

Article

Investigation of Soft Story Irregularity in RC Structures via Pushover Analysis: From 2D Frames to 3D Buildings

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Abstract

Soft story irregularity poses a critical seismic risk to existing building stocks. While current seismic codes define stiffness irregularity factors to detect this vulnerability, they are typically evaluated based solely on initial elastic properties. This study investigates the evolution of these code-defined factors (ASCE/SEI-7, UBC, NBC, TBEC-2018, and BSL) within the post-elastic range to examine how structural damage affects soft story irregularity. The methodology comprises two phases: a low-strength RC plane frame (Case A) and a parametric study on a 3D RC building with incrementally increased ground story heights (Case B). Nonlinear pushover analyses were conducted to track the variation in irregularity factors at each pushover step and examined graphically. Results demonstrate that soft story behavior is not a static characteristic; irregularity factors deteriorate significantly as plastic hinges form. Crucially, several models that initially satisfied code limits in the elastic range eventually exceeded irregularity thresholds under inelastic behavior. This indicates that relying solely on initial stiffness may mask latent irregularities emerging during seismic actions. Consequently, to capture the true severity of soft story mechanisms, it is recommended that stiffness irregularity factors be evaluated at target displacement levels corresponding to the design earthquake.

Keywords: stiffness irregularity factor; soft story; international codes; nonlinear pushover; reinforced concrete



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1. Introduction

Field investigations in earthquake-prone regions worldwide have consistently identified low concrete strength and various construction defects in reinforced concrete (RC) buildings. These deficiencies, particularly prevalent in the older building stock, can lead to catastrophic failure when coupled with structural irregularities. The seismic vulnerability, dynamic behavior, and global collapse mechanisms of RC structures are significantly governed by various sources of structural irregularities. Generally, these geometric and mechanical discontinuities can be broadly classified into two main categories: irregularities in plan and irregularities in height.

Irregularities in plan typically include torsional irregularity, diaphragm discontinuities, and re-entrant corners. Torsional irregularity occurs when the eccentricity between the center of mass and the center of rigidity exceeds a specific limit due to the asymmetric layout of the lateral force-resisting elements. Diaphragm discontinuities refer to the presence of large openings or vertical shafts (e.g., stairwells, elevator cores) that disrupt the rigid diaphragm behavior of the floor slab and induce stress concentrations. Re-entrant corners

(projections in plan) involve building footprints with “U, L, T, Y, or H” configurations that strongly amplify torsional modes, or structural overhangs (e.g., cantilevered balconies) that complicate global system behavior.

Conversely, irregularities in height generally encompass weak stories, soft stories, and the vertical discontinuity of lateral force-resisting elements. A weak story is defined by a significant reduction in the effective shear area (lateral strength) compared to the adjacent story. A soft-story irregularity is associated with a sudden reduction in lateral stiffness or a corresponding drastic amplification in the interstory drift ratio. Finally, vertical discontinuity involves hazardous load paths where vertical structural elements (e.g., columns, shear walls) deviate from their axes, are abruptly terminated, or are subjected to indirect loading—such as resting a column on a cantilevered edge, transferring shear wall forces onto supporting beams or columns, or planting a column mid-span on a beam.

The complex nonlinear behavior induced by these irregularities often challenges the reliability of conventional static assessment procedures, necessitating more advanced evaluation approaches such as nonlinear static (pushover) analysis. The investigations conducted by Ruggieri and Uva [1,2] may be regarded as representative examples of this. They investigated the reliability of the response spectrum analysis (RSA)-based load pattern definition, as described in recent codes for pushover analyses, by comparing it with traditional uniform and inverse-triangular lateral loading patterns on new and existing archetype buildings with varying degrees of in-height irregularities. The results demonstrated that the RSA-based loading pattern approach provided no significant improvements over conventional methods in predicting dynamic responses [1]. They also investigated the effectiveness of pushover analysis guidelines described in latest release of the Italian Building Code in evaluating spatial variability and the seismic response of archetype-RC buildings characterized by varying degrees of in-plan structural irregularity. To achieve this, the authors generated a set of three-dimensional archetype models with progressively modified centers of stiffness and conducted a comparative sensitivity analysis to assess both global and local structural performance [2].

Among the structural irregularities governing the dynamic response of buildings, soft story irregularity (i.e., vertical stiffness irregularity) stands out as a critical vulnerability. Structures exhibiting this irregularity are susceptible to local or total collapse due to loss of stability during strong ground motions. Consequently, the assessment of soft story irregularity in existing buildings is fundamental to characterizing their seismic behavior and enhancing overall structural safety.

In the literature, the influence of soft story irregularity on structural behavior has frequently been examined by increasing the height of the ground story. Studies by Yousef et al. [3], Döndüren and Nakipoğlu [4], Khanal et al. [5], and Zavala et al. [6] investigate soft story irregularity according to various building codes. Specifically, Döndüren and Nakipoğlu [4], Khanal et al. [5], and Merajuddin and Azeem [7] analyzed buildings with varying degrees of soft story irregularity by altering ground story heights. Regarding the identification of soft story conditions, Yousef et al. [3] utilized UBC-97 (IBC-2000), Eurocode 8 (EC-8), the Egyptian Load Code (ECL-08), and ESEE-88; Döndüren and Nakipoğlu [4] considered DBYBHY-2007, IS 1893-1-2002, ASCE 7-2002, and the Japanese code; Khanal et al. [5] evaluated the Japanese, Turkish, and IS codes; and Zavala et al. [6] applied ASCE/SEI 41-13. Both Döndüren and Nakipoğlu [4] and Khanal et al. [5] concluded that the Japanese code tends to yield more conservative assessments for soft stories. Furthermore, Zavala et al. [6] incorporated P- Δ effects in their study. Their findings indicate that the significance of P- Δ effects increases when stiffness irregularity exists in lower stories; stiffness reductions of up to 56.30% were observed due to this irregularity, and structures evaluated considering both stiffness irregularity and P- Δ effects developed a higher number

of plastic hinges. Furthermore, Nezhad and Poursha [8] evaluated the seismic demands of vertically irregular frames along the height of building and noted that while Modal Pushover Analysis (MPA) and Consecutive Modal Pushover (CMP) are generally reliable, they may underestimate the plastic rotation demands in structures with significant stiffness or strength irregularities along the height.

Regarding the determination of the code-defined interstory stiffness ratio (k_{i+1}/k_i), Tabeshpour and Noorifard [9] conducted a comparative study using various lateral load distributions for stiffness computation. They concluded that a triangular distribution resembling seismic forces yields both acceptable accuracy and the desired computational efficiency. Vijayanarayanan et al. [10] proposed a procedure for assessing the presence of stiffness irregularity based on the normalized fundamental lateral translational mode shape. They derive the relationship from the ratio of story stiffness ratio (k_{i+1}/k_i) based on the undamped free vibration equation of a multiple-degree-of-freedom system. The study conducted by Inan et al. [11] evaluates the effects of different plan geometry by parametric seismic analysis. While the study confirmed that T-shaped models maintained stiffness irregularity coefficient (η_{ki}) below the code limit of 2.0, it highlighted a progressive increase in these coefficients as building height increased.

Research has also addressed soft story irregularity arising from the omission of infill walls. For instance, Arlekar et al. [12] investigated the seismic response of nine reinforced concrete models by varying the presence of infill walls at the ground story. Their results demonstrated that the removal of infill walls induced pronounced soft story behavior, resulting in higher displacement and strength demands at the ground level. In addition, the study conducted by Santhi et al. [13] emphasizes that the concentration of damage in the open ground floor necessitates specific detailing to accommodate the high ductility demand on columns. Their pushover and experimental analysis conducted by authors revealed that soft-story frames exhibit a shear demand 2.5 times greater than bare frames, accompanied by a critical reduction in ductility. Islam et al. [14] conducted numerical simulations on soft-story buildings lacking masonry infill at the retail level and concluded that base isolation is a superior mitigation strategy compared to fixed-base designs and they highlighted that the optimization of isolation properties are important. Tasleem et al. [15] evaluated the seismic vulnerability of open ground story buildings using nonlinear time history analysis, incorporating soil-structure interaction and masonry infill as diagonal strut elements. Their study revealed that the absence of infill wall stiffness in numerical models leads to excessive drift demands, whereas modeling the infill as struts significantly mitigates the soft-story effect. Furtado et al. [16] investigated how the presence and distribution of central openings in masonry infill walls affect the seismic behavior of RC frames. The vertical irregularity due to the distribution of openings modifies the initial stiffness values and maximum resistance by between 10 and 25 findings revealed that infill wall openings drastically diminish the natural frequencies, lateral stiffness, and load-bearing capacity of the structure, shifting its dynamic characteristics and change potential failure modes. Mohabbi [17] investigated the performance and damage index of RC frames across various masonry infill configurations, including the soft-story case, by employing both nonlinear static pushover and time-history analyses. Soft-story configuration exhibited a 65% reduction in displacement capacity, low structural ductility and concentrated damage at the ground level, resulting in a brittle failure mechanism and a heightened risk of premature collapse.

Concerning the mitigation of soft stories with retrofitting techniques, in addition to Islam et al. [14], Öztürk et al. [18] examined the impact of soft story irregularities on seismically isolated structures. They revealed that increasing the ground story height leads to higher story accelerations and drifts compared to regular frames. However, the study confirmed that by ensuring the superstructure's lateral stiffness is at least 20 times (k_1/k_{iso})

that of the isolation system, damage at the soft story level can be effectively avoided. Dereje and Kim [19] introduced an optimization-based retrofit strategy for soft-first-story buildings using viscoelastic dampers to mitigate the risks associated with parameter uncertainties. The results confirmed that the framework delivers robust solutions capable of preventing excessive drifts in the vulnerable first story, regardless of variations in soil conditions or damper characteristics. Beyond seismic retrofitting of soft stories, the deployment of advanced intelligent algorithms continues to broaden the scope of structural optimization across various domains. As a recent example of this versatility, modified algorithms, such as the strengthened elitist genetic algorithm (SEGA), have been successfully implemented to optimize the intricate geometric and cross-sectional parameters of prestressed stayed steel columns [20].

Conversely, research has also extended to soft story irregularities at locations other than the ground level. Parekar and Datta [21], Adhav and Birajdar [22], El-Salakawy et al. [23] and Ujwal et al. [24] analyzed configurations featuring soft stories at the ground, intermediate, and top levels. Parekar and Datta [21] reported that soft story irregularity amplified interstory drift ratios at the soft story and adjacent levels, whereas drifts in the remaining stories decreased. They concluded that stiffness irregularity at lower levels exerts a more severe impact than at upper levels. Similarly, Adhav and Birajdar [22] observed that structural ductility diminishes as the soft story height increases and the most significant reduction was recorded in the soft ground story model, while the soft top story model exhibited the least reduction. Specifically, for a case where the ground story possessed 70% stiffness irregularity, a 14% reduction in ductility was noted. El-Salakawy et al. [23] determined that the response modification factor (R) varies significantly with the position of soft stories. Contrary to standard code estimates, the analysis revealed that soft story irregularities in lower floors lead to higher R values, whereas those in upper stories result in a decrease in the factor. Finally, Ujwal et al. [24] investigated the stiffness irregularity through response spectrum and equivalent seismic load analyses, with particular emphasis on stiffness variations. It was reported that soft stories occurring at upper stories were found to preserve the overall structural stiffness more effectively and to provide a more favorable structural response.

Furthermore, Işık et al. [25] investigated the short column problem across various structural irregularities, placing primary emphasis on the soft story effect and stiffness distribution. They conducted a comparative analysis of the short column effect in structures on sloping ground, those with band windows, and those with mezzanines, benchmarking them against a regular reference model. Utilizing both strength-based and deformation-based design approaches, the study evaluated stiffness irregularities and element damage. The results indicated that while the presence of short columns shortened the fundamental period, these elements reached their plastic rotation limits even under low seismic demands. The authors recommended extending this analysis in future research to include low-strength concrete and structural defects that compromise shear capacity [25]. Lakshmanan et al. [26] performed dynamic analyses and system identification on regular, weak-story, and soft-story structural systems. They compared the mode shapes, natural frequencies, and damage indices, and extracted the displacement profiles using wavelet-based multi-resolution analysis and concluded that soft-story irregularity lead to higher damage concentration on columns. Additionally, several studies have focused on defining alternative irregularity indices and establishing their corresponding limit values [27–32].

A review of the literature indicates that studies on buildings with soft story irregularities primarily focus on interstory drifts, story stiffnesses, effect of infill wall elimination, effect of soft story placement, mode shapes, natural periods, member damages, mitigation with retrofitting and standard code-based assessments of severity. While this study also

examines member damage and code compliance, it distinguishes itself by evaluating the evolution of stiffness irregularity factors (indices), which are defined as criteria in building codes, under both linear and nonlinear structural behavior. Rather than merely calculating the initial degree of irregularity, the results derived from the finite element model are presented graphically to illustrate how these factors change throughout the elastic and inelastic ranges. Departing from the conventional practice where code-defined stiffness irregularity factors are determined exclusively via linear analyses, this study scrutinizes these parameters through the lens of nonlinear assessment. Consequently, this research extends the evaluation into the nonlinear domain, capturing the critical post-yield behavior of soft stories.

The study further presents a finite element analysis of a two-story reinforced concrete plane frame, designated as Case A, which features low concrete strength and a deliberately weakened ground story to represent deficiencies common in the existing building stock. The objective is not merely to perform an irregularity assessment, but rather to investigate soft story irregularity using code-defined factors alongside the inelastic behavior of the structure. The numerical results provided for this specific case establish a comprehensive analytical baseline for the laboratory specimen, which will be the subject of planned future experimental investigations. To generalize these findings to real-world structures, the study extends its scope to Case B, a parametric investigation of a 3D reinforced concrete building. In this phase, the ground story height was incrementally increased to comparatively analyze the variation in soft story irregularity indices as the severity of the irregularity intensified. Based on the analysis results, the evolution of the stiffness irregularity coefficient, the adjacent story stiffness ratio, and the reciprocal of the story drift angle (defined as the ratio of the reciprocal of each story's drift angle to the average reciprocal drift angle of all stories) was evaluated as a function of top displacement.

2. Theoretical Methodology

2.1. Detection of Soft Story Irregularity

Building codes stipulate specific criteria for the detection of soft story (i.e., stiffness) irregularity. These criteria are generally formulated as mathematical inequalities, with calculations performed on a story-by-story basis. Satisfying these inequalities indicates that the analyzed story exhibits soft story irregularity. Different codes employ varying criteria to determine whether a story is classified as a soft story. For instance, the Turkish Building Earthquake Code (TBEC-2018) [33] defines a stiffness irregularity coefficient. This coefficient, computed as the ratio of the average interstory drift ratios between adjacent stories, indicates the presence of soft story irregularity when its value, denoted as η_{ki} , exceeds the threshold value of 2.0 [33].

$$\eta_{ki} = \frac{\frac{\Delta_i}{h_i}}{\frac{\Delta_{i+1}}{h_{i+1}}} > 2 \quad (1)$$

In Inequality (1), i denotes the story level under assessment; η_{ki} represents the stiffness irregularity coefficient (i.e., factor); h_i , is the corresponding story height; and Δ_i is the relative story displacement (interstory drift).

According to the Uniform Building Code (UBC-97), the predecessor to the International Building Code (IBC), a soft story is directly defined as a story where the lateral stiffness is less than 70% of the story above, or less than 80% of the average lateral stiffness of the three stories above [3]. The American Society of Civil Engineers (ASCE/SEI 7-10) [34] standard, in alignment with the International Building Code (IBC), stipulates a similar criterion for soft stories but further distinguishes an 'extreme soft story' condition. This

severe irregularity is defined as existing “where there is a story in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above” [34] (p. 83). Similarly, the National Building Code of Canada (NBC) considers stiffness irregularity to exist when the lateral stiffness of any story is less than 70% of that of an adjacent story, or less than 80% of the average stiffness of the three stories above or below [35]. Likewise, other international standards such as the Indian Seismic Code (IS 1893:2002), Bangladesh National Building Code (BNBC-1993), and New Zealand Standard (NZS 1170.5), prescribe same comparable criteria based on lateral stiffness ratios [4,5,36,37]. In this study, the most critical threshold, which satisfies the encompassing limits of all three codes, corresponds to the extreme soft story criterion (ASCE/SEI 7-10), as formulated in Inequality (2) and (3).

$$\frac{k_{i+1}}{k_i} > 1.67 \quad (2)$$

$$\frac{k_m}{k_i} > 1.43 \quad (3)$$

In Inequality (2), k_i denotes the lateral stiffness of i th story, and k_{i+1} represents the stiffness of the story immediately above. The threshold value of 1.67 corresponds to the reciprocal of 60% (i.e., $1/0.60 \cong 1.67$). Exceeding this limit indicates the presence of stiffness irregularity in accordance with UBC, ASCE, and NBC (as well as the other aforementioned) codes. It should be noted that since the investigated frame system (Case A) consists of only two stories, the criterion specified in Inequality (3), which considers the mean stiffness of the three stories above, is not applicable. In this expression, k_m denotes the average lateral stiffness of the three stories above the considered story. However, Inequality (3) was explicitly considered in the parametric study of the three-dimensional four-story RC building (Case B), serving to complement and generalize the insights derived from the frame analysis.

As observed, while the ASCE, UBC, and NBC codes evaluate stiffness irregularity using ratios of story lateral stiffness, the Turkish Building Earthquake Code (TBEC-2018) characterizes stiffness irregularity based on interstory drift ratios. Distinctively, the Japanese seismic design code (BSL) adopts an approach based on the reciprocal of the story drift angle (drift ratio) and the arithmetic mean of these values across all stories.

According to the Building Standard Law (BSL) of Japan [38], a soft story irregularity is deemed to exist when the parameter R_{si} , defined as the ratio of the reciprocal of the story drift angle to the arithmetic mean of the reciprocals of the drift angles for all stories, falls below the limit value of 0.6 [4,5,35].

$$R_{si} = \frac{r_{si}}{\bar{r}_s} < 0.6 \quad (4)$$

$$\bar{r}_s = \frac{\sum_{i=1}^n r_{si}}{n} \quad (5)$$

Here, n denotes the total number of stories; i indicates the corresponding story level; and r_{si} , represents the reciprocal of the story drift angle (i.e., the inverse of the interstory drift ratio), calculated as the ratio h_i/Δ_i [39]. Furthermore, $\bar{r}_s$ corresponds to the arithmetic mean of the reciprocal drift angles of all stories, as defined in Equation (5).

To facilitate a meaningful comparison among the stiffness irregularity factors defined in the codes, namely η_{ki} , k_{i+1}/k_i , and R_{si} , the directions of the inequalities were aligned. Since the inequality in Inequality (4) is opposite to those in Inequality (1) and Inequality (2), it was inverted. Consequently, the parameter R_{si}^{-1} was introduced in Inequality (6), with a corresponding threshold value of 0.6–1 (approx. 1.67). Satisfying Inequality (6) is, therefore, mathematically equivalent to satisfying Inequality (4) in the context of stiffness irregularity

verification. This adjustment ensures that all international codes investigated in this study share a consistent criterion format, specifically ‘greater than the limit value’.

$$R_{si}^{-1} = \frac{\bar{r}_s}{r_{si}} > 1.67 \quad (6)$$

The soft story irregularity factors defined in the international codes and examined in this study are summarized in Table 1, with their inequality limit value.

Table 1. Summary of code-defined criteria evaluated in this study.

Code	Factor	Expression	Condition	Limit Value
ASCE/SEI-7-10 ¹	k_{i+1}/k_i	$\frac{k_{i+1}}{k_i}$	To Be Greater Than	1.67
	k_m/k_i	$\frac{k_{i+1}+k_{i+2}+k_{i+3}}{3k_i}$	To Be Greater Than	1.43
TBEC-2018 ²	η_{ki}	$\frac{\Delta_i}{h_i}$	To Be Greater Than	2.00
		$\frac{\Delta_{i+1}}{h_{i+1}}$		
BSL ³	R_{si}^{-1}	$\frac{\sum_{j=1}^n r_{sj}}{nr_{si}}$	To Be Greater Than	1.67

¹ ASCE/SEI-7-10: American Society of Civil Engineers/Structural Engineering Institute 2010. ² TBEC-2018: Türkiye Building Earthquake Code—2018. ³ BSL: Building Standard Law of Japan.

2.2. Modeling and Analysis Procedure of Case A: RC Frame System

The half-scale low-strength reinforced concrete plane frame, illustrated in Figure 1b, was analyzed using SAP2000 [40] software. The structural system consists of a two-story, single-bay plane frame with a ground story height of 2.7 m, a second story height of 1.3 m, and a beam span of 2.5 m. A recent study by Bahşi et al. [41] indicates that existing reinforced concrete structures evaluated for seismic risk in Turkey since 2012 exhibit a mean compressive strength of 11.65 MPa. Consequently, a concrete compressive strength of 12 MPa was adopted for the frame to simulate the low-strength concrete characteristic of older buildings. No infill walls were included in the model. As depicted in Figure 1c, the uniformly distributed load representing the cantilever slab and the supplemental dead load acting on the beams were introduced as 5 kN/m in the computational model.

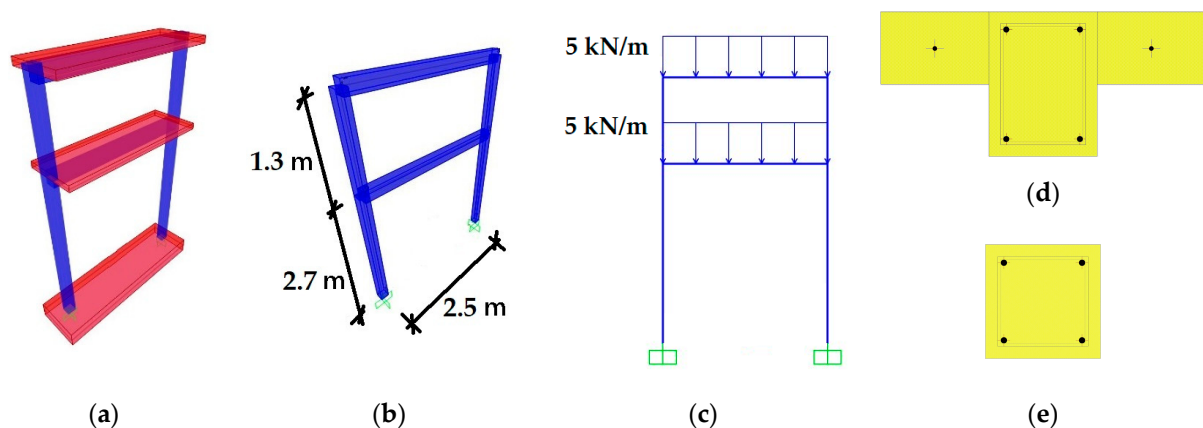


Figure 1. (a) Schematic representation of the frame; (b) SAP2000 model view of the frame; (c) Vertical loads acting on beams; (d) Flanged beam section; (e) Column section.

In the RC frame system, column cross-sections measure 15×15 cm, while the beams measure 15×20 cm. Both columns and beams are reinforced with $4\phi 8$ longitudinal bars and $\phi 8/20$ stirrups, utilizing S420 grade steel. The design of structural element intentionally determined such that the criterion of columns being stronger than beams cannot be considered fully satisfied, which is also commonly observed in older buildings at

seismic sites. However, the RC design meets the joint shear control, and the concrete shear strength defined in TBEC-2018 [33] satisfies the shear force values obtained throughout the nonlinear static analysis. Thus, the structural members reach their flexural bending moment capacities under increasing top displacements. The Mander confined concrete model was implemented in the SAP2000 Section Designer module, accounting for the 20 cm stirrup spacing (poor confinement). The cantilever slab was specified to have a thickness of 10 cm, a width of 80 cm, and a length of 2.5 m. However, it was not explicitly modeled and was accounted for as an additional load. For the flanged beams, the effective flange width was defined as 45 cm. The modulus of elasticity of the concrete was assumed to be 27 GPa. Cross-sectional details and reinforcement layouts for the column and beam elements are presented in Figure 1d and Figure 1e, respectively.

To evaluate the presence of soft story irregularity in the frame system, the linear equivalent lateral force (ELF) method was employed [33]. The lumped story masses were calculated as 690 kg for the first story and 530 kg for the second story. Additionally, a uniform load of 5 kN/m, representing the slab and superimposed dead loads on the 2.5 m beam span, contributed an additional mass of 1274 kg. Consequently, the total structural mass (excluding the foundation) was determined to be 2.77 tons. The base shear force was derived assuming a unit spectral acceleration (1.0 g) and was distributed along the building height. Accordingly, the additional equivalent lateral force acting at the story level was calculated as 0.55 kN. The detailed mass and force parameters are summarized in Table 2. It should be noted that, in the ELF model, while nonlinearity is not considered, whether the representative spectral acceleration is reduced using the response modification factor (R) or not, any change in the base shear will result in linear proportional changes in displacements, and the dimensionless stiffness irregularity factors will remain unchanged under proportional scaling of the base shear, since the load pattern and structural stiffness ($V_t/u_t = 36.97/58.17 \cong 0.64$ kN/mm) is constant.

Table 2. The parameters for the equivalent lateral force (ELF) method.

m_1 (kg)	m_2 (kg)	m_T (kg)	S_a (g)	V_t (kN)
1965	1805	3770	1	36.97
H_1 (mm)	H_2 (mm)	$\sum m_j H_j$ (kgm)	F_1 (kN)	F_2 (kN)
2700	4000	12,525	15.98	20.99

The parameters used in the equivalent lateral force method are detailed in Table 2. Here, m_1 and m_2 denote the masses of the first and second stories, respectively, while m_T represents the total mass of the structure. H_1 and H_2 indicate the cumulative heights of the corresponding stories from the base level. The term $\sum m_j H_j$ refers to the summation of the mass-height products, which serves as the basis for distributing the base shear force. V_t denotes the base shear force, calculated as 36.97 kN. F_1 and F_2 correspond to the equivalent lateral loads applied at the first and second story levels, respectively. Following the application of these lateral forces (Figure 2a) and the assignment of effective stiffness modifiers (0.35 for beams and 0.70 for columns) in accordance with [33], the linear static analysis was performed. The resulting displacement contour diagram story displacements are presented in Figure 2b. In Figure 2b, u_1 corresponds to the lateral displacement of the ground story, whereas u_2 represents the lateral story displacement of the upper (i.e., top displacement, u_t) story.

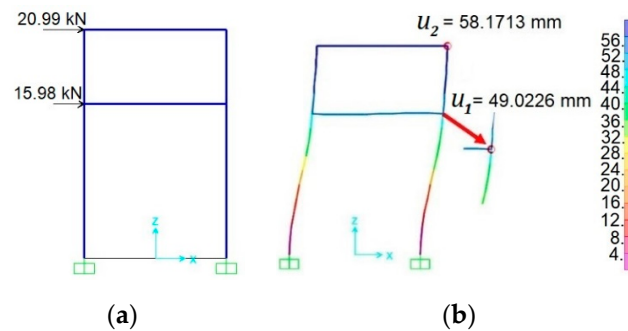


Figure 2. Equivalent lateral force method: (a) Lateral load pattern; (b) Displacement contour diagram and lateral story displacements (mm).

Table 2 and Figure 2b present the required parameters, namely story shears, story heights, and story displacements, for the calculation of stiffness irregularity factors. Upon applying the soft story irregularity criterion stipulated by TBEC-2018 (Inequality (1)), the presence of a soft story mechanism in the ground floor was confirmed. As demonstrated in Equation (7), the calculated stiffness irregularity coefficient (η_{k1}) is 2.58, which clearly exceeds the code-specified limit value of 2.0.

$$\eta_{k1} = \frac{\frac{\Delta_1}{h_1} \left(\frac{\text{mm}}{\text{m}} \right)}{\frac{\Delta_2}{h_2} \left(\frac{\text{mm}}{\text{m}} \right)} = \frac{\frac{49.02}{2.7}}{\frac{58.17-49.02}{1.3}} = 2.58 > 2 \quad (7)$$

Regarding the ASCE, UBC, and NBC assessments, the lateral story stiffness (k_i) was derived by dividing the acting story shear (V_i) by the corresponding interstory drift (Δ_i). Here in the ELF method, the story shear equals the cumulative sum of the equivalent lateral forces acting above the story in question. By substituting these values into Inequality (2), the stiffness ratio between the second and first stories was evaluated. As presented in Equation (8), the resulting ratio of 3.04 significantly exceeds the critical threshold (limit value) of 1.67 (which corresponds to the 60% relative stiffness limit), thereby verifying the irregularity according to these international standards.

$$\frac{k_2}{k_1} = \frac{\frac{F_2}{\Delta_2 - \Delta_1} \left(\frac{\text{kN}}{\text{mm}} \right)}{\frac{V_1}{\Delta_1} \left(\frac{\text{kN}}{\text{mm}} \right)} = \frac{\frac{20.99}{58.17-49.02}}{\frac{36.97}{49.02}} = 3.04 > 1.67 \quad (8)$$

Finally, the soft story assessment according to the Building Standard Law (BSL) of Japan was conducted using Inequality (4) and Equation (5). As detailed in Equation (9), the calculated R_{s1} value is 0.56, which falls below the limit value of 0.60, confirming the existence of irregularity.

$$R_{s1} = \frac{\frac{h_1}{\Delta_1} \left(\frac{\text{m}}{\text{mm}} \right)}{\frac{1}{2} \left(\frac{h_1}{\Delta_1} + \frac{h_2}{\Delta_2} \right) \left(\frac{\text{m}}{\text{mm}} \right)} = \frac{\frac{2.7}{49.02}}{\frac{1}{2} \left(\frac{2.7}{49.02} + \frac{1.3}{58.17-49.02} \right)} = 0.56 < 0.6 \quad (9)$$

Alternatively, when evaluated using the unified criterion proposed in this study (Inequality (6)), the reciprocal value is obtained as $R_{s1}^{-1} = 1.79$. This result exceeds the threshold of 1.67, thereby yielding a consistent conclusion regarding the irregularity status.

In summary, the elastic assessment of the Case A frame, conducted via the equivalent lateral force method, confirmed the presence of a soft story irregularity at the ground level according to all examined codes. It is noteworthy that this soft story behavior is inherent to the bare frame configuration itself, independent of any stiffness discontinuity caused by infill walls. It is important to emphasize that the application of the equivalent

lateral force (ELF) method to calculate code-based irregularity factors serves strictly as a preliminary baseline for this study. The fundamental proposal of this research is to move beyond traditional elastic approaches and investigate the severe discrepancy between these conventional assessments and the true inelastic structural response. To capture the evolution of this irregularity beyond the elastic limit, a detailed nonlinear analysis is presented in the subsequent section.

2.2.1. Nonlinear Soft Story Behavior of RC Frame

Physically, as a structure undergoes nonlinear deformation, its global stiffness matrix continuously changes. As a result, the soft-story behavior is not a static property; it evolves, rendering initial elastic evaluations insufficient. Therefore, by comparatively tracking the continuous trends of how code-defined factors deviate from their elastic limit values throughout the nonlinear domain, this study emphasizes the absolute necessity of evaluating stiffness irregularity through a nonlinear lens and the capacity of the structural system under increasing displacements. Key findings derived from these evolutionary trends are subsequently discussed to highlight the true amplification of the soft-story mechanism.

A nonlinear static (pushover) analysis was performed using a displacement-controlled approach. Gravity loads were considered as the initial condition, and geometric non-linearity, including P- Δ effects, was accounted. Lumped plastic hinges accounting for axial-flexural (P-M) interaction were assigned to the element ends. The plastic hinge length (L_p) was assumed to be half of the section depth ($0.5 h$), and the hinges were located at a distance of $L_p/2$ from the face of the connecting elements. The analysis proceeded up to a target top drift ratio of 1% (corresponding to a top displacement of 40 mm), during which interstory drifts, story shears, and stiffness irregularity factors were recorded at each step. Given the symmetry of the planar frame, the analysis was restricted to the +x direction. Prior to the pushover analysis, the fundamental vibration period (T_1) was determined to be approximately 0.45 s, with a dominant mass participation ratio of 99% in the x-direction (see Figure 3b). This indicates that the system's response is governed almost entirely by the first mode, which exhibits significantly larger modal amplitudes at the ground story. Consequently, the lateral load pattern adopted for the pushover analysis followed the distribution defined by the equivalent lateral force (ELF) method, which effectively captures the inertial forces associated with this dominant first mode. The first (dominant) mode shape is given in Figure 3b.

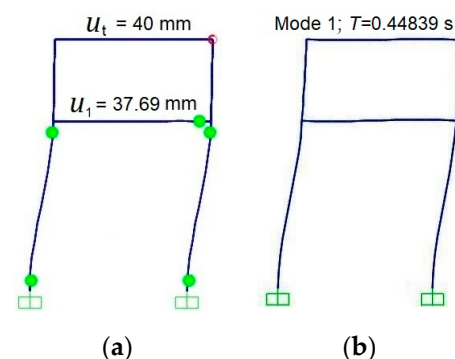


Figure 3. (a) Nonlinear state of the frame at 1% top drift ratio from pushover analysis; (b) Dominant mode shape of the frame system.

Figure 3a shows the final plastic hinge distribution of the frame. It was observed that plastic hinges formed at both the top and bottom ends of the ground story columns, signaling the development of a soft story mechanism. The pronounced concentration of plastic hinges within the ground story explicitly demonstrates the dominance of soft story

irregularity on the nonlinear response. The step-wise evolution of this behavior can be inferred by calculating the ratio of ground-story displacement to the top displacement (Δ_1 / u_t). Crucially, within the elastic range, the ground story already contributed 84.3% to the total system displacement. However, following the formation of the first plastic hinge, this contribution began to escalate. At the final step of the analysis, the ground story sustained a relative displacement (drift) of 37.69 mm, whereas the upper story exhibited a mere 2.31 mm. Consequently, 94% of the total top displacement was accommodated by the soft ground story, with only 6% attributed to the upper level. This finding underscores that as the structure enters the inelastic range, stiffness degradation concentrates disproportionately in the soft story, causing the drift demands to increase significantly more rapidly at this ground story compared to the story above.

A step-by-step examination of the pushover analysis reveals that the first plastic hinges formed at the base of the ground story columns in Step 3. By Step 4, hinges had developed at the upper end of the right column and the beam end. Subsequently, at a top displacement of approximately 16.5 mm (Step 5), the upper end of the left column also yielded, completing the formation of a soft story mechanism. It was observed that the base shear capacity was reached at this step, corresponding to a global drift ratio of only 0.41%. This value is notably low compared to conventional structures, a result attributed primarily to the severe strain concentration in the soft story, compounded by low concrete compressive strength and limited ductility. Beyond this peak, strength degradation initiates with a constant negative slope. Although a complete ground-story mechanism forms at the peak base shear capacity, the structure continues to sustain lateral loads with reduced strength due to the remaining plastic rotation capacity of column hinges and the axial force redistribution resisting the overturning moment. Collapse does not occur immediately, and the post-peak behavior is governed by strength degradation and P- Δ effects.

2.2.2. The Results of Nonlinear Static Analysis and Stiffness Irregularity Factors

Interstory drifts, story stiffnesses, and story shear forces were extracted at each increment of the nonlinear pushover analysis. These parameters were then utilized to compute the stiffness irregularity factors defined in the relevant seismic codes, similar to calculation given in Equations (7)–(9) but for every pushover step, as presented in Table 3 (tabular) and Figure 6 (graphical). This approach allowed for a detailed examination of the evolution of soft story behavior across the entire capacity curve, encompassing both the elastic and inelastic regions. The numerical results, along with the corresponding stiffness irregularity (soft story) factors, are summarized in Table 3. In this table, the subscript ‘1’ denotes parameters associated with the ground story, while ‘2’ designates those corresponding to the upper story.

In Table 3, the structural parameters are listed as top displacement (u_t), story drifts (Δ_1 , Δ_2), story shear forces (V_1 , V_2), and lateral story stiffnesses (k_1 , k_2). Furthermore, the table presents the evolution of the code-based irregularity indices: the stiffness ratio (k_2/k_1), the ratio of interstory drift ratio (η_{k1}), and the reciprocal drift angle parameters (R_1 and its inverse, R_1^{-1}). Specifically, the ratio k_2/k_1 corresponds to the criteria defined in the UBC, ASCE, and NBC codes; η_{k1} pertains to the Turkish Building Earthquake Code (TBEC-2018); and R_1 relates to the Japanese BSL standard. Given the established vulnerability, the comprehensive evaluation of these factors focused exclusively on the ground story. A comparison of the initial values in Table 3 with the analytical ELF results provided in Equations (7)–(9) confirms that the elastic phase of the pushover analysis yields identical results to the ELF assessment.

Due to its limited ductility and plastic deformation capacity, the system underwent a rapid transition into a soft-story mechanism between Step 3 and Step 5, accompanied by

increases in stiffness irregularity factors. As inelastic behavior developed, all three factors, k_2/k_1 , η_{k1} , and R_1^{-1} , exhibited a consistent monotonic increasing trend. To further elucidate this phenomenon, the post-elastic evolution of these parameters is analyzed using the distribution diagrams presented in Figure 6.

Table 3. Results of nonlinear pushover analysis and code-based stiffness irregularity factors.

Step	u_t (mm)	Δ_1 (mm)	Δ_2 (mm)	V_1 (kN)	V_2 (kN)	k_1 ($\frac{\text{kN}}{\text{mm}}$)	k_2 ($\frac{\text{kN}}{\text{mm}}$)	k_2/k_1	η_{k1}	R_1^{-1}	R_1
1	4.00	3.37	0.62	2.54	1.44	0.75	2.31	3.07	2.60	1.80	0.56
2	8.00	6.74	1.25	5.08	2.88	0.75	2.30	3.05	2.59	1.80	0.56
3	11.68	9.85	1.83	7.43	4.22	0.75	2.30	3.05	2.59	1.79	0.56
4	14.27	12.20	2.07	7.86	4.46	0.64	2.16	3.35	2.84	1.92	0.52
5	16.55	14.33	2.22	8.05	4.57	0.56	2.06	3.67	3.11	2.05	0.49
6	17.69	15.47	2.22	8.04	4.56	0.52	2.05	3.95	3.35	2.18	0.46
7	17.69	15.47	2.22	8.04	4.56	0.52	2.05	3.95	3.35	2.18	0.46
8	17.69	15.47	2.22	8.04	4.57	0.52	2.05	3.95	3.35	2.18	0.46
9	18.69	16.47	2.22	8.03	4.56	0.49	2.05	4.21	3.57	2.28	0.44
10	18.69	16.47	2.22	8.03	4.55	0.49	2.05	4.21	3.57	2.28	0.44
11	18.69	16.44	2.25	8.00	4.54	0.49	2.02	4.14	3.51	2.26	0.44
12	19.00	16.74	2.26	8.03	4.56	0.48	2.02	4.20	3.56	2.28	0.44
13	19.00	16.74	2.26	8.03	4.56	0.48	2.02	4.20	3.56	2.28	0.44
14	19.00	16.66	2.34	7.91	4.49	0.47	1.92	4.05	3.43	2.22	0.45
15	19.91	17.56	2.35	8.02	4.55	0.46	1.94	4.24	3.60	2.30	0.44
16	23.91	21.57	2.34	7.96	4.52	0.37	1.93	5.23	4.43	2.72	0.37
17	27.91	25.58	2.34	7.90	4.49	0.31	1.92	6.22	5.27	3.14	0.32
18	31.91	29.58	2.33	7.85	4.45	0.27	1.91	7.22	6.12	3.56	0.28
19	35.91	33.59	2.32	7.79	4.42	0.23	1.91	8.22	6.98	3.99	0.25
20	39.91	37.60	2.31	7.73	4.39	0.21	1.90	9.24	7.84	4.42	0.23
21	40.00	37.69	2.31	7.73	4.39	0.21	1.90	9.26	7.85	4.43	0.23

2.2.3. Story Shear Curves and Story Displacement Profiles

In the pushover analysis, story shear forces were computed by summing the shear forces acting on columns at each respective story level. Accordingly, the relationship between story shear and top displacement was plotted in Figure 4 for both stories. Since the total shear force at the ground story is identical to the base shear, the ground story shear curve in Figure 4 effectively represents the global capacity (pushover) curve of the frame. The initial (elastic) tangent stiffness obtained from the linear portion of the pushover curve ($V_t/u_t = 7.43/11.68 \cong 0.64$ kN/mm) is identical to the global lateral stiffness calculated using the ELF method, as the same lateral load pattern is employed in both procedures.

In Figure 4, the locations of plastic hinges that formed along the structural members was also presented with their corresponding analysis step. They correspond to Steps 3, 4, and 5 of the pushover analysis, respectively. The initial degradation in structural stiffness is observed at Step 3, triggered by the yielding of the ground story column bases. Subsequently, the attainment of maximum base shear capacity (zero tangent stiffness) coincides with Step 5, where plastic hinges develop at both the top and bottom ends of the ground story columns, completing the story mechanism.

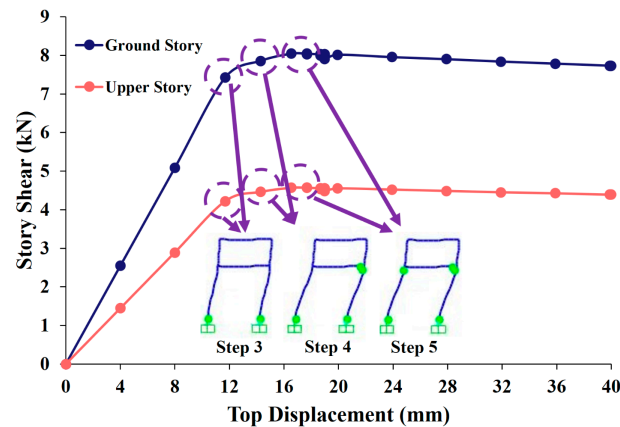


Figure 4. Story shear-top displacement curves and presentation of plastic hinge formation sequence.

Due to the pronounced soft story irregularity, plastic hinge formation was concentrated in the ground story columns, preceding any significant yielding in the beams. This sequence rapidly precipitated the development of a soft-story mechanism, limiting the inelastic deformation capacity prior to peak strength. As illustrated in Figure 4, following the completion of the mechanism at Step 5, both the ground story shear (base shear) and upper story shear forces began to decline with increasing top displacement. This behavior marks the onset of the softening (strength degradation) branch of the pushover curve. Beyond this peak, although the structure cannot resist increased lateral forces, it retains the capacity for further inelastic deformation. Consequently, despite the observed gradual strength degradation, the system demonstrated sufficient post-peak deformability to sustain gravity loads up to the target displacement limit without experiencing immediate numerical instability or collapse. It should be noted that, due to the modeling assumptions—particularly the definitions of plastic hinges and geometric nonlinearity—this region is obtained as exhibiting linear degradation.

To visualize the progressive intensification of the soft story mechanism, the displacement profiles along the building height were plotted for 14 distinct steps of the pushover analysis (omitting intermediate steps with overlapping results), as shown in Figure 5. As observed in Figure 5, a distinct slope change (kink) develops at the first story level in the subsequent inelastic steps and ground story exhibits progressively larger relative displacements compared to the upper story, clearly illustrating the concentration of deformation in the soft ground story. Sudden changes in the slope of the displacement profile are attributed to stiffness irregularity between the ground and upper stories [42].

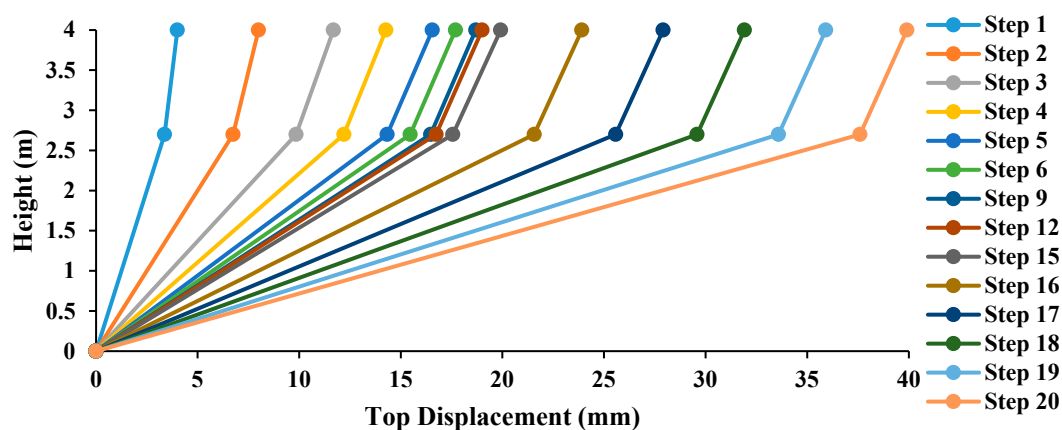


Figure 5. The displacement profiles along pushover steps.

This behavior can be further elucidated through the lens of the Japanese Seismic Code (BSL). As the top displacement increases, the interstory drift angle of the ground story (represented as $1/r_1$) increases disproportionately compared to the upper story. Consequently the parameter r_1 , the reciprocal of the angle in the displacement profile, decreases significantly more than r_2 . Since the irregularity coefficient R_1 is directly proportional to r_1 (as shown in Inequality (4)), this reduction causes the R_1 value to fall progressively further below the critical limit of 0.6. This trend, observable from left to right in Figure 5, quantitatively confirms that the irregularity severity exacerbates as the structure is pushed further into the inelastic range.

A quantitative comparison between the initial elastic step ($u_t = 4$ mm) and the final plastic step ($u_t = 40$ mm) reveals a striking disparity in the magnitude of deformation. While the upper story drift increased by a factor of 3.7, the ground story drift amplified by a factor of approximately 11. This result confirms that as the top displacement increases, the deformation concentrates disproportionately in the soft story. This divergence is clearly visualized in the displacement profiles presented in Figure 5, where the ground story exhibits a progressively severe slope change compared to the upper level.

2.2.4. Evolution of Stiffness Irregularity Factors with Increasing Top Displacement

In this section, a comparative examination is conducted on the variation in stiffness irregularity indices defined by different seismic codes. Specifically, the variation in the TBEC-2018 coefficient (η_{k1}), the ASCE/UBC/NBC stiffness ratio (k_2/k_1), and the Japanese BSL factor (R_i) is analyzed as the lateral load is incrementally increased. These factors were computed at each step of the pushover analysis and plotted against the top displacement, as presented in Figure 6a–d.

The resulting plots reveal two distinct trends dictated by the mathematical definitions of the factors. The factors η_{k1} and k_2/k_1 , along with the reciprocal BSL parameter (R_1^{-1}), exhibit a monotonic increasing trend, whereas the standard BSL factor (R_1) displays an inverse increasing (decreasing) orientation. However, despite these opposing mathematical directions, all indices fundamentally signal the same physical behavior: a progressive divergence from their respective limits. The graphs illustrate three metrics with a consistent rising tendency and one with a descending tendency, all signaling the progressive worsening of the soft story irregularity. Consequently, regardless of the calculation method, all codes consistently indicate a severe aggravation of the soft story irregularity as the structure undergoes inelastic deformation.

In Figure 6a–d, the calculated irregularity parameters are plotted alongside their respective code-specified limit values (indicated by dashed lines). To correlate the evolution of these irregularities with the global structural elastic and post-elastic behavior, the normalized (or scaled) pushover curve (base shear vs. top displacement) is superimposed on the background of each graph. A comparative analysis of the graphs in Figure 6a–c reveals a consistent pattern in the evolution of stiffness irregularity parameters.

A soft-story irregularity is present when the k_2/k_1 factor plotted in Figure 6a exceeds 1.67 according to Inequality (2), η_{k1} factor plotted in Figure 6b exceeds 2.0 according to Inequality (1), R_1^{-1} factor plotted in Figure 6c exceeds 1.67 according to Inequality (6), and also R_1 factor plotted in Figure 6d is less than 0.6 according to Inequality (4) independently. Review of the graphs indicates that the stiffness irregularity (soft story) factors consistently breach the code-specified limits throughout all pushover steps. While the structure remains in the elastic range, the values of the stiffness irregularity factors specified in the codes remain essentially constant even if the base shear is increased. The severity of this irregularity escalates dramatically with the onset of inelasticity. Across all investigated codes, the adverse effects of soft story behavior begin to intensify markedly at a top displacement

of approximately 12 mm. This critical threshold coincides with Step 3, where the first plastic hinge forms at the column base. Crucially, the initiation of the monotonic increase (or decrease for R_1) in the irregularity factors does not wait for the formation of the full soft-story mechanism (Step 5). Instead, it coincides with the initiation of the first plastic hinge (Step 3). Subsequently, throughout the region of stiffness reduction and strength degradation (i.e., negative stiffness), the rate of increase in the stiffness irregularity terms continues consistently. These can be readily observed by comparing Figure 6a–c, which illustrate the variation in stiffness irregularity factors during the pushover analysis, with Figure 4, which presents the pushover curve and hinge formation sequence.

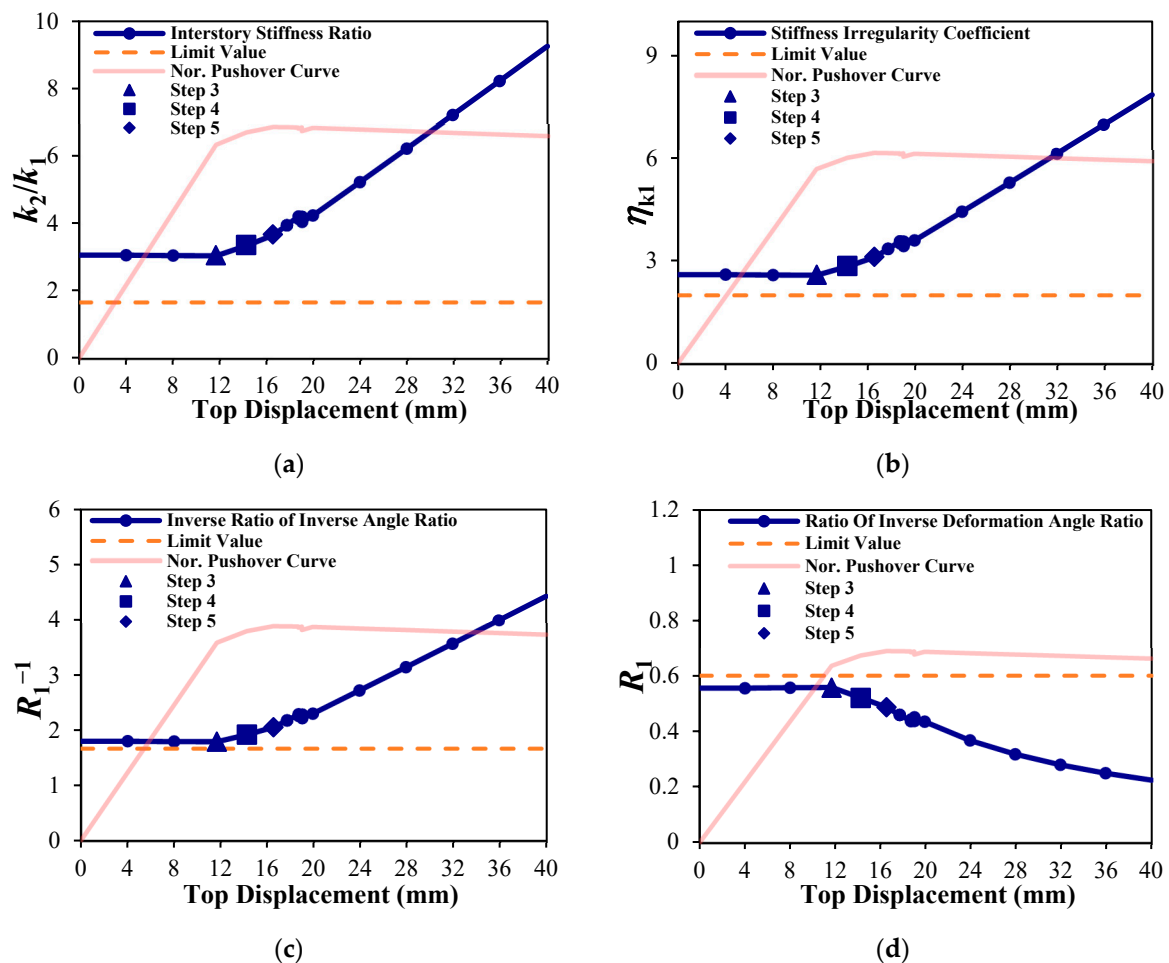


Figure 6. Variation in code-defined stiffness irregularity factors with respect to top displacement: (a) Interstory stiffness ratio (k_2/k_1) for ASCE, UBC, and NBC; (b) Ratio of interstory drift ratio (η_{k1}) or TBEC-2018; (c,d) ratio between reciprocal of column displacement profile angle and its arithmetic mean of all story (R_1^{-1} and R_1) for BSL (Note: The normalized pushover curve is superimposed in the background for reference).

Moreover, the distribution of these stiffness irregularity parameters aligns well with the pushover curve (see Figure 4) in terms of the transition from the elastic to inelastic range in the pushover curve occurs at the same steps where the irregularity factors begin their monotonic increase, and the slopes of the elastic and inelastic regions of irregularity factor exhibit a nearly bilinear behavior. However, a comparative analysis of Figure 6a–d reveals a consistent pattern in the evolution of stiffness irregularity parameters, characterized by three distinct regions rather than a simple bilinear trend.

1. Elastic Region (Step 0–3): In the initial phase, the irregularity factors remain essentially constant, forming a flat plateau;

2. Transition Region (Step 3–5): Upon the formation of the first plastic hinge at Step 3 (approx. 12 mm displacement), the curves exhibit sharp slope increases. In this specific Case A frame, this region is relatively narrow due to the rapid progression from initial yielding to the full soft-story mechanism at Step 5;
3. Post-Peak (Softening) Region (Step 5+): Beyond the peak strength, as the structure undergoes strength degradation (negative stiffness), the irregularity factors continue to deviate progressively from the code limits linearly. For models exhibiting nonlinear softening in the pushover curve, this final region would likewise be expected to follow a nonlinear trend.

This trilinear-like behavior highlights that the adverse effects of soft story irregularity intensify immediately after the first yield (Step 3), accelerating further as the mechanism fully develops. This behavior is revealed more distinctly in Case B that transition region is not linear. The deviation of these parameters from the safety limits serves as a quantitative indicator of the increasing dominance of the soft story behavior in the inelastic range.

As evidenced by the comparative graphs in Figure 6a–d and the governing inequalities, the intensification of soft story behavior correlates with an increase in η_{k1} and k_2/k_1 , and a corresponding decrease in R_{si} . However, the utilization of the reciprocal format (R_{si}^{-1}) harmonizes these directions, demonstrating that all examined codes yield mathematically consistent trajectories. Despite relying on distinct formulation parameters—ranging from story stiffness ratios (ASCE/UBC/NBC) to relative drift ratios (TBEC) and inverse displacement profile slopes (BSL)—the codes do not diverge in their fundamental assessment. Instead, they converge on a unified conclusion: a severe, nonlinear aggravation of the soft story irregularity under increasing displacement demand. Consequently, regardless of the specific computational criterion employed, all standards effectively capture the same underlying structural vulnerability and exhibit nearly identical curvilinear trends in the inelastic range.

2.3. Parametric Analysis of Stiffness Irregularity Factors of Case B: 3D Reinforced Concrete Building

In this part of the study, a parametric analysis was conducted on a three-dimensional four-story building to investigate the variation in stiffness irregularity factors with nonlinear behavior, with the aim of generalizing the results obtained from the frame systems and further investigate the proposed analysis on a real scale building model. While it is well established that infill walls significantly affect the lateral stiffness and seismic behavior of reinforced concrete frames, they are deliberately excluded from the current analytical models. Since both the removal of infill walls and an increase in story height alter lateral stiffness, a two-variable analysis was avoided. To maintain a controlled analytical environment and eliminate the uncertainties of compounded effects, this investigation focuses exclusively on bare frame configurations. Therefore, consistent with Case A, only the ground story height is adopted as the source of stiffness irregularity. For this parametric study, seven models were developed by increasing the ground-story height of the full-scale three-dimensional structure shown in Figure 7, and nonlinear pushover analyses were performed. Displacement-controlled pushover analyses were conducted up to a uniform target top displacement of 146 mm across all models. This threshold was established to approximate a 2% top drift ratio for Model 7, the tallest structure investigated in this study. The analyses were performed by pushing the building exclusively along the positive X-axis, i.e., weak axis. To determine story shear forces, the ‘Section Cut’ feature was utilized to determine the shear forces of all columns at each respective story level. The obtained story shear forces were divided by the corresponding interstory drifts, and the story stiffness values were calculated accordingly. Second-order P- Δ effects and large displacement geometric

nonlinearity were incorporated into the analysis procedure. Regarding nonlinear modeling, the ‘Idealized Flexural Hinge’ option—based on an ideal elasto-plastic model—was selected from the SAP2000 auto-hinge library. Additionally, by maintaining the plastic moment capacity, the load-carrying capacity beyond point E, which is the last point of the lumped plasticity model and corresponds to the red-colored hinge state in Figure 7b,c, is extrapolated. This plastic hinge modeling approach was adopted to ensure numerical stability and convergence within advanced plastic regions and to generate smooth stiffness irregularity factor plots, which are highly sensitive to fluctuations in the pushover curve shape. For the defined P-M2-M3 interaction hinges, the plastic hinge length was set to half of the section depth. While the assigned plastic hinges are presented in Figure 7a, Figure 7b illustrates the initiation of plastic hinging in columns for the model in which all story heights are equal (i.e., no soft-story irregularity). In contrast, Figure 7c shows that, for the case with the most severe soft-story irregularity, even at the final analysis step, almost all plastic hinges are concentrated in the ground-story columns and beams.

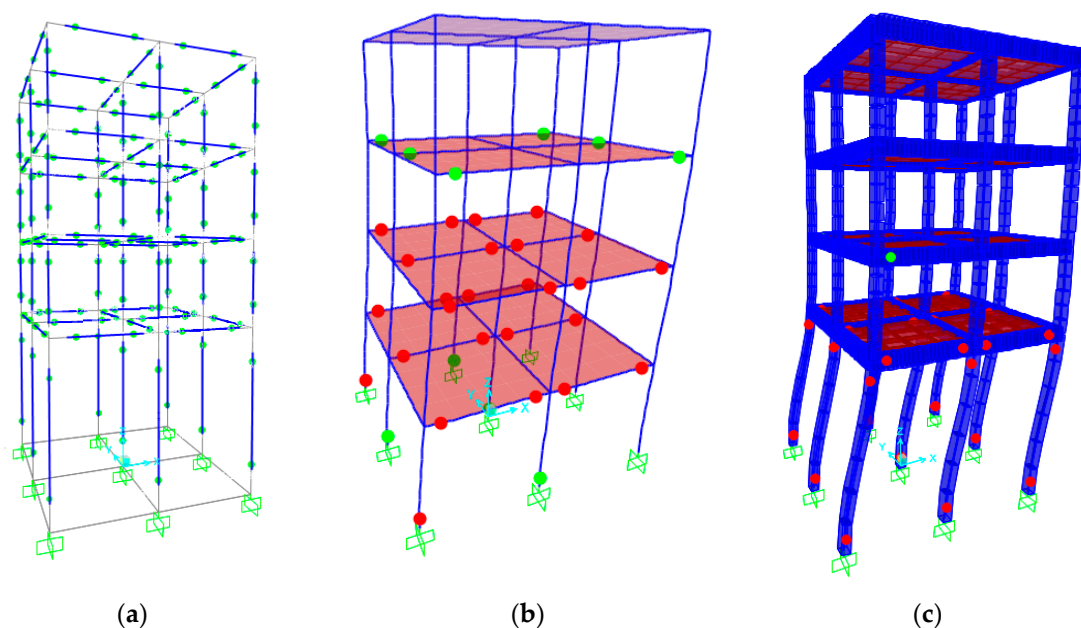


Figure 7. Plastic hinge distributions: (a) Assigned PMM plastic hinges; (b) Initiation of plastic hinging in columns for the model with equal story heights (no soft-story irregularity); (c) plastic hinge distribution at the final analysis step for the model with the most severe soft-story irregularity.

In Figure 7b,c, green-colored hinges represent plastic hinges that have exceeded the yield moment, while red-colored hinges indicate exceedance of the ultimate rotation capacity. Unlike the frame (Case 1) analysis, plastic hinges initially form in the beams for all seven models. As the severity of the soft-story irregularity increases (from ground story height $H_{gr} = 2.6$ m to $H_{gr} = 5.0$ m), the number of beams undergoing plastic hinging decreases and becomes increasingly concentrated at the ground story.

To simulate varying degrees of structural vulnerability, the ground floor column length was treated as the primary variable. Seven models were developed, ranging from a baseline structure with no irregularities to a case exhibiting extreme soft-story behavior. The ground-floor height was incrementally increased across the models as 2.6 m, 3.0 m, 3.4 m, 3.8 m, 4.2 m, 4.8 m, and 5.0 m. The building given in Figure 7a–c is modeled as a bare frame without any infill walls or shear cores. Regarding the structural components, the columns measures are assumed as 30×25 cm, while the beams are 30×40 cm. When the moment of inertia of columns is maintained significantly higher than that of beams, the beams in the upper stories are unable to provide sufficient rotational restraint at the

column ends. Consequently, the coefficient of the shear stiffness (EI/L^3) tends to decrease from 12 toward 3. However, at the ground story, fixed supports are assumed to possess infinite stiffness; therefore, due to these boundary conditions, the corresponding coefficient remains larger compared to that of the upper-story columns. This condition may lead to a greater reduction in the drift of the ground story relative to the drift of the first story. In that regard, to achieve soft-story irregularity at relatively lower ground-story heights and to observe its effects more clearly, the column cross-sections were selected as 30×25 cm, which corresponds to the minimum limits permitted by older building design codes such as Ministry of Public Works and Settlement, (year 1998) [43] and Eurocode 8 (year 1998) [44]. However, as required by the principles of ductile reinforced concrete design, the columns should be detailed to remain stronger than the beams; the flexural capacity of the columns was increased by providing a greater number and larger diameter of reinforcing bars compared to those of the beams and ensured that beams would yield prior to columns under conditions where the soft-story irregularity is not severe.

All slabs are 12 cm thick and act as rigid diaphragms. The loading scheme applies a dead load (g) of 1.5 kN/m and a live load (q) of 2 kN/m, resulting in a defined mass source of $g + 0.3q$ [45]. A summary of the structural information and reinforcement design is provided in Table 4.

Table 4. Key input parameters for the RC building models.

Column Section (cm)	30 × 25	Ground story height (m)	2.6–5	Confinement rebar (mm)	φ12
Beam section (cm)	30 × 40	Typical story height (m)	2.6	Confinement spacing (cm)	10
Bay width (m)	3	Concrete class	C30	Effective stiffness of beam	0.35
Support Type	Fixed	Reinforcement class	S420	Effective stiffness of column	0.7
Number of story	4	Slab type	Shell	Effective stiffness of slab	0.25
Number of bay	2	Longitudinal rebar of column (mm)	8φ16	Longitudinal rebar of beam (mm)	4φ12

The top displacements corresponding to the initiation of the first plastic hinge in beams and columns, as well as the top displacements associated with the maximum base shear (i.e., capacity) of the structure during the nonlinear pushover analysis steps, are presented in Table 5.

Table 5. The top displacement values corresponding to the plastic hinge initiation of beam, column and base shear strength.

Ground Story Height of the Analysis Model	Top Displacement at First Beam End Plastic Hinge	Top Displacement at First Column End Plastic Hinge	Onset of the Negative Stiffness Region
Ground Story Height 2.6 m	30.65 mm	70.76 mm	>246 mm
Ground Story Height 3.0 m	31.44 mm	59.27 mm	198.37 mm
Ground Story Height 3.4 m	33.13 mm	59.81 mm	161.00 mm
Ground Story Height 3.8 m	35.66 mm	63.23 mm	146.37 mm
Ground Story Height 4.2 m	38.97 mm	72.75 mm	143.33 mm
Ground Story Height 4.6 m	43.00 mm	70.57 mm	137.21 mm
Ground Story Height 5.0 m	47.74 mm	76.16 mm	139.94 mm

In all seven models, plastic hinge formation consistently initiated in the beams first. With increasing ground story height, beam plastic hinging is slightly delayed, while column plastic hinging initiates at significantly earlier stages as shown in Table 5. Increasing soft-story severity concentrates lateral deformations in first-story columns, causing earlier column hinging and slightly delayed beam hinging at higher top displacement levels. Although increasing soft-story severity leads to larger ground displacement, the same is

not necessarily true for the top displacement. Overall, with increasing soft-story severity, the structure attains its maximum load capacity at lower displacements and demonstrates reduced structural ductility. The values presented in Table 5 were used to analyze the trends of stiffness irregularity factors on an interval basis.

Figure 8a presents the pushover curves for all seven models with varying ground story heights. For the reference model, where the ground story height matches the upper stories (2.6 m), it is observed that the structure does not reach its ultimate strength capacity within the target displacement range. Conversely, as the ground story height increases, the structure attains its ultimate strength earlier, and the onset of the first plastic hinge occurs at lower top displacement levels. The specific behavioral phases identified in the pushover curves—namely the elastic range, the post-elastic range initiated by stiffness degradation due to initiation of beam end section yielding and the onset of column hinging, the peak strength state (extremum point corresponding to the mechanism), and the post-peak negative stiffness region—are interpreted separately in the subsequent stiffness irregularity index graphs.

Representing the primary focus of this study, the variation in soft story irregularity factors (defined by international codes) with respect to the structure's nonlinear behavior was investigated by increasing the ground story height of the building. These variations, evaluated both in terms of inter-index and intra-index relationships, are illustrated in the following Figure 8b–f.

In the graphs presented in Figure 8b–f, the transition from elastic to post-elastic behavior (marking the first plastic hinge in beams) is indicated by a triangle marker, the step where the first plastic hinge occurs in columns is denoted by a square marker, and the structure's ultimate lateral load-carrying capacity is marked with a diamond marker. In the elastic region (up to the green marker), no significant incrementation occurred at the stiffness irregularity factors across all graphs and for all ground story heights. The findings indicate that as top displacement increases, the adverse effects of soft story behavior at the ground story become more pronounced, similar to the trend identified for Case A. Additionally, a different behavior is observed in the graphs at the green-black marker interval for the ASCE/SEI 7-10 k_2/k_1 factor (Inequality (2)) and the TBEC-2018 η_{k1} factor (Inequality (1)), where it is evident that plastic hinging in the beams reduces the values of these soft story irregularity indices, as if it were reducing the irregularity of the soft story. This phenomenon is not observed in other factors such as k_m/k_1 , R_{s1} , and R_{s1}^{-1} , which account for story-based averages. This phenomenon is also not clear in the result plots of the Case A analysis results shown in Figure 6a–d, since plastic hinges formed in the columns prior to those in the beams of RC frame.

Subsequently, once plastic hinging initiates in the columns, the decreasing trends in Figure 8b,c begin to reverse and increase, while the already increasing trends in Figure 8d–f rapidly. For all factors exhibiting an increasing trend (Figure 8b–e), the rate of increase in the soft story factors stabilizes at a constant slope beyond the structure's ultimate strength point. Note that for the trends illustrated in Figure 8b–f and the comments conducted in this study, 'increasing trend' corresponds to deviation from the prescribed limit values, reflecting a higher severity of soft-story irregularity, while a 'decreasing trend' represents convergence toward these limits.

A further striking inference concerns the curves that initially remain below the threshold limit during elastic analysis—and are thus not identified as soft stories—but subsequently exceed the limit as plastic hinging develops. When evaluating only the pre-story-mechanism (i.e., before of strength degradation), the specific cases where soft story irregularity is absent in the elastic range but emerges due to nonlinear behavior (surpassing the limit value) are as follows:

- k_2/k_1 : Models with ground story heights of 3.0 m and 3.4 m;
- k_m/k_1 : Models with ground story heights of 2.6 m and 3.0 m;
- η_{k1} : Models with ground story heights of 3.8 m and 4.2 m;
- R_{s1} and R_{s1}^{-1} : Models with ground story heights of 2.6 m and 3.0 m.

While these models would have been deemed ‘regular’ (free of soft story irregularity) had the assessment been limited to elastic analysis, they clearly violate the limits under nonlinear conditions. Notably, as the ground story height increases, the transition into the soft story region occurs at progressively lower top displacement values.

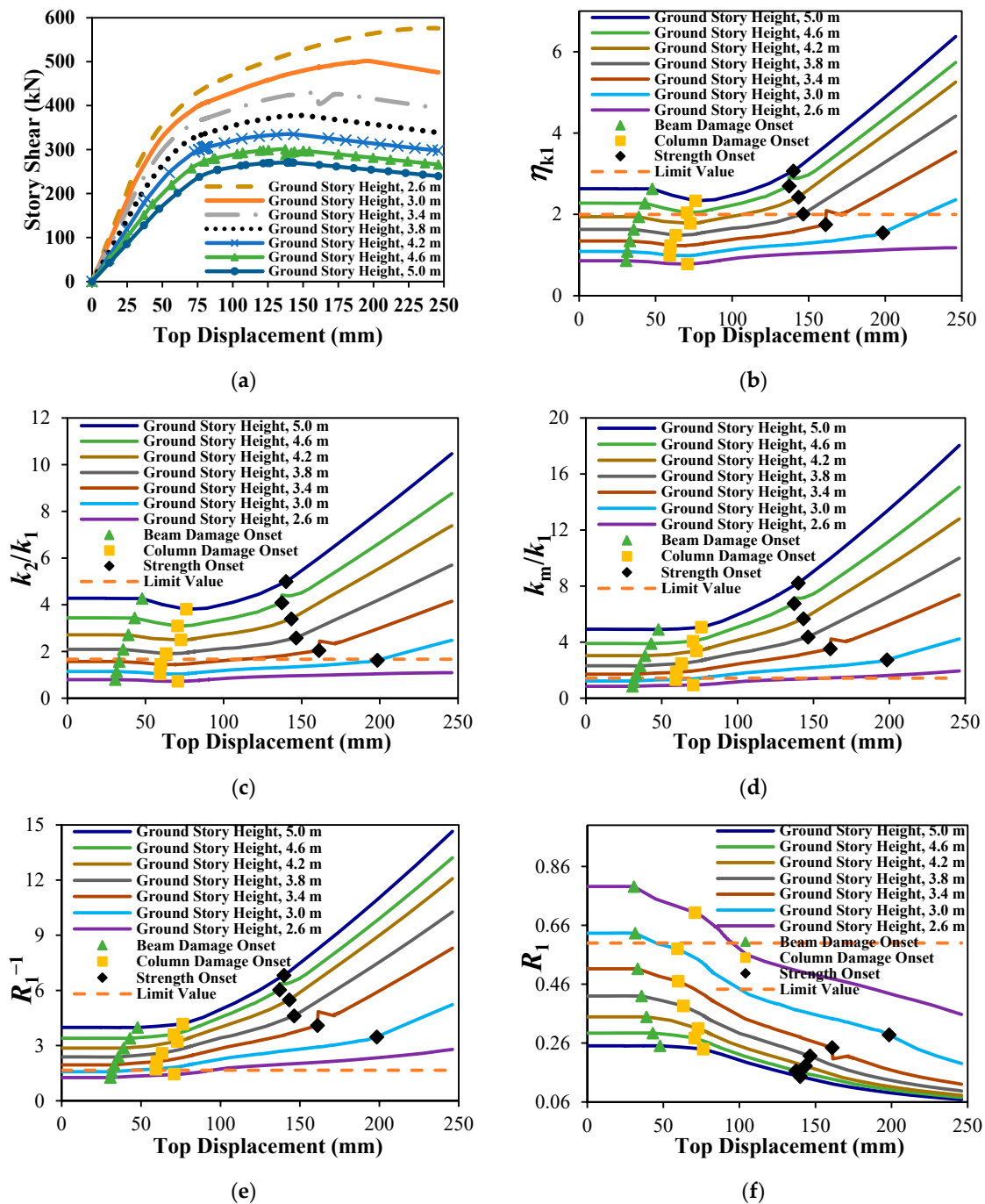


Figure 8. The distribution of code-defined soft story irregularity parameters according to top displacements: (a) Pushover curves; (b) Ratio of interstory drift ratio (TBEC-2018); (c) Ratio of interstory stiffness (ASCE/SEI-7-10); (d) Ratio between the story stiffness and the stiffness of the three stories above (ASCE/SEI-7-10); (e,f) Ratio between reciprocal of column displacement profile angle and its arithmetic mean of all story (BSL).

As an additional remark, had the assessment been restricted to elastic analysis (considering only the initial elastic region in Figure 8b–f, 5 out of the 7 analyzed models would be classified as having soft story irregularity according to the BSL and ASCE/SEI 7-10 (along with UBC and NBC) codes. In contrast, only 2 models are initially classified as such under TBEC-2018. Consequently, when comparing the safety tendencies of these regulations, it is observed that the BSL and ASCE/SEI 7-10 codes remain on the more conservative side. Also, as can be observed, stiffness irregularity of a building can arise solely by varying the ground-story height, even without the effect of elimination of infill walls.

To strictly quantify the extent to which inelasticity exacerbates the soft story irregularity, a numerical comparison is presented in Table 6. The table summarizes the absolute values of the stiffness irregularity factors across three critical response stages: the initial elastic state (Δ), the formation of the first column plastic hinge ($\#$), and the onset of the soft-story mechanism ($\blacklozenge$). The values in parentheses indicate the percentage deviation relative to the elastic baseline.

Table 6. Calculated values of stiffness irregularity factors including percentage deviations relative to the elastic baseline for different ground story heights.

$H_{gr}(m)$	Stage *	k_2/k_1	k_m/k_1	η_{k1}	R_{s1}^{-1}	R_{s1}
2.6	Δ	0.796	0.851	0.858	1.263	0.792
	$\#$	0.720 (−9.5%)	0.939 (+10.3%)	0.776 (−9.5%)	1.453 (+15.1)	0.703 (−11.2%)
	$\blacklozenge$	>1.094 (+37.4%)	>1.949 (+129.0%)	>1.179 (+37.4%)	>2.798 (+121.5%)	<0.357 (−54.9%)
3.0	Δ	1.140	1.232	1.086	1.578	0.634
	$\#$	1.038 (−8.9%)	1.321 (+7.2%)	0.989 (−9.0%)	1.723 (+9.2%)	0.580 (−8.4%)
	$\blacklozenge$	1.624 (+42.5%)	2.735 (+122.0%)	1.546 (+42.4%)	3.472 (+120.0%)	0.288 (−54.5%)
3.4	Δ	1.569	1.714	1.344	1.951	0.512
	$\#$	1.440 (−8.2%)	1.841 (+7.4%)	1.232 (−8.3%)	2.127 (+9.0%)	0.470 (−8.3)
	$\blacklozenge$	2.043 (+30.2%)	3.528 (105.8%)	1.748 (30.1%)	4.091 (109.7%)	0.244 (−52.3%)
3.8	Δ	2.090	2.311	1.629	2.381	0.420
	$\#$	1.906 (−8.8%)	2.474 (+7.0%)	1.484 (−8.9%)	2.588 (+8.7%)	0.386 (−8.0%)
	$\blacklozenge$	2.581 (+23.5%)	4.360 (+88.7%)	2.007 (+23.2%)	4.616 (+93.9%)	0.217 (−48.4%)
4.2	Δ	2.710	3.034	1.939	2.864	0.349
	$\#$	2.492 (−8.0%)	3.365 (+10.9%)	1.780 (−8.2%)	3.228 (+12.7%)	0.310 (−11.3%)
	$\blacklozenge$	3.394 (+25.3%)	5.666 (+86.7%)	2.423 (+25.0%)	5.485 (+91.5%)	0.182 (−47.8%)
4.6	Δ	3.435	3.895	2.273	3.400	0.294
	$\#$	3.087 (−10.1%)	4.064 (+4.3%)	2.037 (−10.4%)	3.604 (+6.0%)	0.277 (−5.7%)
	$\blacklozenge$	4.088 (+19.0%)	6.753 (+73.4%)	2.697 (+18.7%)	6.030 (+77.4%)	0.166 (−43.6%)
5.0	Δ	4.269	4.905	2.627	3.986	0.251
	$\#$	3.805 (−10.9%)	5.057 (+3.1%)	2.332 (−11.3%)	4.174 (+4.7%)	0.240 (−4.5%)
	$\blacklozenge$	4.998 (+17.1%)	8.218 (+67.5%)	3.065 (+16.7%)	6.821 (+71.1%)	0.147 (−41.6%)

* Δ : Value at the elastic limit; $\#$: Value at the onset of the first column plastic hinge; $\blacklozenge$: Value at the onset of the structural mechanism. Values in parentheses indicate the percentage change relative to the elastic stage (Δ).

A detailed examination of Table 6 reveals a counter-intuitive but critical phenomenon regarding the amplification of irregularity. Contrary to the expectation that severe geometric irregularities would lead to higher inelastic divergence up to mechanism point, the percentage amplification relative to the elastic baseline is observed to remain higher in models with lower ground story heights (e.g., 3.0 m and 3.4 m) compared to those with extreme soft stories (e.g., 5.0 m).

For instance, in the 3.0 m model, the transition from the elastic range to the mechanism onset triggers a drastic surge of 42.5% in the stiffness ratio (k_2/k_1) and a 54.5% reduction in

the BSL factor (R_{s1}). In contrast, for the 5.0 m model, while the absolute values of irregularity are significantly higher, the relative inelastic amplification is limited to approximately 17%.

The discrepancies quantified in Table 6 correspond to specific structural milestones (e.g., first column hinging, mechanism onset) that occur at varying top displacements for each model. Therefore, comparing models solely based on these milestones may not fully reflect the evolution of irregularity under identical displacement demands. To further investigate this phenomenon and isolate the influence of inelasticity at every step of the response, the variation in the stiffness ratio (k_2/k_1) was normalized by its constant elastic value. The resulting irregularity magnification factor, which represents how many times the instantaneous irregularity exceeds the elastic prediction at a given displacement, is plotted in Figure 9.

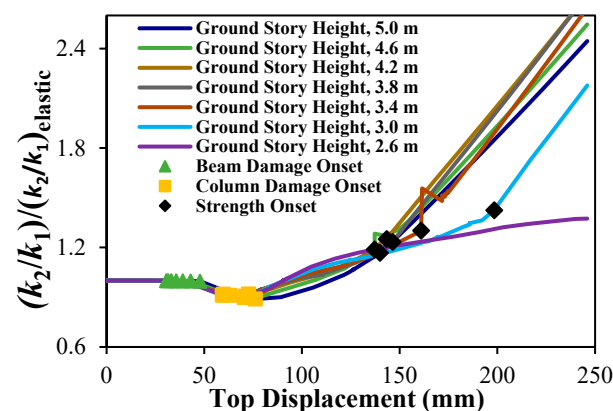


Figure 9. Variation in the stiffness irregularity magnification factor (normalized by the initial elastic value) for ASCE story stiffness ratio (k_2/k_1) with respect to top displacement for different ground story heights, highlighting the convex vs. concave amplification trends in the inelastic range.

A critical examination of Figure 9, particularly in the inelastic transition zone between column yielding (■) and mechanism onset (◆), reveals a distinct divergence in the amplification behavior of models with moderate versus extreme ground story heights.

1. **Behavior of Regular Models (Convex Trajectory):** Models with shorter ground stories (e.g., 2.6–3.4 m), which are closer to the regularity limits, exhibit a convex magnification curve with a steep gradient. This indicates that the onset of column plasticity triggers a sudden and disproportionate surge in stiffness irregularity. In these ‘ostensibly regular’ buildings, the localized damage drastically alters the relative stiffness balance, causing the system to diverge rapidly from its elastic baseline;
2. **Behavior of Irregular Models (Concave Trajectory):** Conversely, the models with extreme soft stories (e.g., 4.6–5.0 m) display a concave progression with a comparatively lower rate of relative increase in this zone. Since the initial elastic irregularity (k_2/k_1) is already excessively high, the marginal impact of plasticity leads to a less dramatic percentage amplification compared to the regular models.

Consequently, while taller ground stories result in higher absolute irregularity values, the sensitivity of the irregularity parameter to inelasticity is paradoxically higher in shorter ground stories. This implies that initially regular buildings lose their safety margins much more abruptly once the elastic limit is exceeded, whereas irregular buildings maintain a more consistent—albeit severely deficient—behavior pattern. Specifically, the stiffness irregularity factor in ‘regular’ systems escalates rapidly from a lower initial baseline, whereas in extreme ground height models, the factor initiates from a significantly higher value but exhibits a slower rate of amplification between column yielding and mechanism onset.

This finding highlights a distinct danger: In buildings with extreme geometric irregularity (5.0 m), the elastic analysis already successfully identifies the severity of the soft story.

However, in ‘borderline’ cases, the elastic analysis may suggest relatively regular behavior, masking the potential for a disproportionate increase in irregularity during a seismic event. A pertinent example of this is the model with a 3.4 m ground story height. As evidenced in Figure 8c, this model satisfied the regularity limits within the elastic range; however, as illustrated by its convex trajectory in Figure 9, it underwent a rapid degradation between the onset of plasticity (first hinge) and the mechanism formation, effectively transitioning into a soft-story status under inelastic displacements. Consequently, the discrepancy—and the risk of underestimating the soft story potential—is most critical in buildings with moderate ground story heights, where the reliance on elastic limits provides a false sense of security.

Through the conducted parametric analysis, Case B generalizes the results obtained for Case A (a laboratory 1/2 scaled frame which exhibits a very severe soft-story irregularity) with additional comments, by varying the degree of soft-story irregularity for a full-scale building. Except for the influence of beam hinging and some other additional investigations, similar graphical trends were observed in the analyses of Case A (see Figures 6a–d and 8b–f). Accordingly, the interpretations regarding the form of the soft-story factor diagrams presented in Figure 6a–d for Case A are generally suitable here in the Case B as well.

The values of the stiffness irregularity factors specified in all of the examined codes deviate further from their limit values when the lateral push is increased particularly after the formation of plastic hinges. Consequently, the influence of the soft story behavior in the ground story also becomes more pronounced as the top displacement increases. As is well known, the inelastic displacement demand of an earthquake is directly related to the point reached on the capacity curve of the structure under the corresponding seismic action. As the plastic seismic demand increases, the resulting top displacement likewise increases, and the value of stiffness irregularity factors associated with that top displacement also increase.

3. Results and Discussion

This study establishes a general framework for the evaluation of soft story irregularity by utilizing nonlinear static analysis to monitor the evolution of code-defined factors across increasing damage levels. This framework integrates multi-level assessments through a detailed reference frame (Case A) and an extensive 3D parametric building investigation (Case B), thereby offering a robust alternative to conventional linear ELF procedures by extending their scope to incorporate inelastic structural behavior. The study rigorously evaluates soft story irregularity factors (described in ASCE/SEI-7-10 et al., BSL, and TBEC-2018 codes) using the nonlinear static analysis method, departing from the standard linear analysis approach prescribed by codes, and analyzes how various code-defined factors respond to increasing levels of damage. In that regard, the inelastic investigation of the soft story irregularity of a low-strength RC planar frame (Case A), designed with a ground story height much higher than the upper story, was carried out using different criteria in international codes via nonlinear pushover analysis. First, the presence of a soft story was determined using the equivalent lateral force (ELF) method, which confirmed that the considered frame exhibited soft story irregularity according to all codes. This was included as a preliminary step for comparison with the increases in the irregularity factors to be observed in the nonlinear analysis results, which constitute the main focus of this study. Afterwards, a nonlinear static pushover analysis was conducted to obtain story drifts, story shear forces, story stiffnesses, and the pushover curve. Stiffness irregularity factors, defined in the codes for soft story detection, were calculated for each pushover step, and the corresponding plots (Figure 6a–d) are presented and evaluated. Verification of the elastic model parameters was performed by comparing the linear ELF analysis results

with the pre-yield section of the pushover curve, yielding identical stiffness characteristics. Thus, Case A serves as a rigorous analytical baseline to scrutinize the code-based factors prior to the planned shaking table experimental phase.

As depicted in the hinge formation sequence in Figure 4, the nonlinear response is entirely dominated by the formation of plastic hinges at the ends of the ground story columns. Following the onset of the complete soft-story mechanism, the global pushover curve explicitly enters a strength degradation (softening) phase having a constant negative slope. It should be noted that the study's primary objective is to trace the continuous evolution of stiffness irregularity factors throughout the structure's stable inelastic deformation zone. Therefore, simulating a sudden, discrete drop in section capacity (ultimate physical collapse) was deliberately avoided, as it would cause premature analytical termination. Instead, numerical stabilization techniques—specifically idealized flexural hinges with post-point E extrapolation—were employed. This ensured the continuous tracing of the descending branch and the reliable generation of stiffness irregularity factor plots, which are highly sensitive to numerical fluctuations. Furthermore, physically, the global capacity curve of such a framed system exhibits a gradual negative stiffness branch due to internal load redistribution and P- Δ effects. Once column hinges form, the system resists the overturning moment primarily through an axial force couple, preventing an instantaneous vertical drop in global capacity. Ultimately, this post-peak slope confirms the degrading nature of the columns under pure soft-story mechanism, entirely precluding any ductile beam-sway contribution.

Subsequently, to demonstrate that similar characteristics are observed in existing buildings and to investigate how stiffness irregularity factors vary with the degree of soft story irregularity, a parametric study was conducted using nonlinear pushover analysis (Case B). In this analysis, the ground story height of a 3D building was incrementally increased from 2.6 m to 5.0 m. As stiffness irregularity factors, the stiffness irregularity coefficient defined in TBEC-2018; the story stiffness ratio specified in the UBC, ASCE, and NBC codes (represented herein by the ASCE/SEI-7-10 extreme soft-story criterion); and the ratio of the mean inverse column lateral displacement angle prescribed in the Japanese code (BSL) were calculated and plotted against top displacement. The results are plotted in Figure 8b–f, and the trends are interpreted in conjunction with the nonlinear analysis outcomes. Although this study investigates the variation in code-based criteria through nonlinear analysis, the calculations performed for these criteria represent the extent to which structural engineering quantities—such as stiffness and relative interstory drift ratios of adjacent stories—differ from one another. Consequently, the study inherently includes a comparative nonlinear assessment of soft ground stories.

3.1. Inelastic Evolution of Stiffness Irregularity in Planar Frame (Case A)

The study revealed that stiffness irregularity factors defined in TBEC-2018, ASCE/SEI-7-10, and BSL codes remain essentially constant within the elastic range. However, once the structure enters the inelastic domain (specifically after the first plastic hinge formation), all factors deteriorate rapidly. This behavior indicates that the effects of soft story behavior intensify after the structure transitions into inelastic behavior. Similar trend also observed in the displacement profiles presented in Figure 5. Comparing the initial and final steps of the pushover analysis for Case A, it was observed that while the upper story drift increased by approximately 3.7 times, the soft story drift amplified by nearly 11 times. This disproportionate increase confirms that damages are heavily concentrated in the soft story.

From the formation of the first plastic hinge to the final pushover step, the values of the parameters η_{k1} and k_2/k_1 increased by approximately three times, the value of R_1^{-1} increased by about 2.5 times, and the value of R_1 decreased to 41% of its original value.

It is evident that the codes under consideration provide mutually consistent assessments regarding the deterioration of soft story behavior throughout the inelastic region of the structure. Specifically, the transition point from the elastic to inelastic region in the pushover curve of Figure 4 coincides with the point in Figure 6a–c where the irregularity factors start their monotonic increase. Also while the irregularity factor results of the elastic part of the pushover analysis and the ELF method coincides together, the irregularity factor results of the post-elastic part of pushover analysis becomes greater than ELF method. It is clearly observed that the stiffness irregularity factors determined by linear calculation methods in current building codes significantly misestimate the situation for actual demand and the associated damage level.

There exists a relationship in terms of graphical form between the variations in the stiffness irregularity factors throughout the pushover steps and the variations in the base shear-top displacement relationship at static pushover curve. Consequently, an interaction arises between the influence of soft story behavior and the inelastic response of the system. According to the comparisons in analysis results of the frame already exhibiting soft story behavior, the intensification starts at first yielding and the severity of this behavior increases after the inflection point of the static pushover curve;

At the exact onset of the soft-story mechanism (pushover step 5), the k_2/k_1 and η_{k1} ratios increased by 120% compared to the elastic state, while R_1^{-1} increased by 114% (see Table 3). It was observed that the rate of increase in stiffness irregularity factors was proportional to the rate of reduction in the overall stiffness of the structure. For the investigated system exhibiting extreme soft-story irregularity, the values of the soft-story irregularity factors continued to increase after the initiation of plastic hinge formation at the ends of the soft-story columns, i.e., pushover step 5. As a suggested approach, these stiffness irregularity factors may be evaluated at the target displacement corresponding to the inelastic displacement demand that the structure is expected to undergo under the design earthquake, in order to achieve a more reliable identification of soft-story behavior.

3.2. Parametric Sensitivities in 3D Building Models (Case B)

The parametric investigation conducted on 3D full-scale buildings (Case B) highlighted a critical discrepancy between elastic and inelastic assessments. While elastic analysis classified only 2 out of 7 models as having soft story irregularity according to TBEC-2018, and 5 according to ASCE/BSL, the nonlinear analysis revealed that almost all models eventually exceeded the irregularity limits as plastic hinges developed. This implies that elastic analysis may produce ‘false negatives’ in terms of soft story detection if the structure is expected to sustain damage, as often observed in older buildings during post-earthquake field investigations. When comparing the safety tendencies of the regulations based on elastic results, the BSL and ASCE/SEI 7-10 codes were found to be more conservative compared to TBEC-2018.

Unlike the frame model (Case A), the 3D building models exhibited initial plastic hinging in the beams, which temporarily reduced the stiffness irregularity factors (by about 8–10%) in the ASCE and TBEC-2018 definitions. However, this is a transient phenomenon; once column hinging initiates, the irregularity factors deteriorate rapidly and monotonically. Thus, it is observed that stiffness irregularity factors tend to deteriorate rapidly, particularly in relation to damage occurring in columns. Furthermore, as the ground story height increased, the transition into soft story behavior occurred at progressively lower top displacement levels. Models with extreme soft story irregularity reached their ultimate base shear strength earlier and exhibited reduced ductility.

A critical quantitative finding is that the percentage amplification of irregularity factors relative to the elastic baseline was significantly higher in models with lower ground

story heights (e.g., 3.0 m). While models with extreme geometric irregularity (e.g., 5.0 m) maintain a consistently high irregularity level (concave amplification), the ostensibly ‘regular’ or borderline models exhibit a rapid and convex surge in irregularity once the elastic limit is exceeded. This phenomenon highlights a latent risk: relying solely on elastic analysis for structures with moderate ground story heights may induce a false sense of security, masking the potential for disproportionate stiffness degradation during severe seismic events.

Critically, modern seismic design codes rely on energy dissipation through ductile behavior, implicitly accepting that structures will undergo significant inelastic deformations during design-level earthquakes. This study demonstrates that soft story irregularity is not a static property; rather, it amplifies significantly within this expected inelastic range. Since the structure is destined to function in the post-yield domain during a strong seismic event, evaluating stiffness irregularity solely based on initial elastic properties leads to an unconservative assessment. Therefore, to capture the true vulnerability of the structure, stiffness irregularity factors should ideally be checked at the target displacement demand corresponding to the design earthquake, rather than relying on elastic limits.

4. Conclusions

This study investigated the evolution of code-defined soft story irregularity factors (TBEC-2018, ASCE/SEI-7-10, and BSL) from the elastic to the inelastic range using nonlinear static analysis. Based on the numerical evaluations of a reference planar frame (Case A) and a parametric 3D building investigation (Case B), the most critical findings are summarized as follows:

1. Soft story irregularity is not a static property. Code-defined irregularity factors remain constant in the elastic region -consistent with the traditional elastic ELF irregularity detection calculation-, but deteriorate rapidly and monotonically once the structure enters the inelastic domain, specifically after column hinging initiates.
2. Stiffness irregularity factors calculated using standard linear methods significantly underestimate the actual irregularity level. Nonlinear analyses revealed that structures classified as ‘regular’ under elastic code criteria may exceed irregularity limits as damage progresses, leading to “false negatives”.
3. Structures with balanced story heights exhibit a much higher percentage amplification of irregularity factor level in the post-yield stage compared to structures with extreme soft story irregularity for the same target top displacement level. Relying solely on elastic analysis for moderate ground story regular-seeming buildings may induces a false sense of security against severe seismic events.
4. In 3D structural systems, the initial formation of plastic hinges in beams can temporarily reduce the calculated stiffness irregularity factors (by approximately 8–10%). However, this apparent mitigation is strictly a transient phenomenon; once yielding transfers to the columns, the irregularity factors deteriorate very rapidly and monotonically, proving that early beam ductility cannot prevent the ultimate severity of the soft-story mechanism.
5. Since structures are expected to undergo inelastic deformations during strong earthquakes, identifying soft story irregularity based solely on initial elastic properties is insufficient. It is recommended that stiffness irregularity factors be evaluated at the target displacement corresponding to the design earthquake to capture the true structural vulnerability. As the core implementation of the proposed approach, this study establishes a general framework that evaluates stiffness irregularity factors at the target displacement, which may correspond to the design earthquake. By shifting the assessment from initial elastic properties to the expected inelastic displacement de-

mand, this framework provides a more realistic identification of soft-story irregularity and vulnerability during an earthquake in diverse structural systems.

Finally, it should be noted that the present study primarily focuses on the evolutionary trends of stiffness irregularity factors and, in general, the interpretation of the analysis results is performed up to the onset of the soft-story mechanism. A detailed numerical comparison deep within the post-mechanism (softening) region was not performed. Since the structural response in this severe degradation phase is highly sensitive to P-Delta effects and local plastic hinge definitions, future research aiming to specifically evaluate this ultimate zone may require the implementation of different more complex lumped –or distributed- plasticity models that explicitly incorporate sudden strength loss (degradation) at the cross-section level.

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References

1. Ruggieri, S.; Uva, G. Extending the concepts of response spectrum analysis to nonlinear static analysis: Does it make sense? *Innov. Infrastruct. Solut.* **2024**, *9*, 235. [[CrossRef](#)]
2. Ruggieri, S.; Uva, G. Accounting for the spatial variability of seismic motion in the pushover analysis of regular and irregular RC buildings in the new Italian building code. *Buildings* **2020**, *10*, 177. [[CrossRef](#)]
3. Yousef, A.M.; El-Metwaaly, E.; El-Mandouh, M.A. Seismic response of vertically irregular HSC moment-resisting building frames. *J. Eng. Appl. Sci.* **2010**, *57*, 409–430. [[CrossRef](#)]
4. Döndüren, M.S.; Nakipoğlu, A. Comparison of R/C buildings with a soft-storey irregularity with respect to various national building codes. *Mater. Technol.* **2018**, *52*, 575–581. [[CrossRef](#)]
5. Khanal, N.; Singh, S.K.; Wagley, S. Seismic consideration of soft story in RC frame buildings using various national codes. *Int. J. Civ. Eng. Technol.* **2019**, *10*, 343–352.
6. Zavala, D.J.; Torres, C.J.; Moreno, J.D. Influence of the P- Δ effect and stiffness irregularity on the structural behavior of reinforced concrete buildings. *J. Phys. Conf. Ser.* **2022**, *2287*, 012047. [[CrossRef](#)]
7. Merajuddin, M.; Azeem, M.A. A study on estimation of stiffness irregularity in RC buildings. *Int. J. Appl. Eng. Res.* **2020**, *15*, 74–80.
8. Nezhad, M.E.; Poursha, M. Seismic evaluation of vertically irregular building frames with stiffness, strength, combined-stiffness-and-strength and mass irregularities. *Earthq. Struct.* **2015**, *9*, 353–373. [[CrossRef](#)]
9. Tabeshpour, M.R.; Noorifard, A. Comparing calculation methods of storey stiffness to control provision of soft storey in seismic codes. *Earthq. Struct.* **2016**, *11*, 1–23. [[CrossRef](#)]
10. Vijayanarayanan, A.R.; Goswami, R.; Murty, C.V.R. Identifying stiffness irregularity in buildings using fundamental lateral mode shape. *Earthq. Struct.* **2017**, *12*, 437–448. [[CrossRef](#)]
11. Inan, T.; Korkmaz, K.; Cagatay, I.H. An investigation on plan geometries of RC buildings: With or without projections in plan. *Comput. Concr.* **2012**, *9*, 439–455. [[CrossRef](#)]

12. Arlekar, J.N.; Jain, S.K.; Murty, C.V.R. Seismic response of RC frame buildings with soft first storeys. In Proceedings of the Golden Jubilee Conference on Natural Hazards in Urban Habitat, New Delhi, India, 10–11 November 1997.
13. Santhi, M.H.; Knight, G.M.S.; Muthumani, K. Evaluation of seismic response of soft-storey infilled frames. *Comput. Concr.* **2005**, *2*, 423–427. [\[CrossRef\]](#)
14. Islam, A.B.M.S.; Hussain, R.R.; Jumaat, M.Z.; Darain, K.M. Implication of rubber- steel bearing nonlinear models on soft storey structures. *Comput. Concr.* **2014**, *13*, 603–619. [\[CrossRef\]](#)
15. Tasleem, M.; Firoj, M.; Bahuguna, A. Effect of open-ground storey on RC frame buildings incorporating soil–structure interaction. *Asian J. Civ. Eng.* **2022**, *23*, 471–485. [\[CrossRef\]](#)
16. Furtado, A.; Rodrigues, H.; Arede, A. Effect of the openings on the seismic response of an infilled reinforced concrete structure. *Buildings* **2022**, *12*, 2020. [\[CrossRef\]](#)
17. Mohabbi, M. Infill walls effect on the structural performance of a RC buildings frame: A study based on wall modeling by strut element. *Buildings* **2026**, *16*, 1423. [\[CrossRef\]](#)
18. Öztürk, H.; Çavdar, E.; Özdemir, G. Effectiveness of seismic isolation in a reinforced concrete structure with soft story. *Struct. Eng. Mech.* **2023**, *87*, 405–418. [\[CrossRef\]](#)
19. Dereje, A.J.; Kim, J. Seismic retrofit design framework for asymmetric soft-first story structures considering uncertainties. *Struct. Eng. Mech.* **2023**, *86*, 249–260. [\[CrossRef\]](#)
20. Li, P.; Chu, S.; Qin, S.; Ding, H.; Luo, N.; Yu, Y.; Zhang, T.; Xiong, G. Optimisation of prestressed stayed steel columns based on strengthen elitist genetic algorithm. *J. Constr. Steel Res.* **2025**, *227*, 109324. [\[CrossRef\]](#)
21. Parekar, S.D.; Datta, D. Seismic behaviour of stiffness irregular steel frames under mainshock–aftershock. *Asian J. Civ. Eng.* **2020**, *21*, 857–870. [\[CrossRef\]](#)
22. Adhav, A.A.; Birajder, B.G. Stiffness irregularity in RC high-rise building. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1326*, 012035. [\[CrossRef\]](#)
23. El-Salakawy, T.S.; El-Diasity, M.; Naguib, M.M.; Hamdy, M. Effect of vertical irregularity of concrete frame systems on the seismic response modification factor. *Comput. Concr.* **2025**, *36*, 127–140. [\[CrossRef\]](#)
24. Ujwal, M.S.; Kumar, G.S.; Sathvik, S.; Ramaraju, H.K. Effect of soft story conditions on the seismic performance of tall concrete structures. *Asian J. Civ. Eng.* **2024**, *25*, 3141–3149. [\[CrossRef\]](#)
25. Işık, E.; Ulutaş, H.; Harirchian, E.; Avcil, F.; Aksoylu, C.; Arslan, M.H. Performance-based assessment of RC building with short columns due to the different design principles. *Buildings* **2023**, *13*, 750. [\[CrossRef\]](#)
26. Lakshmanan, N.; Raghuprasad, B.K.; Muthumani, K.; Gopalakrishnan, N.; Sreekala, R. Seismic damage estimation through measurable dynamic characteristics. *Comput. Concr.* **2007**, *4*, 167–186. [\[CrossRef\]](#)
27. Bhosale, A.S.; Davis, R.; Sarkar, P. Vertical irregularity of buildings: Regularity index versus seismic risk. *ASCE-ASME J. Risk Uncertain. Eng. Syst. Part A Civ. Eng.* **2017**, *3*, 04017001. [\[CrossRef\]](#)
28. Ilgün, A.; Yorulmaz, A.M. Research on A1 irregularity status in different spectral acceleration coefficients on reinforced concrete structures. *Turk. J. Eng.* **2021**, *5*, 177–182. [\[CrossRef\]](#)
29. Nady, O.; Mahfouz, S.Y.; Taher, S.E.D.F. Quantification of vertical irregularities for earthquake resistant reinforced concrete buildings. *Buildings* **2022**, *12*, 1160. [\[CrossRef\]](#)
30. Rathnasiri, H.M.S.C.; Jayasinghe, J.A.S.C.; Bandara, C.S. Development of irregularity index based on dynamic characteristics to quantify the vertical geometric irregularities. *Engineer* **2020**, *53*, 41–51. [\[CrossRef\]](#)
31. Sadashiva, V.K.; MacRae, G.A.; Deam, B.L. Determination of structural irregularity limits—Mass irregularity example. *Bull. N. Z. Soc. Earthq. Eng.* **2009**, *42*, 288–301. [\[CrossRef\]](#)
32. Usta, P.; Bozdağ, Ö.; Onat, Ö. Seismic performance evaluation of RC buildings using irregularity based indices. *Teh. Vjesn.* **2022**, *29*, 1362–1371. [\[CrossRef\]](#)
33. TBEC-2018; Türkiye Building Earthquake Code. Disaster and Emergency Management Presidency: Ankara, Türkiye, 2018. (In Turkish)
34. ASCE/SEI-7-10; Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers/Structural Engineering Institute: Reston, VA, USA, 2010.
35. Seyed, B. Structural irregularities and the building codes. In Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, Toronto, ON, Canada, 25–29 July 2010.
36. Hasnat, A.; Rahim, M.R.I. Response of building frames with vertical and stiffness irregularity due to lateral loads. *Int. J. Eng. Res. Technol.* **2013**, *2*, 795–799.
37. Sadashiva, V.K.; MacRae, G.A.; Deam, B. Seismic response of structures with coupled vertical stiffness–strength irregularities. *Earthq. Eng. Struct. Dyn.* **2012**, *41*, 119–138. [\[CrossRef\]](#)
38. BSL; Commentary on the Structural Calculation Based on the Revised Enforcement Order. Ministry of Construction, Housing Bureau and Building Research Institute, Building Standard Law, Building Center of Japan: Tokyo, Japan, 1980. (In Japanese)

39. Aoyama, H. Outline of earthquake provisions in the recently revised Japanese building code. *Bull. N. Z. Natl. Soc. Earthq. Eng.* **1981**, *14*, 63–80. [[CrossRef](#)]
40. *SAP2000*; Version 23.3.0. Integrated Finite Element Analysis and Design of Structures. Computers and Structures Inc.: Berkeley, CA, USA, 2021.
41. Bahşi, E.; Dada, A.; Gümüş, E.; Cenikli, S. Evaluation of the numerical analysis results of the buildings for which risky structures are detected in accordance with the principles regarding the detection of risky structures within the scope of law no. 6306. *Resil. J.* **2023**, *7*, 153–169. (In Turkish) [[CrossRef](#)]
42. Haque, S.; Amanat, K.M. Seismic vulnerability of columns of RC framed buildings with soft ground floor. *Int. J. Math. Models Methods Appl. Sci.* **2008**, *2*, 364–371.
43. *Eurocode 8*; Design of Structures for Earthquake Resistance—Part 2: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization: Brussels, Belgium, 1998.
44. *Turkish Earthquake Code*; Specification for Structures to be Built in Disaster Areas. Ministry of Public Works and Settlement: Ankara, Turkey, 1998. (In Turkish)
45. *TS-498*; Design Loads for Buildings. Turkish Standards Institution: Ankara, Turkey, 1997. (In Turkish)

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