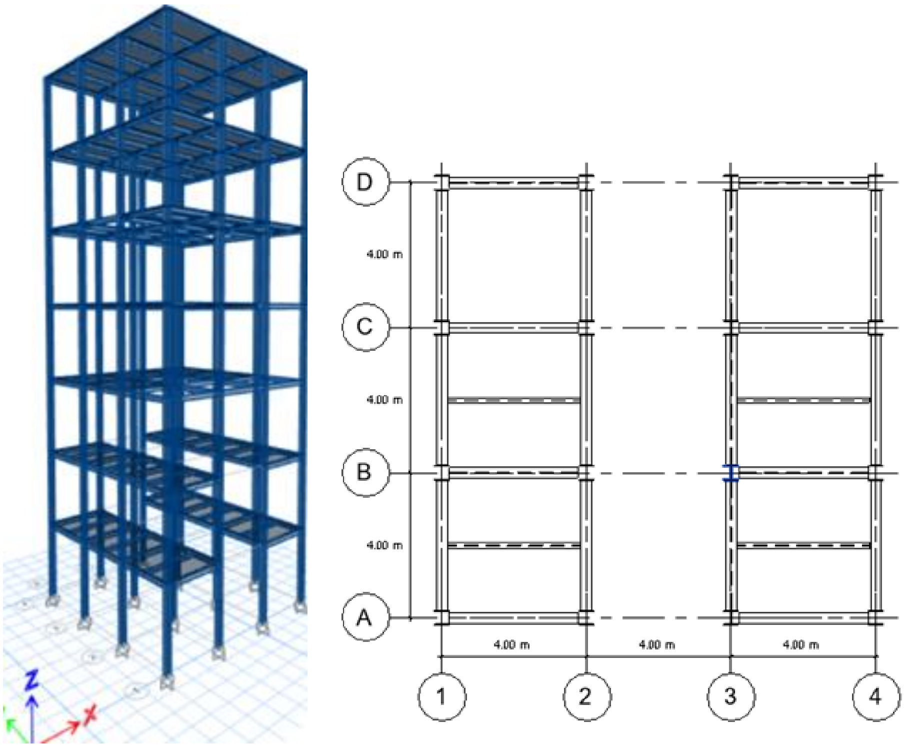

Figure 3. 7-Story Mid-Rise Steel Building Modelling and First-Floor Plan

Specific steel sections for each column and beam were summarized in Table 2.2. These sections also intentionally made the lateral stiffness drops severly, below the 70% threshold required by SNI 1726:2019.

Table 2.2 Damage State Description

Element	Base-Story-1	Story 2-7	Grade
Columns	H 300.300.9.14	H 350.350.12.9	ASTM A36 fy=250 MPa, fu=410 MPa
Beams	IWF 350.200.6.9	IWF 400.200.8.13	
Floor Systems	Composite Slab		fc'= 25 MPa
Mansonry Infill	Remain Open	Brick Walls	

3.2 Pushover Analysis and Fragility Curve

The standard pushover curve presents correlation between force (V) and deformation (Δ), however, earthquake demand is typically measured in Spectral Acceleration (S_a) and Spectral Displacement (S_d). To obtain building capacity with seismic risk, the standard pushover capacity curve must be converted into the Acceleration-Displacement Response Spectrum (ADRS) format using the fundamental mode properties of the building as expressed in Equation 1:

$$S_d = \frac{\Delta_{roof}}{\Gamma.\phi}$$

The spectral displacement (S_d) in Equation 2 is derived from maximum roof displacement (Δ_{roof}), the modal participation factor (Γ). and first modal displacement at roof (ϕ). The fragility function is then developed by defining the intensity measure and lognormal cumulative distribution, where DS denotes the damage state, λ represents median displacement and β is standard deviation obtained from HAZUS value[12], [13].

$$P[DS|S_d] = \phi\left(\frac{\ln(S_d) - \ln(\lambda)}{\beta}\right)$$

4. Result and Discussion

4.1 Pushover Curve Analysis

Figure 4 presents the nonlinear static pushover curves of the soft-story steel frame in both the X-direction and Y-direction, expressed in terms of base shear versus monitored roof displacement. These curves represent the progressive evolution of structural behavior from the elastic stage through yielding, strength degradation, and post-peak response, providing valuable insight into the seismic performance and collapse mechanism of the structure.

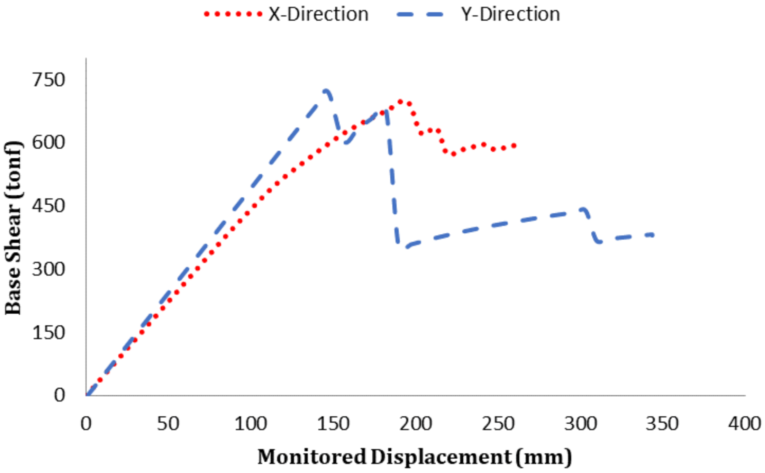

Figure 4. Pushover Curves for both X and Y Direction

The initial portions of both curves exhibit an approximately linear relationship between base shear and displacement, indicating elastic behavior of the structural system. In this region, lateral stiffness remains constant and the structure effectively resists seismic forces without significant damage. As displacement increases, nonlinear behavior begins to develop due to yielding of critical structural components, resulted plastic hinge at column. The X-direction reaches its maximum base shear capacity of 698,66 ton at a displacement of around 193,2 mm, whereas the Y-direction attains a 2,8% higher peak resistance of approximately 717,93 ton at a displacement of about 145,6 mm. This difference indicates that the Y-direction possesses greater initial lateral strength but lower deformation capacity compared to the X-direction. A significant distinction emerges after the peak load is reached. The Y-direction experiences a sudden reduction in base shear from approximately 335,2 ton, corresponding to a strength loss of 54%. Such abrupt degradation is characteristic of a soft-story mechanism, where localized damage at the ground floor rapidly reduces the lateral load capacity of the structure. This behavior suggests the formation of concentrated plastic hinges, local and lateral buckling of steel members, or severe stiffness deterioration within the first-story columns and beam-column connections.

Furthermore, the structural inelastic behavior at the X-direction demonstrates slight ductility and collapse resistance, whereas the Y-direction exhibits a brittle response characterized by rapid strength degradation after yielding. The profound post-peak drop in the Y-direction strongly indicates the activation of a soft-story collapse mechanism, where seismic demand becomes concentrated at the lower level, causing premature deterioration of the primary lateral force-resisting system. Overall, the pushover results illustrate that the structure possesses adequate initial strength in both directions, however, its inelastic performance is highly direction-dependent. The substantial strength degradation observed in the Y-direction suggests that seismic vulnerability is governed primarily by first-story damage concentration and stiffness irregularity.

4.2 Fragility Curve Analysis

The fragility curves presented in Figure 5 illustrate the probability of exceeding four structural damage states, namely, Slight (DS1), Moderate (DS2), Extensive (DS3), and Complete Damage (DS4), as a function of spectral displacement (Sd). Firstly, the parameters were generated from the pushover analysis by considering first mode participation factor and associated HAZUS values for steel moment frame. These curves also provide a probabilistic representation of the seismic vulnerability of the soft-story steel frame by quantifying the specific damage threshold will be exceeded under increasing earthquake demand.

Table 2.3 Spectral Displacement at Yield and Ultimate

$\Delta_{roof\ (yield)}$ (mm)	$\Delta_{roof\ (ult)}$ (mm)	$S_{d\ (yield)}$ (mm)	$S_{d\ (ult)}$ (mm)
40,1	75,8	86,8	162,7

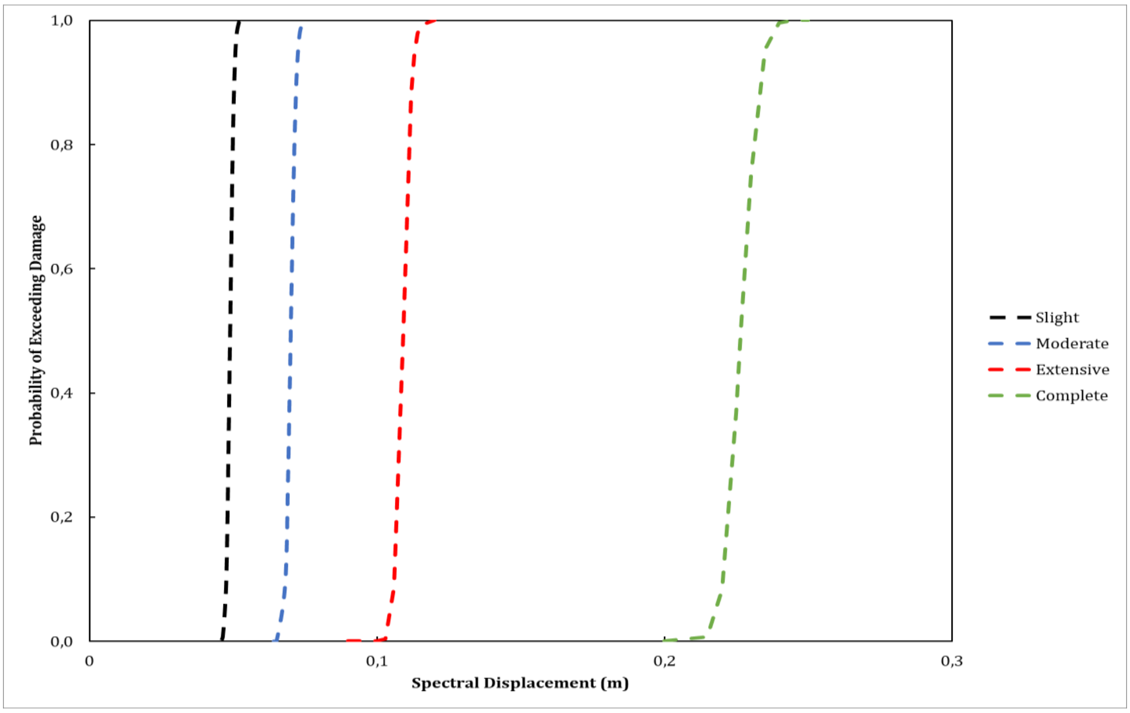

Figure 5. Fragility Curve for Soft-Story Steel Building

A clear rightward progression of the fragility curves is observed as the damage state becomes more severe. The Slight Damage (DS1) curve initiates at a spectral displacement of approximately 0.05 m, indicating that the onset of minor yielding and localized damage occurs under relatively low seismic demand. At this stage, the structure remains essentially elastic, with negligible loss of stiffness and strength. The steep slope of the DS1 curve suggests low uncertainty in the initiation of first yielding, implying that the structural response is relatively predictable within the elastic range.

The Moderate Damage (DS2) curve is centered around a spectral displacement of approximately 0.07 m. This damage state corresponds to widespread yielding of structural components and the beginning of significant stiffness degradation. The transition from DS1 to DS2 occurs over a relatively narrow displacement interval, indicating that once the elastic limit is exceeded, damage accumulation progresses rapidly. Such behavior is typical of soft-story structures where deformation demand is concentrated within a limited number of structural elements, particularly at the ground floor.

The Extensive Damage (DS3) curve exhibits a median displacement capacity of approximately 0.11 m. This stage represents severe deterioration of the lateral force-resisting system, including plastic hinge development in columns and beam-column connections, local buckling of steel members, and significant residual drift. The relatively small displacement increases between DS2 and DS3 suggests that the structure possesses limited reserve capacity after yielding. This finding is characteristic of soft-story mechanisms, where damage localization accelerates structural degradation and reduces the ability of the frame to redistribute seismic forces.

The most significant result is observed in the Complete Damage (DS4) fragility curve, which is centered near a spectral displacement of 0.23 m. The substantial separation between DS3 and DS4 indicates that although severe structural damage develops relatively early, the building retains a certain degree of residual ductility before collapse. In other words, the structure continues to dissipate energy through inelastic deformation after extensive damage has occurred. This behavior is advantageous from a life-safety perspective because it provides warning before total structural failure.

From a seismic risk perspective, the results demonstrate that the soft-story steel frame is highly sensitive to increasing displacement demand. The probability of exceeding slight and moderate damage becomes significant at relatively low spectral displacements, confirming the vulnerability of the ground-story structural system. Furthermore, the relatively close spacing between DS2 and DS3 indicates a rapid progression from repairable damage to near-collapse conditions. Therefore, seismic retrofitting strategies aimed at increasing first-story stiffness and ductility, such as the addition of steel bracing, buckling-restrained braces, or damping systems, would be expected to shift the fragility curves toward higher displacement capacities and reduce the probability of severe damage and collapse.

Overall, the fragility curves confirm that the soft-story configuration governs the seismic performance of the structure by concentrating deformation demand at the lower level, accelerating damage accumulation, and increasing the likelihood of severe structural damage under moderate-to-strong earthquake excitation. These findings highlight the importance of explicitly considering soft-story effects in performance-based seismic assessment and fragility-based risk evaluation of steel frame buildings

5. Conclusion and Recommendation

1 The mid-rise steel building with a soft-story irregularity exhibits significant seismic vulnerability due to the concentration of lateral deformation at the ground floor. The pushover analysis revealed that the first story attracts the majority of the interstory drift demand, resulting in localized yielding, stiffness degradation, and the formation of plastic hinges in critical structural members. This behavior confirms that vertical stiffness irregularity strongly influences the nonlinear seismic response of steel frame structures.

2 The fragility analysis demonstrates that the probability of reaching severe damage states increases rapidly as seismic demand increases. The close spacing between the Moderate Damage (DS2) and Extensive Damage (DS3) fragility curves indicates a limited reserve capacity after initial yielding. Furthermore, the Complete Damage (DS4) curve highlights the susceptibility of the structure to collapse once significant deterioration develops at the soft-story level, emphasizing the importance of considering collapse mechanisms in seismic performance assessment.

3 The pushover results indicate different structural behaviors in the two principal directions, despite the building having similar geometric characteristics. While both directions exhibited adequate initial strength, the Y-direction experienced a profound post-peak strength degradation, suggesting a greater tendency toward soft-story collapse. This finding highlights the importance of evaluating directional effects when assessing the seismic performance of mid-rise steel buildings with vertical irregularities

This study has several limitations that should be considered when interpreting the results. The seismic performance assessment was conducted using nonlinear static pushover analysis, which cannot fully capture dynamic effects such as higher-mode responses, cyclic loading, duration effects, and record-to-record variability associated with real earthquake events.Future research should therefore incorporate nonlinear time-history analysis using multiple earthquake records, investigate the effects of various masonry infill configurations, evaluate different steel structural systems and building heights, and integrate uncertainty analysis into fragility assessment. Moreover, machine learning techniques may be employed to develop predictive fragility models, while the effectiveness of seismic retrofit strategies such as bracing systems, dampers, and base isolation can be explored to improve the resilience of soft-story steel buildings in high-seismic regions.

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