Research Article

The effect of eccentricity and asymmetry in the plan on the performance level in existing steel buildings with a medium bending frame

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ABSTRACT

The evaluation of the torsional effects of earthquakes on the performance of steel buildings with medium-ductility moment frames, which are widely used in seismic regions, is critical because of their high flexibility and significant energy absorption capacity. Amplification of the seismic response of buildings owing to torsion and the precise and influential factors in its creation and amplification during an earthquake is essential. Design and seismic strengthening regulations should pay more attention to geometric asymmetry as a significant factor in amplifying building response. This study investigated the combined effect of geometric asymmetry in one direction with the effect of eccentricity in three states—accidental torsion, significant torsion, and severe torsion—as influencing factors on performance levels and vital parameters such as ductility changes. The selected models with five and nine stories have symmetric and asymmetric plans, at least in one direction, designed according to the Standard 2800 fourth edition and the National Steel Buildings Iran Regulations fifth edition. Then, by creating significant and severe torsional irregularities in the models of existing buildings using the guidelines for seismic rehabilitation of existing structures with nonlinear static analysis (pushover), the performance levels of the buildings were evaluated. The results indicate that the asymmetry in the plan in one direction compared to the symmetric plan reduces the performance level of 5-story models by more than 9-story models. In addition, changes in Ductility and seismic response due to torsion in 5-story buildings are more significant; therefore, asymmetry in one direction with severe torsion causes a 43% reduction in Ductility. These findings underscore the need for further research to fully understand the implications of asymmetry and torsion in seismic design and to incorporate these findings into future seismic codes and design practices.

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INTRODUCTION

One of the most common structural systems is steel frame buildings with moment frames. Due to their high flexibility and significant energy absorption capacity, steel moment frame buildings with medium Ductility are widely used in seismic regions. Past and recent earthquakes have shown that the presence of eccentricity in plans with varying percentages in existing buildings with symmetric and asymmetric plans has affected the performance of buildings due to torsion as a factor causing damage and destruction. Buildings undergo lateral and torsional movements due to earthquakes .[1]. Torsional effects are divided into two categories: inherent torsion and accidental torsion. Inherent torsion can be caused by predictable and measurable sources such as asymmetric building geometry and the uneven distribution of stiffness, member strength, and building mass. [2] Other factors that are difficult or impossible to quantify, and their direct consideration in design codes and evaluating existing buildings are problematic, are referred to as accidental torsion. Accidental torsion accounts for discrepancies between the distribution of mass, stiffness, and strength in analysis and the actual values at the time of an earthquake, torsion due to the earthquake's rotational component, and other sources of torsion. Building codes introduce an additional eccentricity to account for accidental torsion. In the "design accidental eccentricity," four additional load cases with changes in the center of mass along the x and y axes of all floors in both positive and negative directions must be considered [3]. Research by De la Llera and Chopra in the early 1990s, based on records of three buildings, indicated that the torsion rules based on 5% eccentricity were sufficient for the torsional movements observed in the studied buildings during recorded earthquakes .[4] However, these movements increased the member forces by up to 30% in one of the buildings. The results showed that accounting for accidental torsion was unnecessary in the design of two of the buildings for the recorded earthquakes. The study estimated that the rotational component of the earthquake contributed 25-40% of the total accidental torsion in the examined buildings. The accidental torsion rule in building codes, especially when significant approximations, such as typification in member design, are considered, has little impact on member sizing, detailing, and connections in these buildings. Buildings are rarely affected by the accidental design eccentricity rule .[5] Dimova et al. (2003) analytically estimated the dynamic effects on symmetric structures due to the displacement of the center of mass and its application in seismic design. The study results showed that even small eccentricities cause irregular behavior in symmetric structures, and using static application of torsional moments to account for accidental torsion effects is inappropriate. [6] A probabilistic study on short-height buildings, showing that the Ductility requirement for systems designed with and without accidental eccentricity was similar. Ramadan [7] (2008) conducted a

probabilistic study on eight three-dimensional multi-story concrete buildings with symmetric plans under a single horizontal earthquake component, showing that accidental eccentricity significantly affects upper-story floors and is often less than the typical 5% value specified in building codes for floors with more than five upper stories.[8] Symmetric and biaxially eccentric reinforced concrete moment frame buildings. All buildings were designed for three different accidental eccentricities. Results showed that with the introduction of ±5% mass eccentricity, the Ductility requirement was similar in designed and non-designed buildings. Accidental mass eccentricity is insignificant when the building response is highly inelastic. [8] The effect of the number of upper floors, the dead-to-live load ratio, and the number of columns per floor on the amount of accidental eccentricity in rectangular and square plan buildings with 5 and 10 stories was investigated. [9] The results indicated that accidental eccentricity decreases with the number of lateral load-bearing members and increases with the number of upper floors. The dead-to-live load ratio has a minor effect on accidental eccentricity. The quality of the SEI/ASCE7 accidental torsion design requirements on building failure capacity was evaluated. [10] The results showed that the accidental eccentricity rule can be omitted in the seismic design of buildings without significant torsional or asymmetrical irregularities.[10] The importance of accidental eccentricity in symmetrically braced steel buildings with 10% and 20% biaxial eccentricities was studied.[11] First, the buildings were designed with accidental design eccentricities. Then, all these buildings were analyzed under a set of earthquakes that introduced accidental mass eccentricity. The results showed that the design of symmetrical plan buildings with biaxial eccentricities of 10% and 20% using accidental design eccentricity has little impact on the inelastic response of the structures.[11] An analytical and code review of torsional irregularities in low- to mid-rise structures using linear spectral analysis results and applying accidental torsion was conducted.[12] The building models were reinforced concrete with dual systems, and the position of shear walls, the number of floors, and the number of spans were considered to investigate torsional irregularity in one direction. The study results indicated that the maximum torsional irregularity coefficient increases with a decrease in the number of floors. Upper floors have lower torsional irregularity coefficients than lower floors. The results for floor rotations were opposite to those for torsional irregularity coefficients.[12] The effect of eccentricity and asymmetry in plans on performance levels and results in existing steel buildings with medium ductility moment frames could lead to significant discrepancies.[13] The study results indicated up to 18 times more rotation for structures with short-term natural periods. Additionally, the complex shapes of modern buildings often lead to irregular distribution of mass, stiffness, and strength, which can cause unwanted rotation and weaken the building during an earthquake. Based on last research,

geometric asymmetry in plans has been less considered in design and seismic strengthening codes as a significant factor in amplifying the seismic response of structures. This paper examines the simultaneous effect of eccentricity and symmetric and asymmetric plans in at least one direction in three states—Accidental torsion, significant torsion, and severe torsion—on performance levels and key parameters such as structural period and Ductility in these models.

CHARACTERISTICS OF THE STUDIED MODELS

This section introduces the structural system under study, the material properties, and the design method meticulously crafted in strict adherence to national codes and building regulations. The models are steel moment frame buildings with medium ductility considering eccentricity in three states: Accidental torsion, significant torsional irregularity, and severe torsional irregularity according to the standard 2800 fourth edition.[14] These models, with symmetric and asymmetric plans as shown in Figures 1 and 2, with 5 and 9 floors, totaling 12 models, have been designed.

Tables 1 and 2 introduce the names and dimensions of the spans in symmetric and asymmetric plans. The height of all floors in the models is 3 meters.

The construction of the models is considered in zoning with high relative risk (A = 0.30) and type II land with residential use (I = 1.0). The behavior coefficient is equal to 5 (R = 5), and the additional resistance coefficient is equal
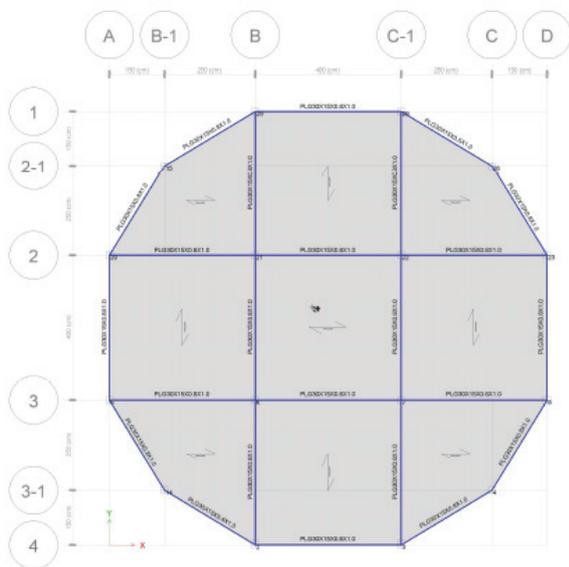

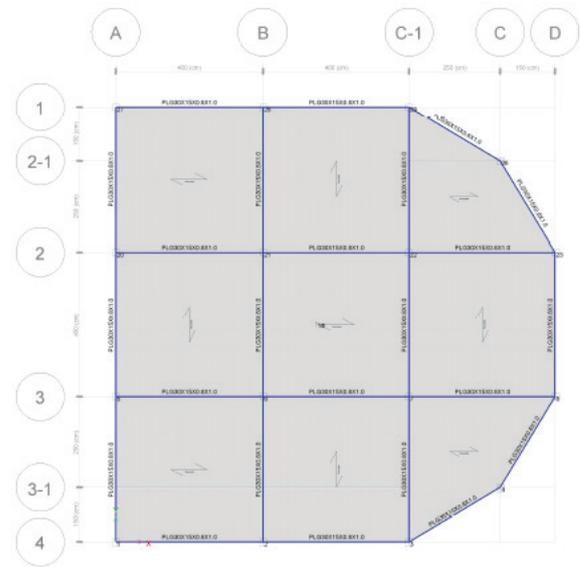**Figure 1.** Symmetric plan of 5 and 9 floor models.

Figure 2. Asymmetric plan of 5 and 9 floor models.

Table 1. The name and size of openings in the symmetrical plan in centimeters in X and Y directions

The name of the opening in the X direction	A-(B-1)	(B-1)-B	B-(C-1)	(C-1)-C	C-D
Opening size (cm)	150	250	400	250	150
Name of opening in Y direction	1-(2-1)	(2-1)-2	2-3	3-(3-1)	(3-1)-4
Opening size (cm)	150	250	400	250	150

Table 2. The name and size of openings in the asymmetric plan in centimeters in X and Y directions

The name of the opening in the X direction	A-B	B-(C-1)	(C-1)-C	C-D	-
Opening size (cm)	400	400	250	150	-
The name of the opening in the Y direction	1-(2-1)	(2-1)-2	2-3	3-(3-1)	(3-1)-4
Opening size (cm)	150	250	400	250	150

to 3 ($\Omega = 3$). The time of the prominent periodicity of the oscillation in 5-story models with symmetric and asymmetric plans, taking into account the effect of the interframe separator in seconds (Tx, Ty=0.488) with the base shear coefficient (Cx, Cy=0.15) and also the effect coefficient of higher modes (K=1) and the main period of oscillation in 9-story models with symmetric and asymmetric plans, taking into account the effect of the interframe separator in seconds (Tx, Ty=0.758) with the basic shear coefficient (Cx, Cy=0.1040) and also the effect coefficient of higher modes for 9-story models (K=1.129) has been calculated and considered, providing significant insights into the structural behavior of the models.

The specifications of the materials used for the steel frame and sections of the St-37 type have been selected. For loading and design, topic 6 of national regulations[15] and standard 2800, fourth edition[14], and topic 10 of national regulations, fifth edition [16] have been used.

The roof system is chosen as a single-sided slab, and the dimensions of the sections in the five and 9-story models with symmetric and asymmetric plans with random departure from the centrality are chosen to meet the design criteria based on national regulations for linear analysis from ETABS software. 2016 has been used. [17] For example, Figure 3 shows the three-dimensional view of the 9-story model with an asymmetrical plan. Figure 4 shows the three-dimensional view of the 5-story model with a symmetrical plan.

According to paragraph 1-7-1 of plan irregularity of clause B of standard 2800, high and severe torsion irregularity is defined in cases where the maximum relative displacement at one end of the building on each floor, including

accidental torsion ing and assuming a magnification factor equal to 1 (Aj=0.1) should be more than 20% of the average relative displacement at both ends of the building on that floor. In these cases, the irregularity is "high," and in cases where this difference is more than 40%, it is described as "severe" torsional irregularity.[14] To create other models, assuming that the models are existing structures in the models designed based on national regulations and standard 2800, according to the criteria for defining high and severe torsional irregularity in standard 2800, the fourth edition, by making severe changes in the initial models and Creation of eccentricity along both axes in symmetric and asymmetric plans, other models have been created for investigation.

Analysis of Models

After modeling and performing linear analysis and design according to national regulations, to investigate the effect of distortion and asymmetry on the level of performance and plasticity of the models in three cases with departure from *accidental torsion*, extensive and severe torsional irregularity during an earthquake, Non-linear static analysis has been used to obtain the capacity curve of the structure. To check the performance level of the structure, it is necessary to find the target point on the capacity curve of the structure. At this point, the forces and deformations of the members for different performance levels should be checked. That point is called the change of target location, so in this research, the method of determining the coefficients of 360 publication was used for non-linear static analysis and obtaining the change of target location. The 360 revision publication of 2013, a significant resource in
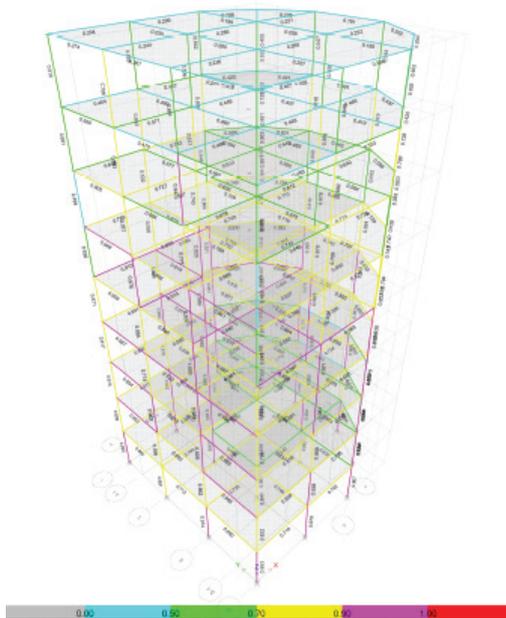

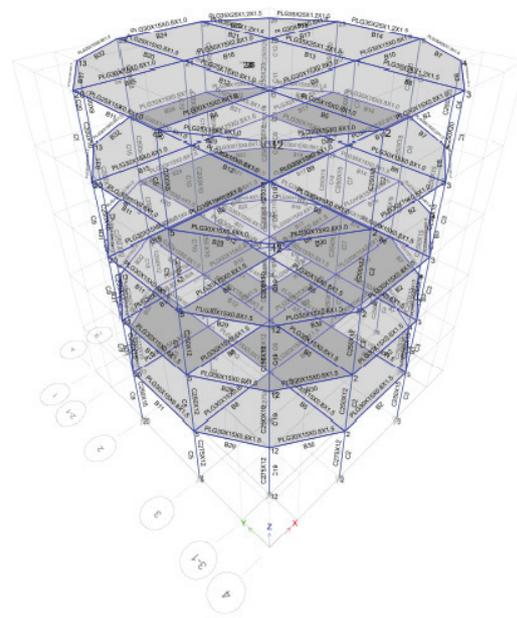**Figure 3.** Designed model of 9 floors with asymmetric plan.

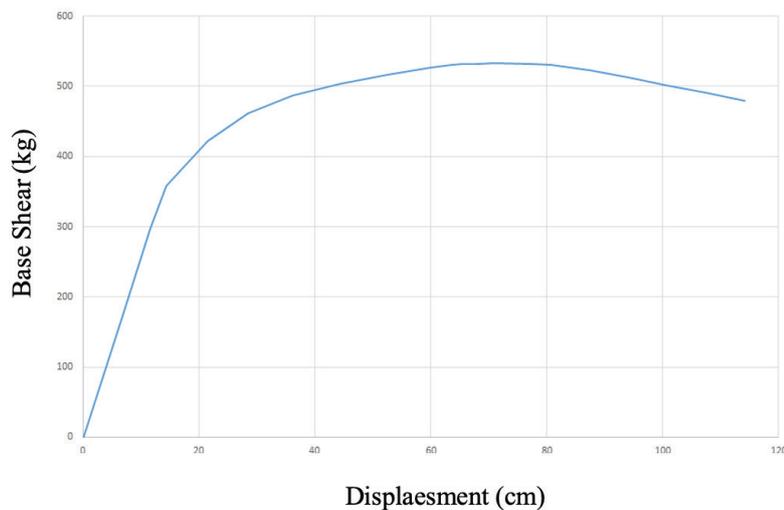**Figure 4.** 3D model of 5 floors with symmetrical plan

Figure 5. The capacity curve of the symmetrical 5-story structure with accidental torsion in the X direction irregularity.
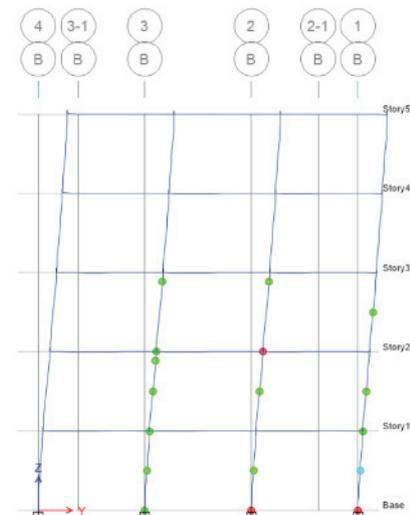
Figure 6. Distribution of plastic hinge in 5-story model with a symmetrical plan with high torsional irregularity.

structural engineering, was used for the non-linear specification of structural members.[18] The models' non-linear static analysis (incremental load) has been done with ETABS 2016, version 16.2.1 software.[16] After performing the non-linear static analysis, the performance level of the models can be observed according to the outputs. The performance level can be checked and observed according to the color of the joints formed at the place of the plastic joints. Also, the bearing curves can be used as an interpretable output to calculate the plasticity of the models and compare the results. For example, Figure 5 shows the capacity curve of a 5-story symmetrical structure with a deviation from the center to create an accidental torsion. Also, according to Figure 6, the distribution of plastic joints in the model with a symmetrical plan of 5 floors is shown with a departure from the centrality, which creates a severe torsion irregularity in the target location change in one of the frames. The formation of a plastic joint at the foot of the column in red indicates that the level of safety performance has been exceeded. Also, the formation of the green plastic joint on axis 3 indicates non-stop performance.

RESULTS AND DISCUSSION

Based on the analyses performed using the results of non-linear static analysis of the models, the role of symmetry and asymmetry in the plan with different percentages of departure from the centrality in three modes of accidental torsion, high and severe torsion irregularity on the structural capacity curve, ductility And the performance levels of the models in target displacement have been analyzed.

Based on the results of the analyses, the changes in the effective period of vibration of oscillation due to asymmetry

in the Y direction are shown in Figure 7. The symbol 5-S-SY denotes the symmetric 5-story building, and the 5-story asymmetric building in the Y direction is denoted by 5-S-ASY. The symbol 9-S-SY denotes the symmetric 9-story building, and the 9-story asymmetric building in the Y direction is denoted by 9-S-ASY.

According to the analysis results shown in Figure 7, it is observed that the presence of asymmetry in one direction, along with accidental torsion, significantly increases the effective period of vibration of oscillation in all models.

As shown in Figure 7, in the 5-story model with a symmetric plan in the Y direction with accidental torsion, the effective period of vibration of oscillation was 0.72 seconds. The simultaneous effect of introducing asymmetry and accidental torsion increased the effective period of vibration to 0.75 seconds. In the 9-story models with a symmetric plan in the Y direction with accidental torsion, the effective period of vibration of oscillation was 1.03 seconds. The simultaneous effect of introducing asymmetry and accidental torsion increased the fundamental period to 1.07 seconds. In the 5-story model with a symmetric plan in the Y direction with significant torsion, the fundamental period of oscillation was 0.98 seconds. The simultaneous effect of introducing asymmetry and significant torsion increased the effective period of vibration to 1.13 seconds. In the 9-story model with a symmetric plan in the Y direction with significant torsion, the effective period of vibration of oscillation was 1.6 seconds. The simultaneous effect of introducing asymmetry and significant torsion increased the fundamental period to 1.9 seconds. In the case of severe torsion in the symmetric 5-story model, the effective period of vibration of oscillation was 0.88 seconds, and the introduction of asymmetry in that direction increased
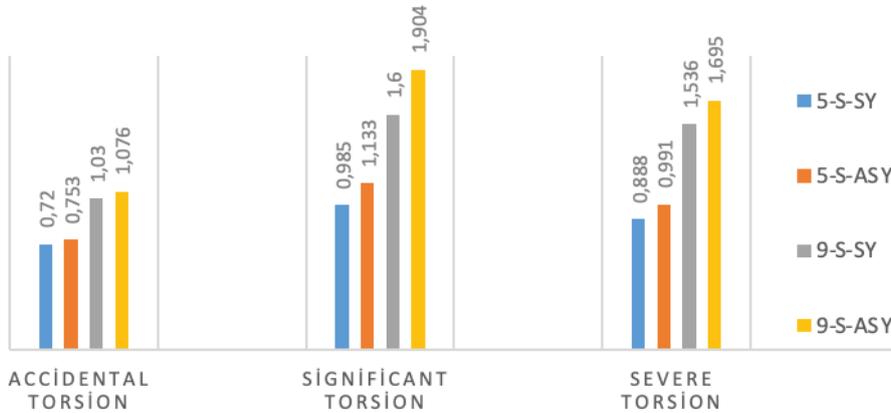
T(SEC)) EFFECTIVE PERIOD OF VIBRATION

Figure 7. Changes in the effective period of vibration of oscillation due to asymmetry in the Y direction.

the period to 0.99 seconds. In the 9-story model with a symmetric plan in the Y direction with severe torsion, the fundamental period of oscillation was 1.53 seconds. The simultaneous effect of introducing asymmetry and significant torsion increased the effective period of vibration to 1.69 seconds. As illustrated in Figure 7, the slightest change in the effective period of vibration of oscillation due to asymmetry in the plan was observed in the 5-story model with accidental torsion. In contrast, the most significant change in the effective period of vibration was observed in the 9-story model with significant torsion.

As depicted in Figure 8, the changes in base shear due to the introduction of asymmetry in the plan in one direction are shown in three conditions: accidental, significant, and

severe torsion across the models. The abbreviations for the models are used similarly to Figure 7 in Figure 8. In all models, it was observed that introducing asymmetry in the plan led to a reduction in base shear. The most negligible impact of asymmetry on base shear was in the 9-story model with accidental torsion, where the base shear for the symmetric model was 697,611 kg, which decreased to 690,829 kg due to the introduction of asymmetry—a reduction of 6,782 kg. The most significant impact of asymmetry on base shear changes was observed in the 5-story model under severe torsion. In the symmetric 5-story model, the base shear was 339,872 kg, and the introduction of asymmetry reduced the base shear to 294,767 kg—a decrease of 45,105 kg (equivalent to 45.1 tons).
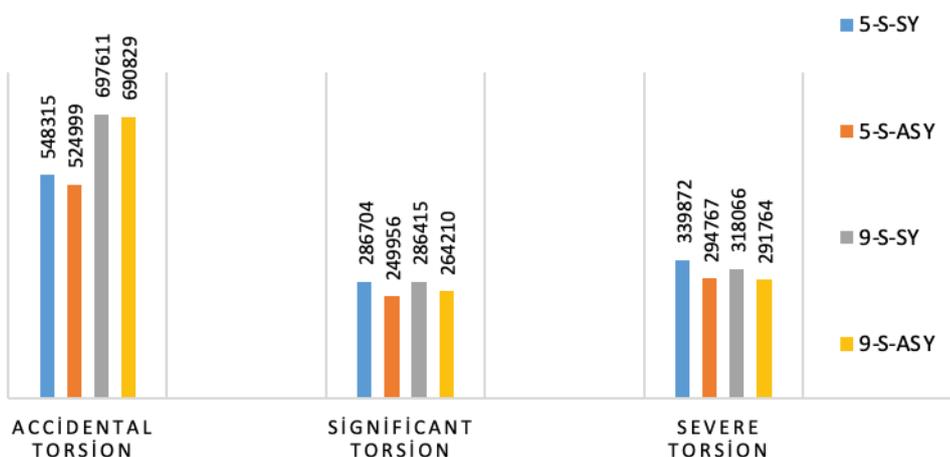
BASE SHEAR(KG)

Figure 8. Changes in base shear due to asymmetry in the Y direction.

One of the most significant effects of asymmetry in one direction of the plan is the change in the ductility factor or simply ductility. A reduction in ductility indicates a decline in the building's performance level. Ductility is one of the most critical properties of structures in the nonlinear region. As shown in Figure 9, in the 5-story models, introducing asymmetry in the plan under all three conditions (accidental torsion, significant torsion, and severe torsion) reduced ductility. In the 5-story model with a symmetric plan and accidental torsion, the ductility factor was 5.21. Introducing asymmetry in the plan with accidental torsion reduced the ductility factor to 4.57, indicating a 1.13-fold decrease in ductility compared to the symmetric plan. This reduction ratio was 1.17 under significant torsion and 1.43 under severe torsion. In the 9-story model with a symmetric plan and accidental torsion, the ductility factor was 3.34. Introducing asymmetry in the plan with accidental torsion increased the ductility factor to 4.5, showing a 1.34-fold increase compared to the symmetric plan. However, under significant torsion, the ductility remained almost unchanged (about 2%), and under severe torsion, instead of increasing, it decreased by a factor of 1.38.

The summary of the results of the models related to 5-story structures with a symmetrical plan that are covered in the positive Y direction according to Table 3, and also,

in this case, the results of the models related to the 5-story structures with an asymmetric plan that are covered in the positive Y direction and is summarized in Table 4.

By comparing Tables 3 and 4, It is possible to analyze the role of symmetry and asymmetry in the 5-story model in the positive Y direction of data overlay. The presence of asymmetry has caused an increase in the adequate rotation time; the highest percentage of increase was related to the mode of creating many twists with 15%. Also, asymmetry has caused a reduction in base cutting, such as changing the target location. The highest percentage of reduction related to severe torsion was about 16%. The increase in the target location change in high and severe torsion mode is significant, with an increase of 21 and 30%, respectively, due to asymmetry. There was no effect in the accidental torsion mode. A significant result is the reduction of ductility in all three modes: 25% in the accidental torsion mode, 31% for significant torsion, and 43% for severe torsion in models with an asymmetric plan.

According to Table 5, the results of models related to 9-story structures with symmetrical plans in all three cases, percentages of eccentricity that cause accidental, significant, and severe torsion and are covered in the negative direction of the Y axis, are written. In Table 6 of the results, the models related to the 9-story structures with asymmetric
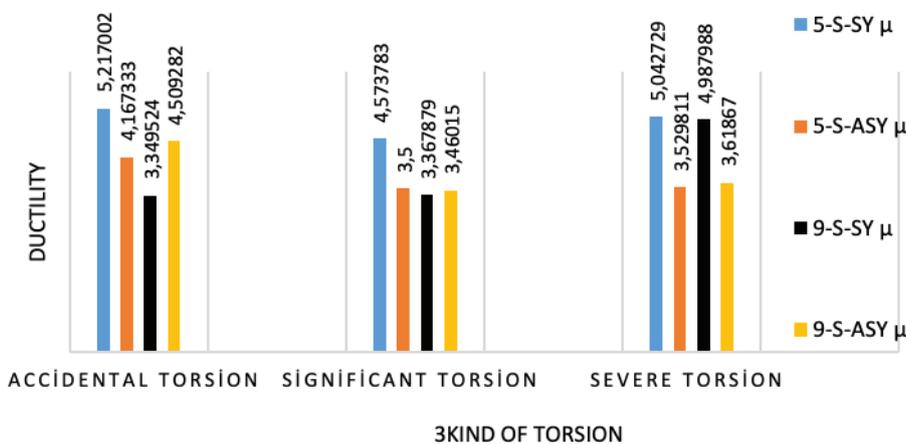

Figure 9. Changes in ductility due to asymmetry in the Y direction.

Table 3. Outputs of the 5-story model with a symmetrical plan with PUSH-YP

Torsion due to off-center modes	μ ductility	Δy Change of location of elastic limit	Δu Final relocation	V(kg) Base Shear	Δt(cm) Change target location	T(Sec) Effective period of vibration
accidental torsion (5)	5.217002	22.35	116.6	548315	10	0.72
significant torsion (1.2)	4.573783	13.35	61.06	286704	14	0.985
severe torsion (1.4)	5.042729	13.34	67.27	339872	13	0.888

Table 4. Outputs of the 5-story model with an asymmetric plan with PUSH-YP

Torsion due to off-center modes	μ ductility	Δy Change of location of elastic limit	Δu Final relocation	V(kg) Base Shear	Δt(cm) Change target location	T(Sec)) Effective period of vibration
accidental torsion (5)	4.167333	15	62.51	524999	10	0.753
significant torsion (1.2)	3.5	13.36	46.76	249956	17	1.133
severe torsion (1.4)	3.529811	13.25	46.77	294767	17	0.991

Table 5. Outputs of the 9-story symmetrical structure model with PUSH-YN

Torsion due to off-center modes	μ ductility	Δy Change of location of elastic limit	Δu Final relocation	V(kg) Base Shear	Δt(cm) Change target location	T(Sec)) Effective period of vibration
accidental torsion (5)	3.349524	19.97	66.89	697611	16	1.03
significant torsion (1.2)	3.367879	24.0098	80.8621	286415	27	1.6
severe torsion (1.4)	4.987988	19.98	99.66	318066	26	1.536

plans covered in the negative direction of the Y axis were collected for all three eccentricity cases.

By comparing Tables 5 and 6, It is possible to analyze the role of symmetry and asymmetry in the 9-story model, which is covered in the negative direction of Y. The existence of asymmetry has caused an increase in the Effective period of vibration; the highest percentage of increase was related to the mode of creating many twists, with 18%. Also, asymmetry has caused a reduction in base cutting, such as changing the target location. The highest percentage of reduction related to severe torsion was about 9%. The increase in the target location change in high and severe torsion mode is significant, with an increase of 22% and 12%, respectively, and with a lesser effect in the accidental torsional mode. The significant result is the reduction of ductility in both modes, 34% in the accidental torsion mode and 34% for severe torsion. 36% increase is less than 3% for significant torsion models with asymmetric plans.

Figure 10 shows capacity curves of 9-story models in four off-center states with symmetric and asymmetric plans, which significantly differ in performance, plasticity, and other parameters.

According to Figure 7, the capacity curves of the 9-story asymmetrical plan model with high torsional irregularity showed lower performance, ductility, and base shear compared to the 9-story symmetrical plan model with Accidental torsion. The impact of asymmetry in the plan is evident as an influential factor. The capacity curves of the 5-story models for all four eccentricity scenarios with symmetrical and asymmetrical plans, which showed significant differences in performance, ductility, etc., are illustrated in Figure 8, highlighting the contrast and its implications.

According to Figure 11, the capacity curves of the 5-story asymmetrical plan model with high torsional irregularity showed lower performance, ductility, and base shear than those of the 5-story symmetrical plan model with Accidental torsion. The impact of asymmetry in the plan as an influential factor in the non-linear behavior of the models is evident.

Table 6. Outputs of the 9-story asymmetric structure model with PUSH-YN

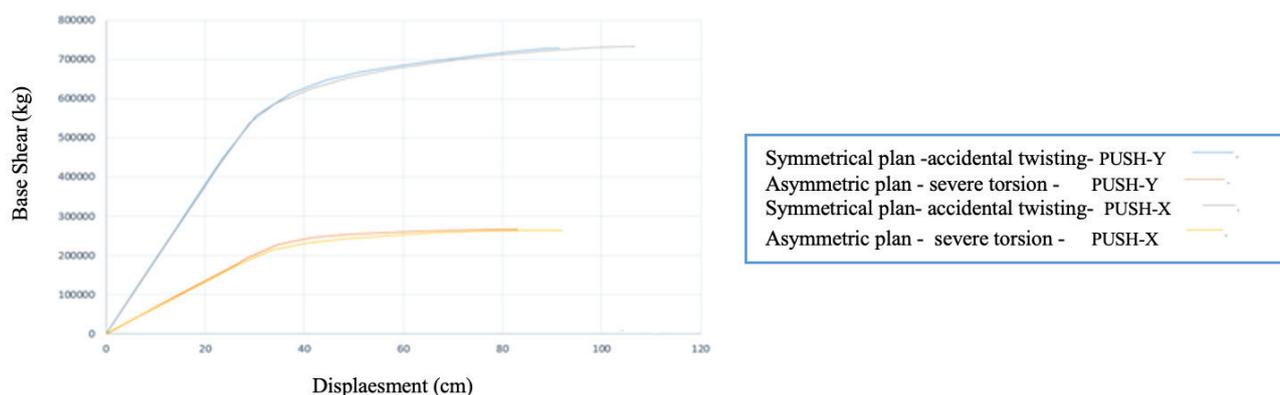| Torsion due to off-center modes	μ ductility	Δy Change of location of elastic limit	Δu Final relocation	V(kg) Base Shear	Δt(cm) Change target location	T(Sec)) Effective period of vibration
accidental torsion (5)	4.509282	19.93	89.87	690829	17	1.076
significant torsion (1.2)	3.46015	26.6	92.04	264210	33	1.904
severe torsion (1.4)	3.61867	19.9659	72.25	291764	29	1.695

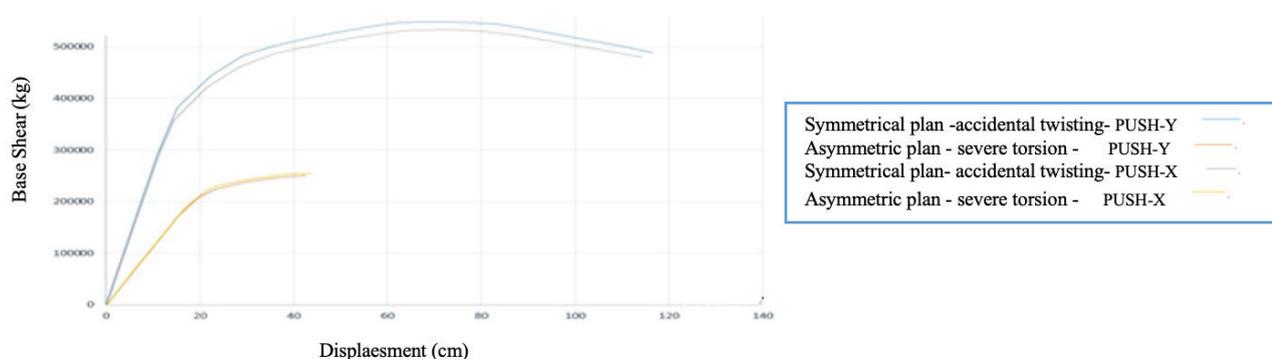**Figure 10.** Selected capacity curves in 9 floor models.

Figure 11. Selective capacity curves in 5-floor models.

CONCLUSION

This study, which is one of the first of its kind, investigated the combined effect of geometric asymmetry in one direction with the effect of eccentricity in three states—accidental torsion, significant torsion, and severe torsion—as influencing factors on performance levels and vital parameters such as ductility, effective period, and distribution of plastic hinges in existing medium steel moment frame buildings. The ductility was analyzed through a rigorous non-linear static analysis for 5-story and 9-story models with symmetrical and asymmetrical plans under three eccentricity scenarios (Accidental torsion, significant torsion irregularity, and severe torsional irregularity). The results showed that symmetry and asymmetry in the plan significantly affect the performance levels, ductility, and seismic response due to torsion, which is more pronounced in 5-story buildings. A notable 43% reduction in ductility was observed due to asymmetry in the severe torsional irregularity scenario compared to the symmetrical scenario. Additionally, the reduction in damage control range in the performance of these models is significant.

Urgent further studies on models with asymmetry in two directions are strongly recommended. Moreover, other steel and concrete buildings with different ductility levels and heights should be examined. Based on the research findings, an influential parameter called the asymmetry coefficient should be incorporated into the seismic design and retrofitting guidelines to reduce structural performance and non-linear analysis results. This study serves as the initial research in this area, and future studies on systems with two-directional asymmetry will be presented in upcoming publications.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. ETHICS There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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