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Effect of Torsional Irregularity on Seismic Performance of Steel Moment Resisting Frame Structures

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ABSTRACT

This paper examines the seismic damage of three-dimensional steel moment-resisting frame (SMRF) structures affected by torsional irregularities. Six steel 3-D SMRF structures with varying degrees of irregularity were evaluated using incremental dynamic analysis (IDA) to determine their dynamic capacity. The aim of the study was to develop a quantifiable damage index based on the results of IDA. The yield point and the point of loss of lateral bearing (collapse threshold) on the IDA curve of each record were used to calculate the proposed damage index, which ranges from 0 to 1 and can be calculated individually in two horizontal directions. The study evaluated the feasibility of a meaningful match between the momentary torsion and the predicted damage by charting the ratio between these two quantities against the damage index findings. The analysis of the average damage at different levels of mild, medium, and high damage, as well as the comparison of the average damage index between the design accelerations corresponding to the return periods of 475 and 2475 years, revealed a general trend towards higher damage in structures with greater irregularity.

Keywords:

Incremental dynamic analysis (IDA), Torsional irregularity, Steel moment resisting frame (SMRF), Damage index, Seismostruct software.

1. Introduction

One of the key issues in studying the behavior of buildings during earthquakes is to pay close attention to the various types of structural irregularities in terms of their plan and height. Previous research in this field has shown that buildings with irregular structures tend to perform poorly during earthquakes compared to those without irregularities [1–3]. Structures can exhibit various forms of irregularities, but among them, torsional irregularity is the most critical as it causes stress concentration due to sudden changes in stiffness and twisting of the structure [2, 4, 5]. In recent years, many researchers have investigated this issue from various perspectives and have provided valuable insights. For example, Bharat et al. studied the effects of structural irregularities by analyzing six L-shaped concrete structures under spectral dynamic analysis. They found that irregularly shaped buildings are more vulnerable to changes in the input response spectrum than symmetrical and regular ones. Their findings highlighted the inadequacy of current rules and regulations in designing structures to address such irregularities [6–9]. Fitrah et al. conducted a study on the Universitas Dharma Andalas building. The analysis of this structure was performed using the equivalent lateral forces and response spectrum method based on SNI1726. The results indicated that structures with torsional irregularity have inadequate seismic performance during earthquakes and should be subjected to lateral resistance seismic design [10, 11]. Other studies have focused on developing new techniques to mitigate the damaging effects of torsion in structures. For example, Gokdemir et al. (2013) proposed new methods in this regard. Additionally [12]. Akyürek et al. compared two methods, integrated control system (ICS) and tuned mass dampers (TMD), for controlling the response of a 9-story steel structure. Their study showed that ICS is a more suitable method for irregular structures [13]. Furthermore, the researcher investigated the performance of a reinforced concrete model with torsional irregularity under time history analysis and proposed some effective approaches to address this issue [14]. Another study focused on analyzing the seismic responses of structures with irregular shapes. The researchers utilized the correlation coefficient and the amount of roof displacement to develop a fragility curve, which visually illustrates the probability of different levels of damage [15]. Recent advancements in the study of torsional irregularity and its impacts have been made by Ghayoumia et al. They investigated a double-reinforced concrete structure with torsional irregularity using push-over analysis and developed a new strategy to address this issue [16]. In contrast, other researchers have explored the effects of torsional irregularity on non-structural components of reinforced concrete moment-resisting frames (MSRFs) with torsional irregularity on two sides. They concluded that torsional irregularity can cause irreparable damage to non-structural components [17]. urthermore, several studies have investigated the impact of torsional irregularity on steel structures. For example, Angelos et al. evaluated 30 steel moment frame structures to investigate plan irregularity. They also examined height irregularity and mass irregularity using 40 MSRFs and 18 other MSRFs, respectively. All structures were designed in accordance with Eurocode 8, and nonlinear analysis based on 42 pairs of earthquake records was conducted. Using the responses of the structures, the researchers developed a data bank with four levels of performance. This data bank was then used to establish relationships such as behavior coefficient and stiffness reduction [18]. Due to the need for precise nonlinear analysis, several studies have utilized Incremental Dynamic Analysis (IDA) for torsional irregularity, despite the fact that it is time-consuming and expensive. [19]. Wang et al. employed IDA analysis in their study to investigate the impact of finite element modeling on the brittleness of the cool air-holding structure and energy dissipation structures. [20]. Arshadi et al. utilized the endurance-time (ET) method in their studies to evaluate the performance of structures during an earthquake and assess their design. Another study utilized IDA analysis to investigate the behavior of high-rise structures with braced cores subjected to near and far field earthquakes, aiming to establish a damage criterion that can more accurately define the moment of collapse of the structure [21]. In the field of seismic engineering, the study of structural irregularities and their impact on building performance during earthquakes has attracted significant attention from researchers. Structural irregularities take various forms, with torsional irregularity being one of the most significant ones due to its potential for stress concentration resulting from abrupt changes in the stiffness and twisting of structures. In past studies investigating this area, it has been shown that irregularly shaped buildings exhibit weaker performance during an earthquake when compared to symmetrical and regular structures. This inadequacy of current rules and regulations for the design of structures with respect to such abnormalities was demonstrated by the findings of Bharat et al., who evaluated the impact of irregularity in the structural design using six L-shaped concrete structures subjected to spectral dynamic analysis. Moreover, researchers have examined the development of novel methods to mitigate the destructive effects of torsion in structures. For instance, Akyürek et al. utilized the modeling of a 9-story steel structure to compare two methods of integrated control system (ICS) and tuned mass dampers (TMD) and ultimately concluded that ICS is the most appropriate method for use in irregular structures. The impact of torsional irregularity on non-structural components of reinforced concrete MSRFs has also been studied. It was found that torsional irregularity can result in irreparable damage to non-structural components. Additionally, researchers have studied how torsional irregularity affects steel structures. Angelos et al. investigated the plan, height, and mass irregularity of 30 steel moment frame structures and created a data bank with four levels of performance based on nonlinear analysis of the structures. However, due to the precise nonlinear analyses required, the use of Incremental Dynamic Analysis (IDA) has become the most effective method among the analytical techniques used to calculate structural damages. The IDA technique has been widely employed in studies on earthquakes and structural engineering since its creation in 1998 [22–24]. This study employs the most precise nonlinear dynamic analysis method, incremental dynamic analysis (IDA), for structural analysis. Furthermore, a novel quantitative damage index (DM) is developed to assess the extent of damage in the modeled structures caused by seismic loading. The DM is a positive numerical value that reflects the response characteristics of the structural model under seismic loads. This article also investigates the possibility of establishing a meaningful correlation between these two quantities and quantifying the relationship between momentary torsion and expected damage by plotting the maximum horizontal displacement ratio in two different directions as a torsion index against the results of the damage index.

2. Methodology

This section presents the methodology used in this study for structural modeling, analysis methods, and damage indexes. In this section, the selected earthquake ground motion records, scaling of the chosen records, and the incremental dynamic analysis method are discussed in detail. To determine the earthquake-induced damage to the structures, the most recent and precise dynamic analysis technique, incremental dynamic analysis (IDA), is employed. This approach allows for the evaluation of the performance of structures subjected to various earthquake records. By comparing the records, analyzing the IDA curves, and drawing damage distribution curves inside the structure, the damage to the structure can be estimated. The outcomes of specific damage index calculations are required to generate the damage distribution curves. To investigate the structures, a three-dimensional approach is used in this study. This approach is particularly useful for studying significant and essential structures with torsional irregularity since earthquake components can be applied in both the X and Y axes. Three-dimensional analysis is essential in this research, as one of the main objectives is to investigate torsion irregularity. In the next phase of the study, seven pairs of accelerograms will be selected from the ATC-63 reference bank, and the scale of the chosen recordings will be determined. IDA analysis will then be performed using the selected earthquake ground motion records to evaluate the performance of the structures. The damage index used in this study is a quantitative measure of the extent of damage to the structures, expressed as a positive numerical value reflecting the excess reaction of the modeled structures under seismic loading. Overall, the methodology used in this study aims to accurately assess the seismic performance and damage of structures, particularly those with torsional irregularity, using the IDA approach and a new damage index.

2.1. Selected earthquake records

The selection of earthquake records is a critical aspect of seismic analysis, as the accuracy and reliability of the results depend on the quality of the input data. In this study, earthquake records from remote regions with a length of more than 7 seconds were selected from the ATC-63 reference bank. The records were chosen to represent a broad range of ground motion characteristics and intensities, which are important factors in assessing the seismic performance of structures. Table 1 provides the features of the selected earthquake records, including the record name, year of occurrence, magnitude, distance, duration, and peak ground acceleration (PGA). The chosen records have a range of magnitudes from 6.2 to 7.7 and distances from 22 to 162 km, providing a diverse set of ground motions for analysis. Additionally, the duration of the records ranges from 10 to 45 seconds, reflecting the variability of earthquake duration in real-world scenarios. The PGA of the records ranges from 0.32 to 1.17 g, which covers a broad range of ground motion intensities that can be experienced in earthquake-prone regions. The selection of these earthquake records enables a comprehensive evaluation of the seismic performance of the analyzed structures under various seismic events, which is crucial in ensuring the safety and reliability of structures in earthquake-prone areas.

Table 1. Characteristics of selected earthquake records [25]

NO	Earthquake Name	Year	Magnitude	Station	PGA(x)	PGA(y)	Duration
1	San Fernando	1971	6.6	LA-Hollywood storFF	0.21g	0.174g	10.49
2	Kokaeli-Turkey	1999	7.5	Duzce	0.728g	0.822g	8.51
3	Imperial-Valley	1979	6.5	EL Centro Array	0.364g	0.380g	8.705
4	Superstition-Hills	1987	6.5	EL Centro. Imp.Co.Cent	0.358g	0.258g	16.05
5	Kobe-Japan	1995	6.9	Nishi.Akashi	0.509g	0.503g	9.72
6	Loma Petria	1989	6.9	Capitola	0.529g	0.443g	11.915
7	Northridge	1994	6.7	Beverly Hills	0.416g	0.516g	9.21

2.2. Response spectrum

The response spectrum of each accelerogram in the both X and Y directions, as well as the average response spectrum for the whole accelerograms, are shown in Figures 1 and 2.

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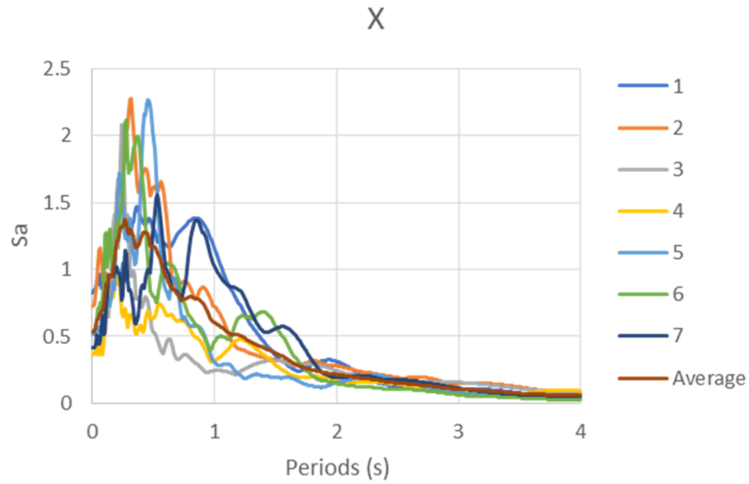


Figure 1. Response spectrum of 7 accelerogram along with the average spectrum in the X direction.

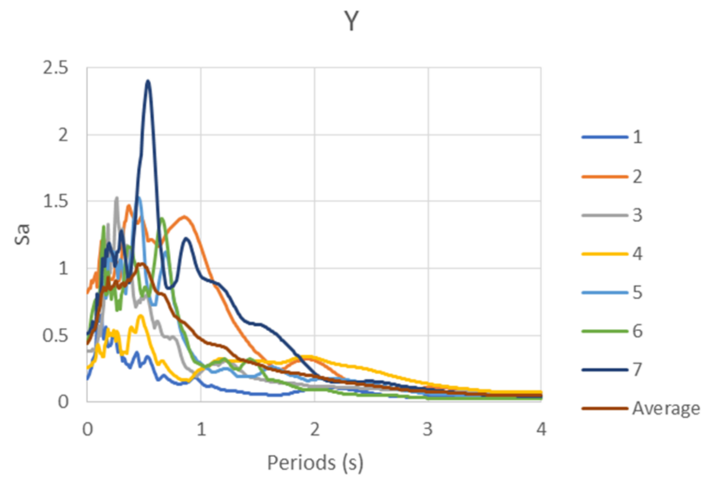


Figure 2. Response spectrum of 7 accelerogram along with the average spectrum in Y direction

2.3. Damage index based on IDA analysis

The accurate assessment of structural damage caused by earthquakes is crucial in designing and retrofitting buildings for seismic safety. To this end, the damage index (DI) developed by Mohebi et al. [26] is applied in this study, owing to its reliance on the results of incremental dynamic analysis (IDA) and its specific applicability to steel moment-resisting frame (SMRF) structures. The maximum inter-story drift ratio (MIDR) is used to compute the required parameters for the damage index [26]. The Mohebi damage index is expressed mathematically through Equations 1-3, which establish the relationship between the damage index and the structural response parameters obtained from IDA analysis. This approach provides a quantitative measure of the extent of structural damage incurred during earthquakes, allowing for a more precise assessment of seismic vulnerability and design optimization. As such, the utilization of this damage index in the current study enables a more comprehensive understanding of the seismic performance of the analyzed structures. Equations 1-3 provide the relationship of the utilized damage index.

$$DI_1 = \frac{d - d_y}{d_u - d_y} \tag{1}$$

$$DI_2 = \frac{PGA - PGA_y}{PGA_u - PGA_y} \tag{2}$$

$$DI = \sqrt{DI_1 \times DI_2}$$

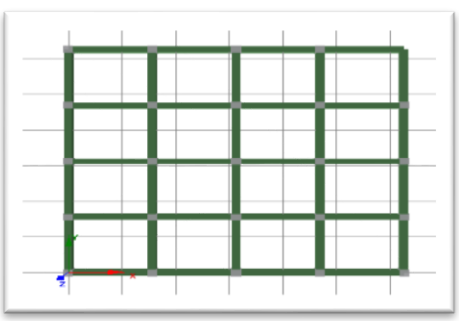
If DI_1 and $DI_2 \leq 0$ Then: DI=0 (3)

If DI_1 and $DI_2 \geq 0$ Then: DI=1

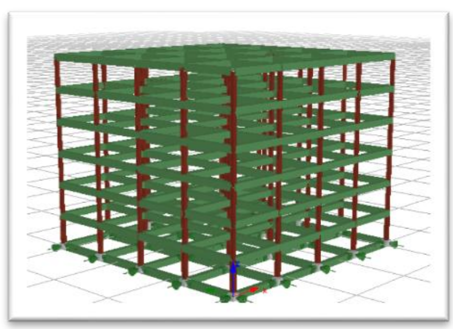
In the presented equations, the variables PGA and d represent the peak ground acceleration and MIDR, respectively, for each accelerogram analyzed. Similarly, the variables and signifies the acceleration and MIDR at the yield point of the structure, while and denote the acceleration and MIDR at the collapse point of the structure. These variables play a crucial role in assessing the seismic performance of structures, as they help determine the level of damage sustained by a structure during an earthquake event. By analyzing the relationship between these variables, researchers can better understand the behavior of structures under seismic loading and design more effective earthquake-resistant structures [26].

2.4. Numerical modeling

In this study, Tzimas et al. examine six steel structures, comprising five structures with a steel moment resisting frame (SMRF) system exhibiting torsional irregularity, and one structure that is regular. Each of the structures is composed of six stories, with a height of 3 meters per story, and four bays that are five meters long in both the X and Y directions. Figure 3 displays the 3D view and floor plan of the structures [11]. The structures analyzed in this study exhibit a range of irregularities. For example, the first structure is a completely regular steel moment frame, standing at a height of six stories (equivalent to 18 meters), whereas the sixth building displays significant torsional irregularity, despite having the same height as the first structure.



(A)



(a)

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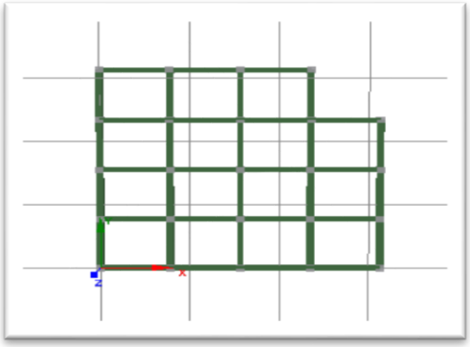
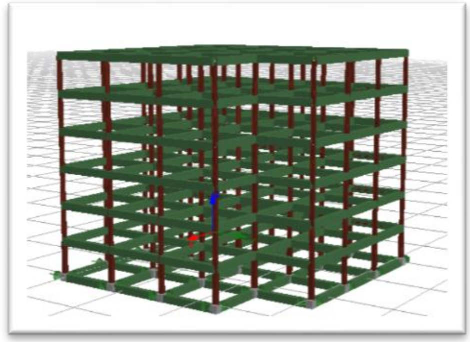


(B)



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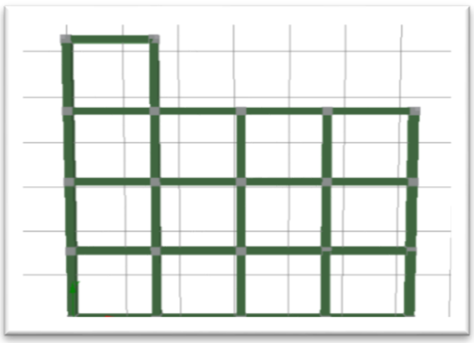
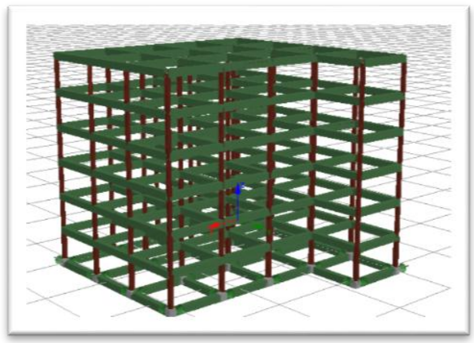
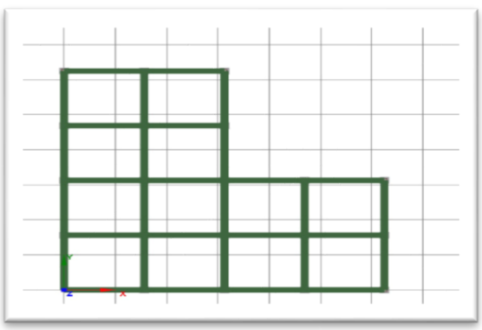


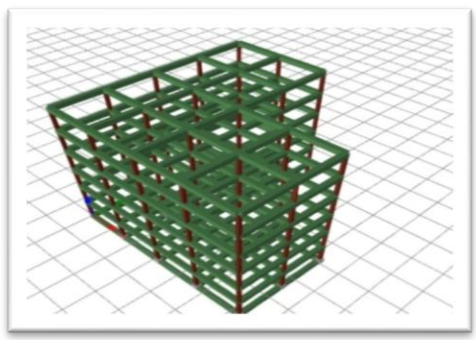
(C)



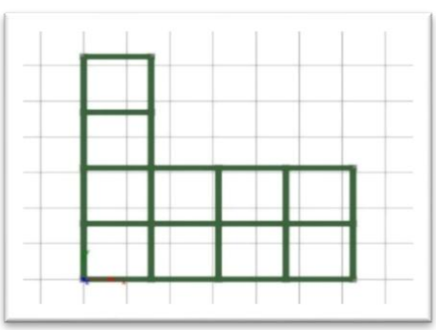
(c)



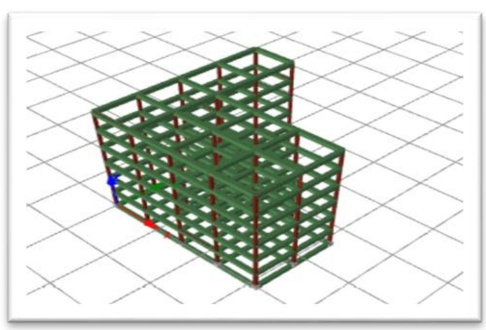
(D)



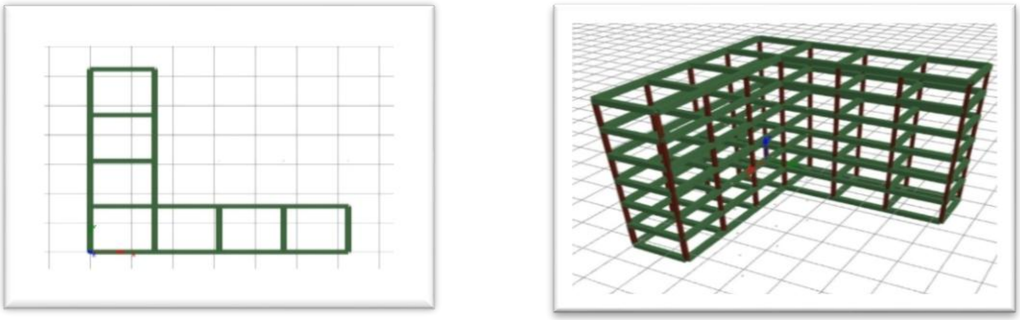
(d)



(E)



(e)



(F) (f)

Figure 3. Plan and three-dimensional perspective of the examined structures.

2.5. Design conditions

In this paper, all structures have been designed in accordance with Eurocode 8 requirements. The structural loading is set to 22 $\mathrm{KN/m^2}$ live load and 6.5 $\mathrm{KN/m^2}$ dead load in all structures and the load combinations are defined as follows:

$$1.3G+1.5Q \tag{4}$$
$$G+0.3Q \mp E_x \mp 0.3E_y \tag{5}$$
$$G+0.3Q \mp E_y \mp 0.3E_x \tag{6}$$

In the above combinations, G shows the dead load and Q utilized for the live load. The structures are built on type 2 soil, and their location is in an area with a very high seismic risk (A = 0.35) [4]. SHS type, GradeS335, and IPE type, GradeS235 sections are used for the columns and beams, respectively. The sections' properties are introduced in Table 2.

Table 2. Specifications of sections used in sample structures [18].

	IPE		SHS
Floor	$B_{xe}B_{ye}$ (mm)	$B_{ix}B_{iy}$ (mm)	C_iC_e (mm)
1	330	360	360×16
2	330	360	300×16
3	330	360	300×16
4	300	330	300×12
5	300	330	300×12
6	300	330	300×12

In Table 2, i represents interior members and e represents exterior members.

3. Numerical results

In this section, we present the results of the Incremental Dynamic Analysis (IDA) in the form of IDA curves. These curves demonstrate the level of damage incurred by the structure under various earthquake intensities. We then draw damage distribution curves to quantify the extent of damage experienced by the structures. We compare the average damage index for all structures, the average damage index for all structures under their highest seismic risk level, and the average damage incurred in terms of mild, moderate, severe, and very severe damage in both the X and Y directions.

In addition, we estimate the level of torsion in the diaphragm by calculating the ratio of the highest horizontal displacement in one direction to the corresponding value in the opposite direction at each analysis step. We examine the relationship between the observed torsion and the damage index by plotting the curve of these ratios against the damage index and fitting a linear model to it.

3.1. IDA curves

The generation of IDA curves is a critical step in this research. IDA analysis is a commonly used method for investigating structural behavior and calculating engineering demand parameters (EDPs). This approach considers parameters ranging from the elastic state to the yield point, non-linear domain, and ultimately dynamic instability. The IDA analysis involves conducting multiple non-linear time history analyses (NTHA) in which the intensity of the ground motion (GM) record, chosen to study damage, is gradually increased until it reaches the point of global collapse capacity of the structure [27–31]. Each IDA curve represents a model that was evaluated using seven different ground motion (GM) record pairings. In this section, we present the IDA curves for each of the tested structures.

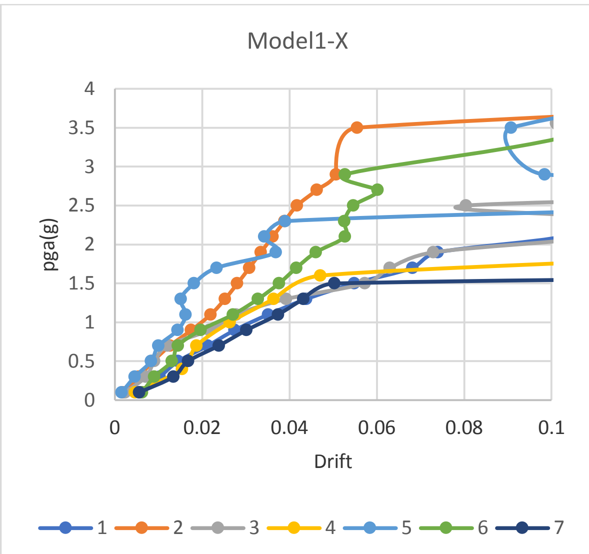


Figure 3. IDA curve in X direction of 1st structure

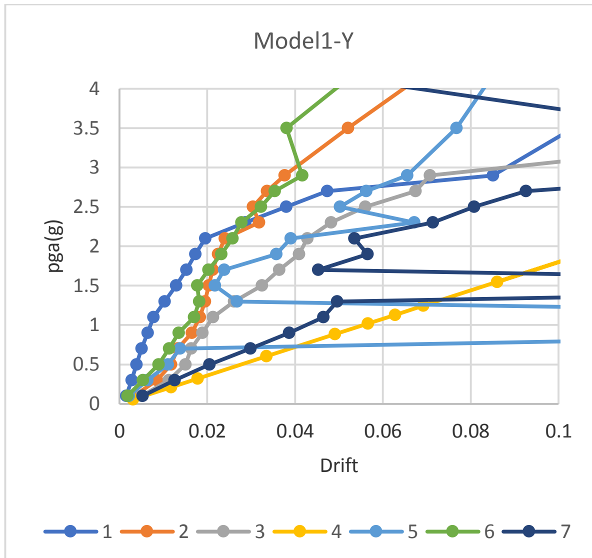


Figure 4. IDA curve in Y direction of 1st structure

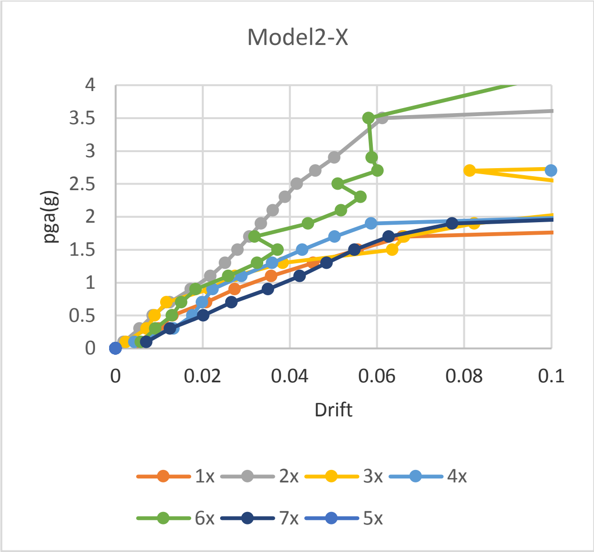


Figure 5. IDA curve in X direction of 2nd structure

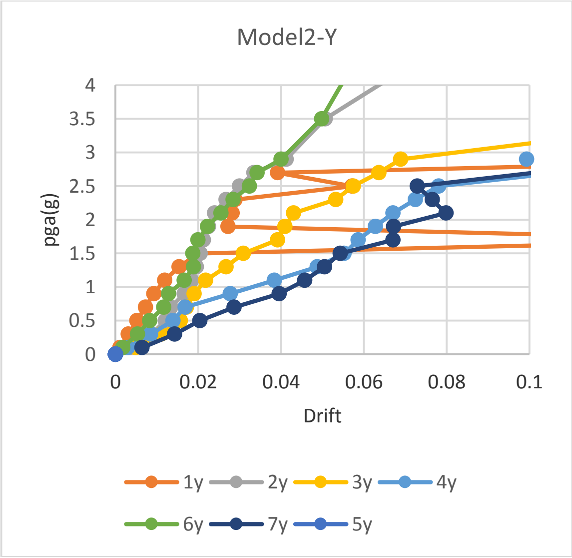


Figure 6. IDA curve in Y direction of 2nd structure

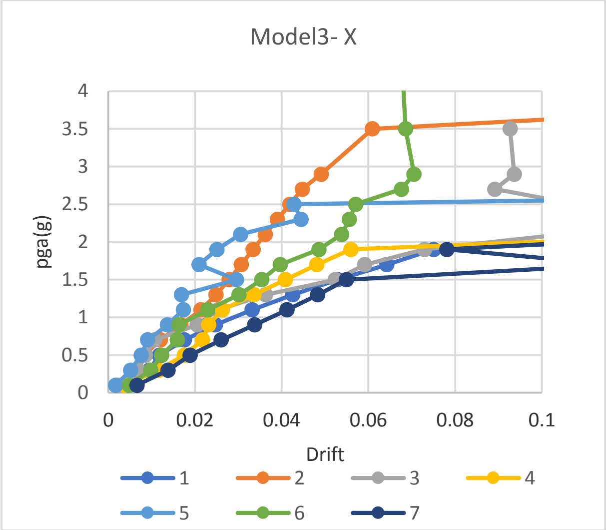


Figure 7. IDA curve in X direction of third structure

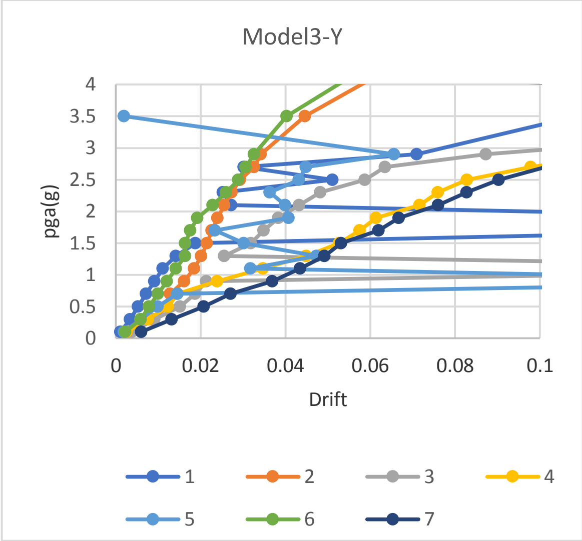


Figure 8. IDA curve in Y direction of third structure

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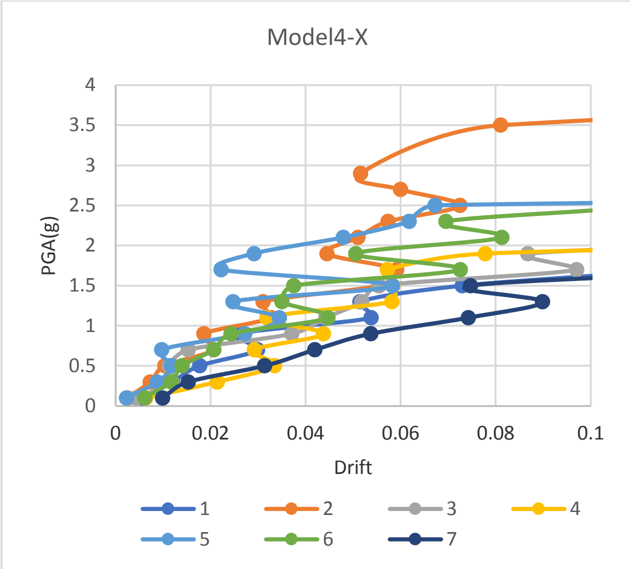

Figure 9. IDA curve in X direction of fourth structure

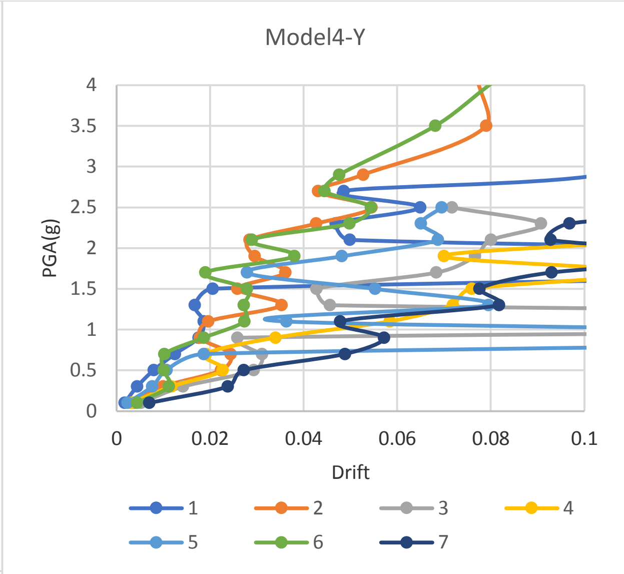

Figure 10. IDA curve in Y direction of fourth structure

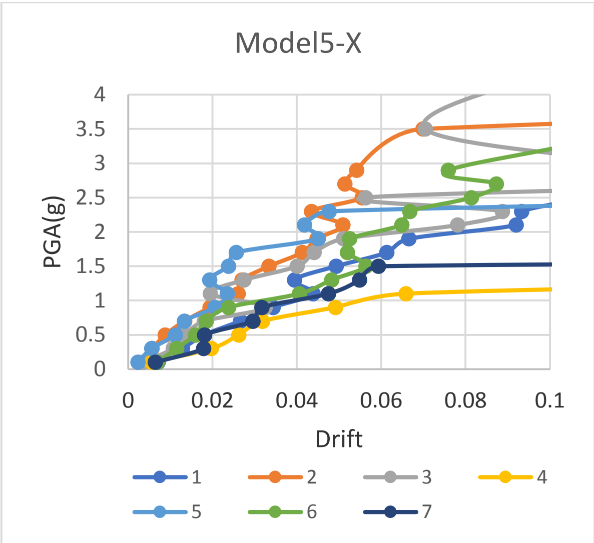

Figure 11. IDA curve in X direction of fifth structure

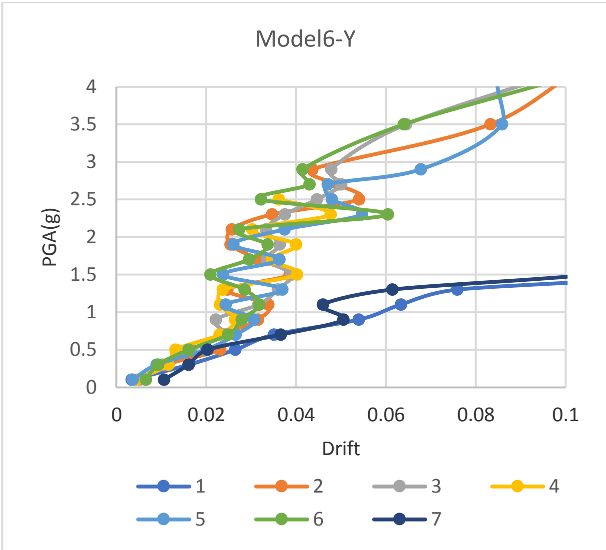

Figure 12. IDA curve in Y direction of fifth structure

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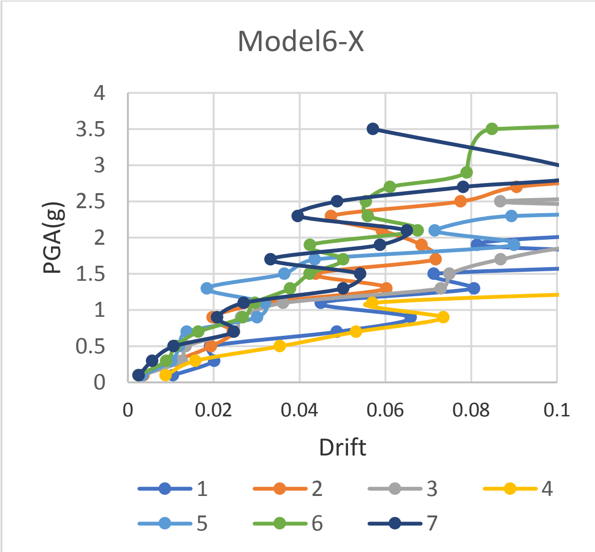

Figure 13. IDA curve in X direction of sixth structure

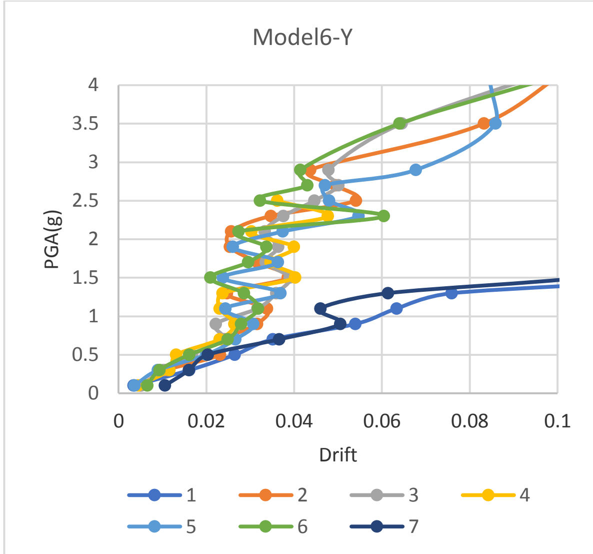

Figure 14. IDA curve in Y direction of sixth structure

The IDA curves provide insights into the different behaviors of the structures under various ground motion records. These behaviors can include sequential hardening and softening, represented by twisting patterns, and immediate dynamic instability of the structure, represented by sharp softening patterns. The hardening phenomenon is caused by an increase in the scale factor of the ground motion record, resulting in small cycles of structural response that are so intense at the beginning of the time history that they cause damage to the structure. This damage alters the structural characteristics and can lead to changes in subsequent strong cycles. Overall, the IDA curves serve as a valuable tool for understanding the structural response and behavior under various seismic intensities [26].

3.2. Damage distribution curves

The extent of damage to the structure is assessed using the damage distribution curve, which utilizes peak ground acceleration (PGA) as an intensity measure (IM). In this study, damage distribution curves for both X and Y directions were generated for each model, with the damage index (DI) represented on the vertical axis and PGA on the horizontal axis. Figures 15-26 illustrate the X and Y damage distribution curves for each model. These curves provide critical insights into the level of damage that the structures can sustain under various seismic intensities.

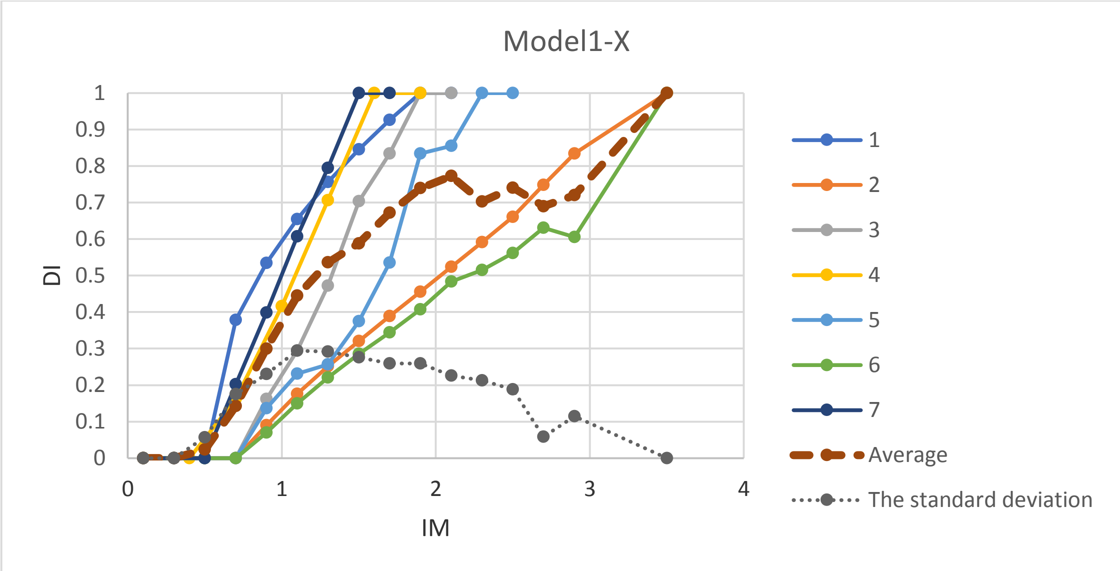

Figure 15. Damage distribution curves in the first structure in the X direction.

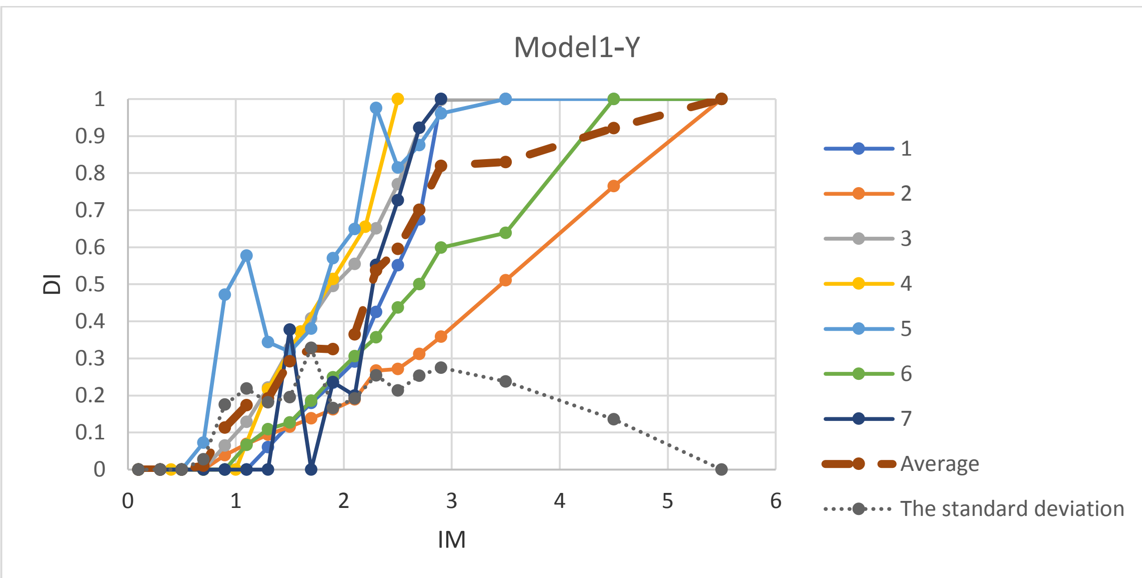

Figure 16. Damage distribution curves in the first structure in the Y direction.

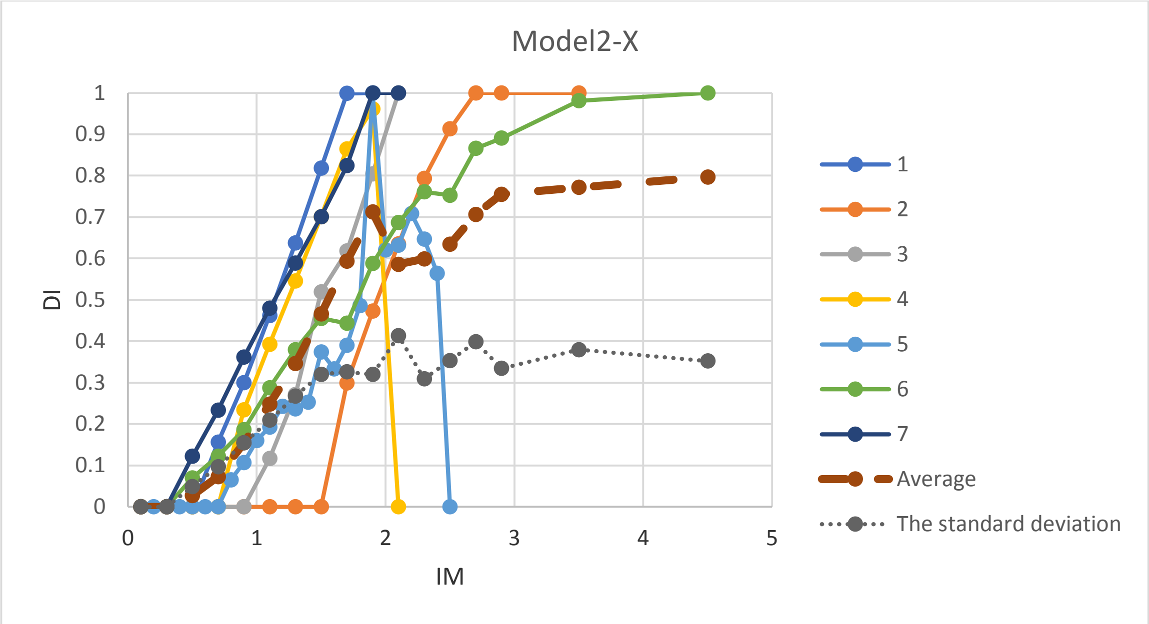

Figure 17. Damage distribution curves in the second structure in the X direction.

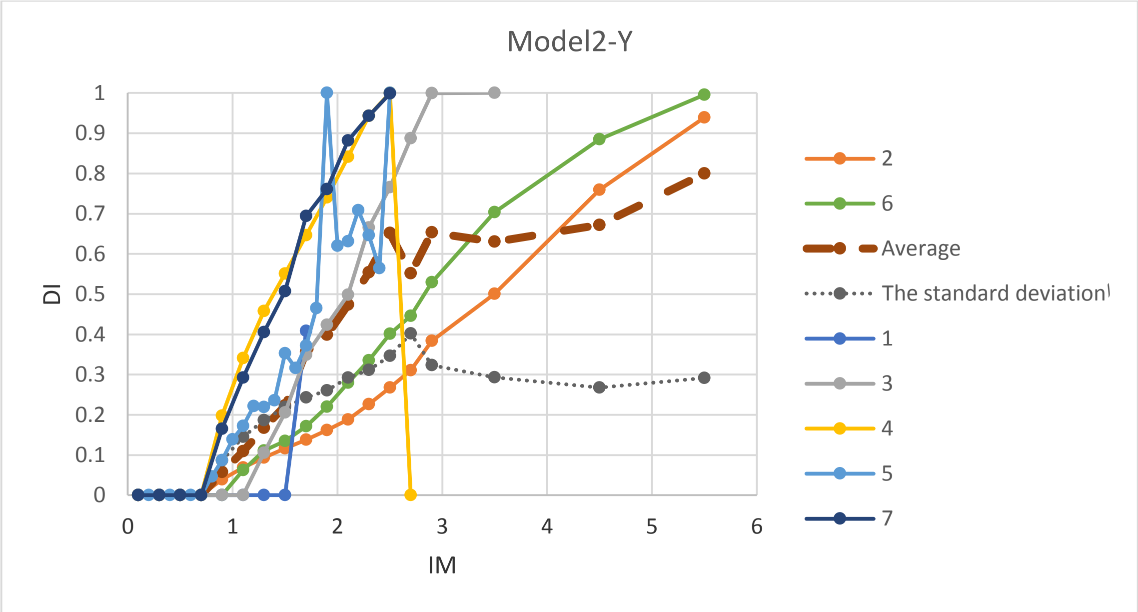

Figure 18. Damage distribution curves in the second structure in the Y direction.

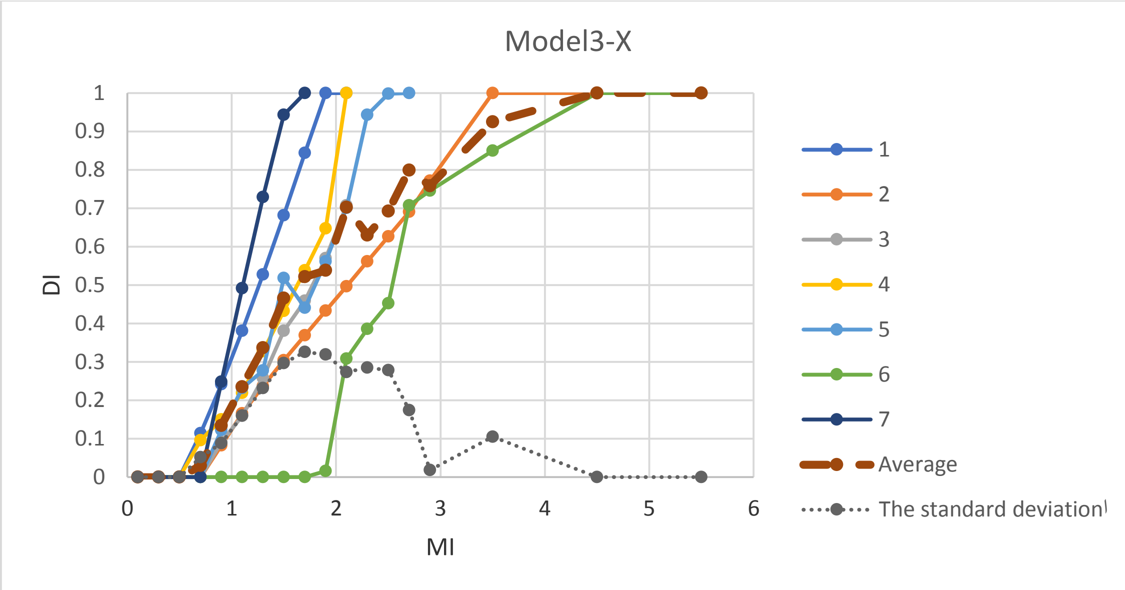

Figure 19. Damage distribution curves in the third structure in the X direction.

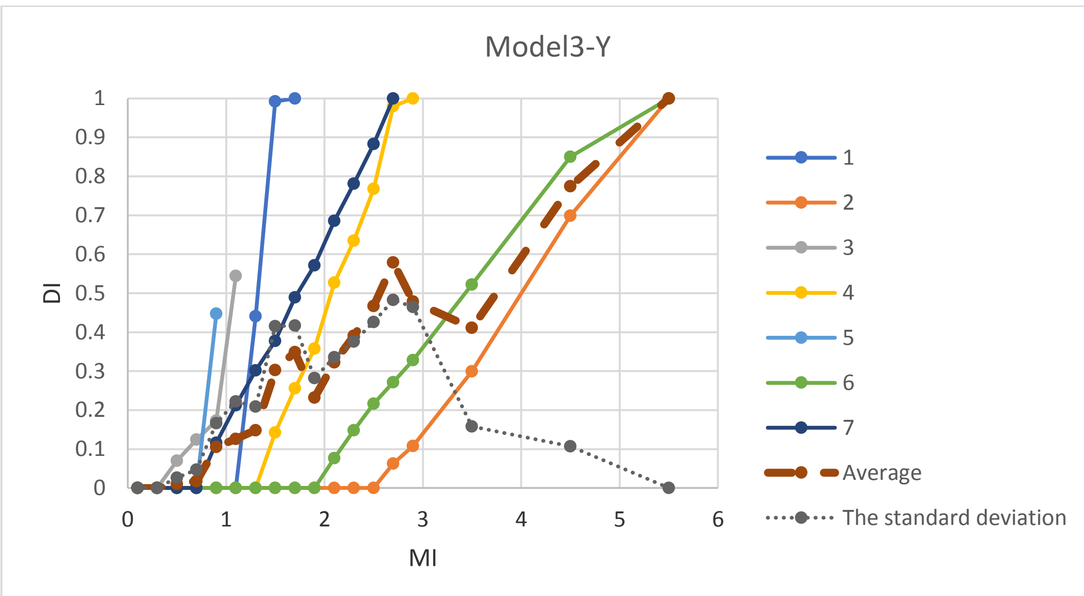

Figure 20. Damage distribution curves in the third structure in the Y direction

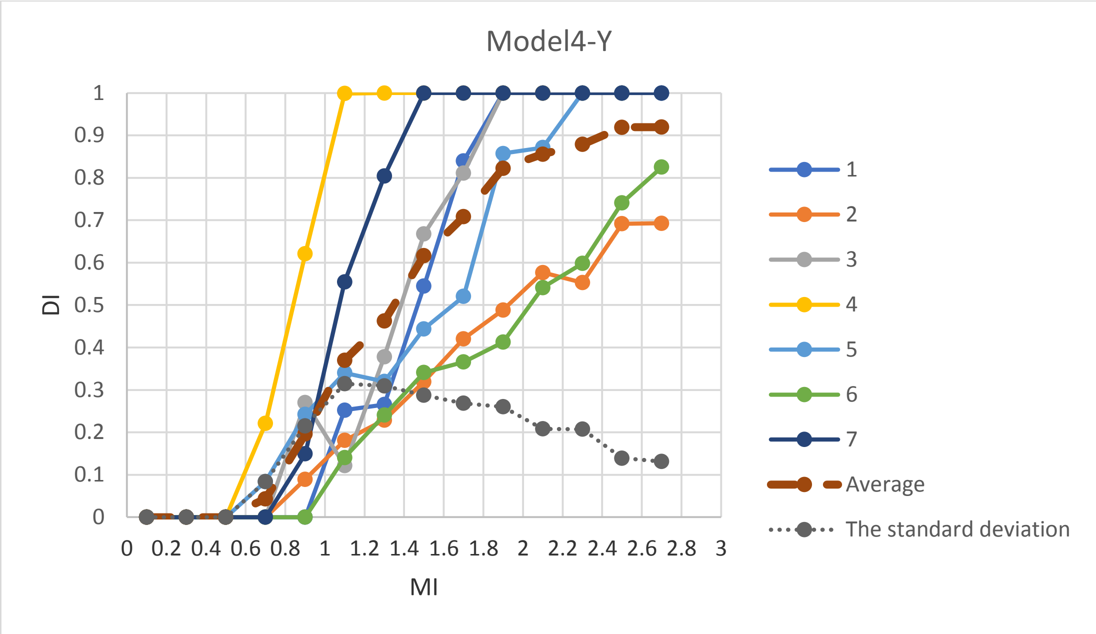

Figure 21. Damage distribution curves in the fourth structure in Y direction.

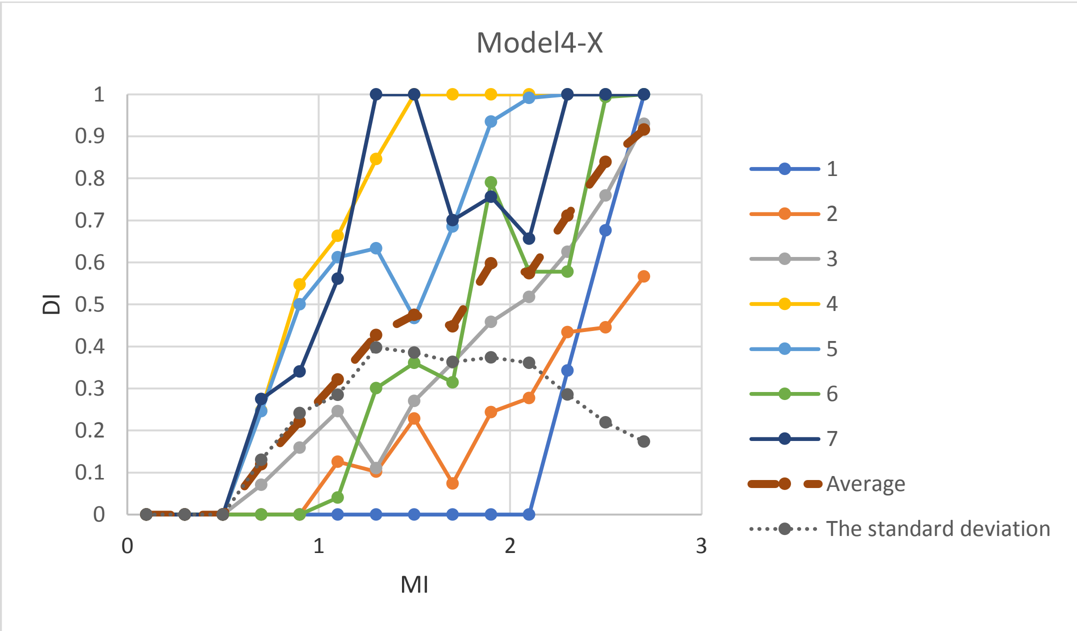

Figure 22. Damage distribution curves in the fourth structure in the X direction.

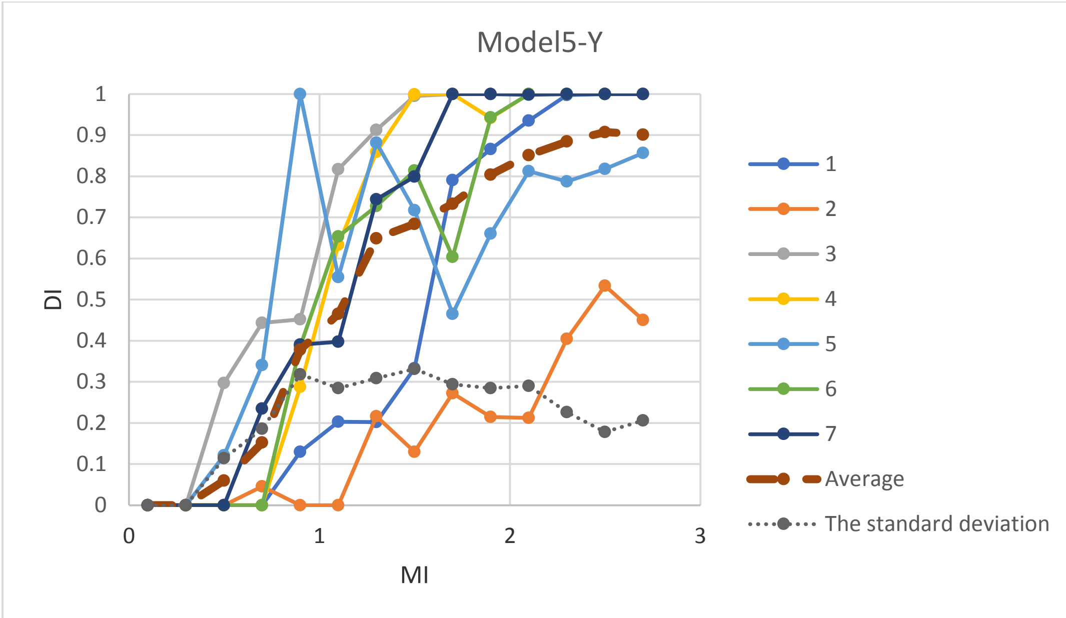

Figure 23. Damage distribution curves in the fifth structure in the Y direction.

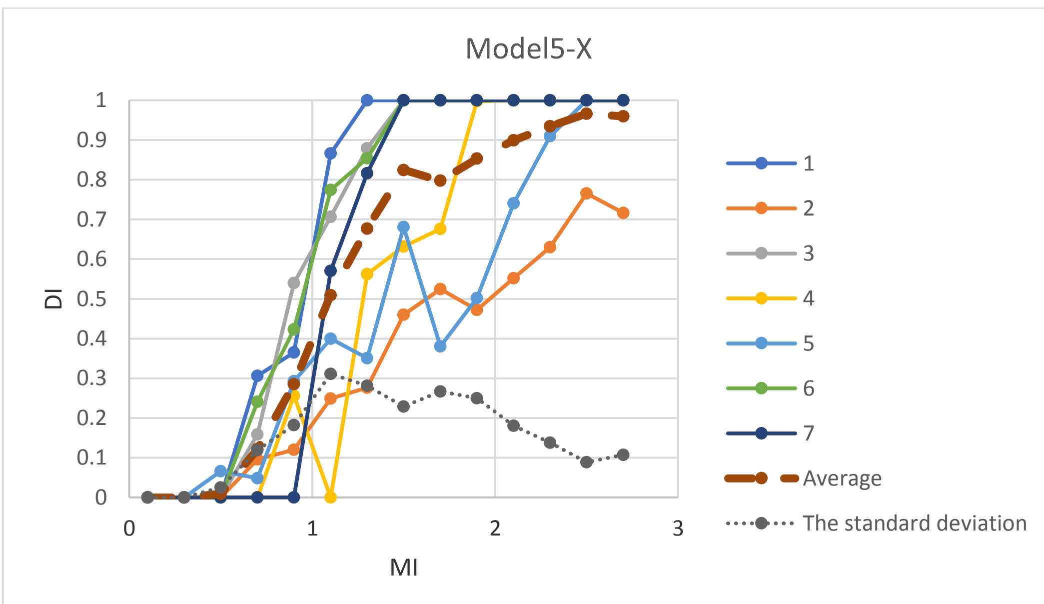

Figure 24. Damage distribution curves in the fifth structure in the X direction.

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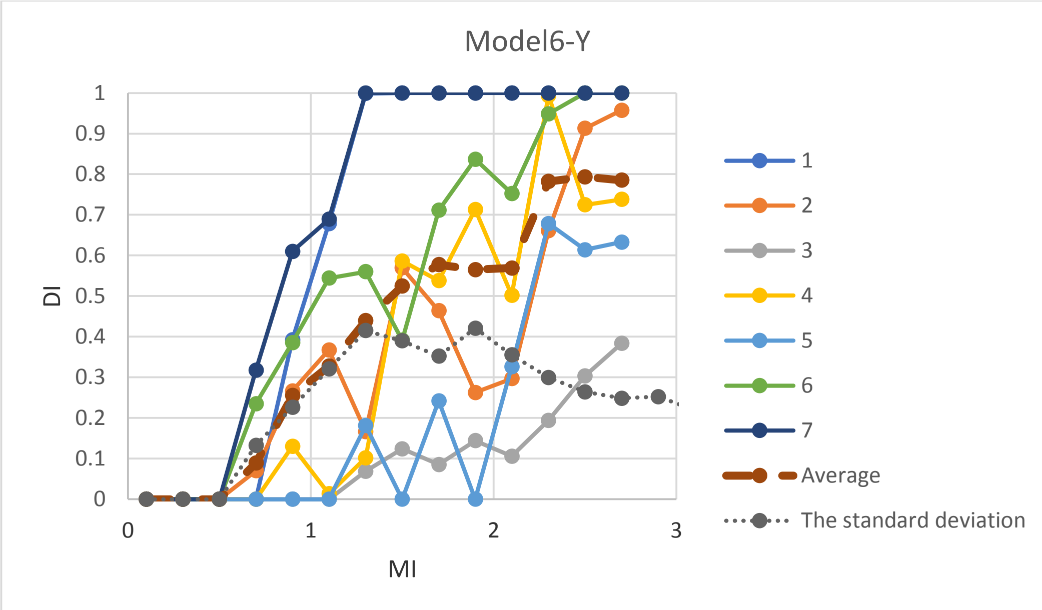

Figure 25. Damage distribution curves in the sixth structure in the Y direction.

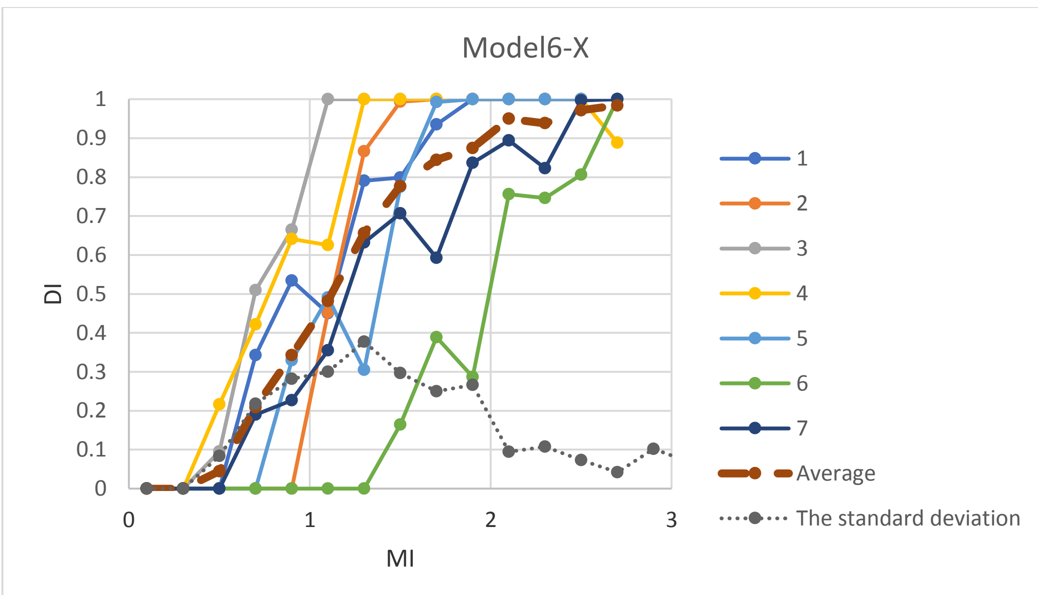

Figure 26. Damage distribution curves in the sixth structure in the X direction.

Across all structures, there is a clear upward trend in the average damage distribution curves and a downward trend in the standard deviation in both the X and Y directions. This indicates that, on average, the structures experience more damage as the PGA increases. Additionally, the reduced standard deviation suggests that the damage patterns across the different models are consistent, indicating that the structural response is predictable under different seismic intensities. These trends can be observed in the damage distribution curves presented in Figures 15-26.

3.3. Correlation between the damage index and the observed torsion

The primary objective of this study is to assess the extent of damage sustained by structures that are susceptible to torsional irregularities. To achieve this goal, the degree of torsion experienced by each of the structures in response to the selected GM records is examined. The results are presented in Tables 3 to 7. Specifically, this section aims to explore the correlation between the observed torsion and the damage index of the structures. By graphing the ratios of the highest horizontal displacement in one direction to the equivalent value in the opposite direction against the damage index, it is possible to evaluate the link between torsion and damage. The results of this analysis provide critical insights into the role of torsional irregularities in the seismic performance of the structures.

Table 3. The correlation between the measured torsion and the first structure's damage index.

MAXDI	DIY	DIX	MAX (DX/DY)	Earthquake record
1.953	0.284	0.554	1.031	1
1.737	0.238	0.414	4.425	2
1.007	0.409	0.406	1.539	3
1.530	0.307	0.469	0.671	4
3.696	0.109	0.402	1.307	5
1.064	0.310	0.330	1.976	6
11.577	0.047	0.445	43.641	7

Table 4. The correlation between the measured torsion and the second structure's damage index.

MAXDI	DIY	DIX	MAX (DX/DY)	Earthquake record
9.639	0.045	0.437	1.114	1
1.796	0.233	0.418	4.678	2
1.218	0.369	0.303	1.338	3
1.308	0.440	0.336	1.482	4
1.112	0.312	0.280	3.288	5
1.700	0.293	0.498	2.232	6
1.017	0.475	0.483	1.555	7

Table 5. The correlation between the measured torsion and the third structure's damage index

MAXDI	DIY	DIX	MAX (DX/DY)	Earthquake record
1.610	0.270	0.435	1.017	1
3.289	0.120	0.396	4.433	2
1.573	0.152	0.239	2.026	3
1.003	0.311	0.310	1.203	4
4.627	0.089	0.414	1.533	5
1.601	0.190	0.304	3.025	6
1.021	0.387	0.379	1.160	7

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Table 6. The correlation between the measured torsion and the fourth structure's damage index

MAXDI	DIY	DIX	MAX (DX/DY)	Earthquake record
4.206	0.144	0.493	5.766	1
2.090	0.178	0.303	2.180	2
1.977	0.322	0.518	3.733	3
1.309	0.639	0.680	6.109	4
1.486	0.577	0.477	3.470	5
1.450	0.354	0.300	1.362	6
1.262	0.592	0.608	3.252	7

Table 7. The correlation between the measured torsion and the fifth structure's damage index.

MAXDI	DIY	DIX	MAX (DX/DY)	Earthquake record
1.817	0.681	0.461	2.409	1
2.414	0.347	0.177	6.411	2
1.314	0.663	0.708	1.638	3
1.505	0.509	0.623	2.050	4
1.547	0.455	0.572	2.285	5
1.406	0.664	0.581	1.880	6
1.256	0.599	0.612	4.274	7

Table 8. The correlation between the measured torsion and the sixth structure's damage index

MAXDI	DIY	DIX	MAX (DX/DY)	Earthquake record
1.264	0.604	0.621	1.533	1
2.228	0.562	0.311	13.553	2
11.114	0.713	0.079	14.345	3
2.545	0.685	0.331	2.827	4
4.152	0.530	0.157	7.439	5
2.487	0.242	0.490	4.776	6
1.694	0.481	0.663	3.210	7

It is worth noting that the diaphragm torsion level has been estimated in each analytical step by dividing the highest horizontal displacement in one horizontal direction by the corresponding value in the opposite direction. This approach allows for a more accurate assessment of the extent of torsional irregularities in the structures, which is critical for understanding their seismic performance. By examining the relationship between the observed torsion and the damage index, it is possible to determine the impact of torsional irregularities on the structural response and identify potential strategies to mitigate their adverse effects. The results of this analysis are presented in the following sections.

3.4. Damage index

The assessment of damages incurred in both the X and Y directions was determined by analyzing Figs. 27 and 28 presented in this section. These figures depict seven distinct accelerograms and their corresponding average damage levels per structure. To ensure the reliability of the results, standard deviation graphs for each damage curve are also provided in Figures 29 and 30.

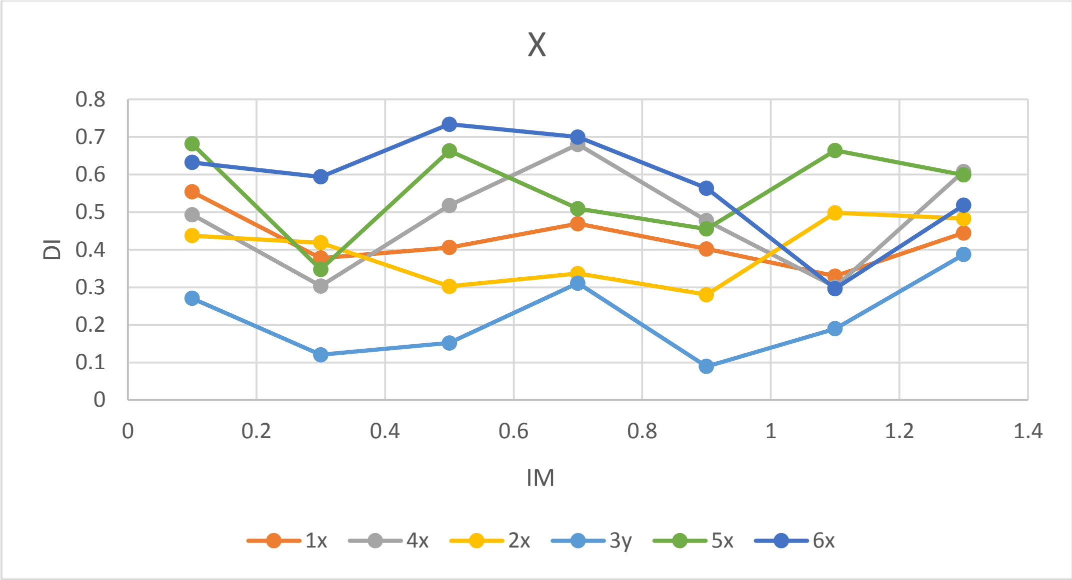

Figure 27. Average damage index in X direction.

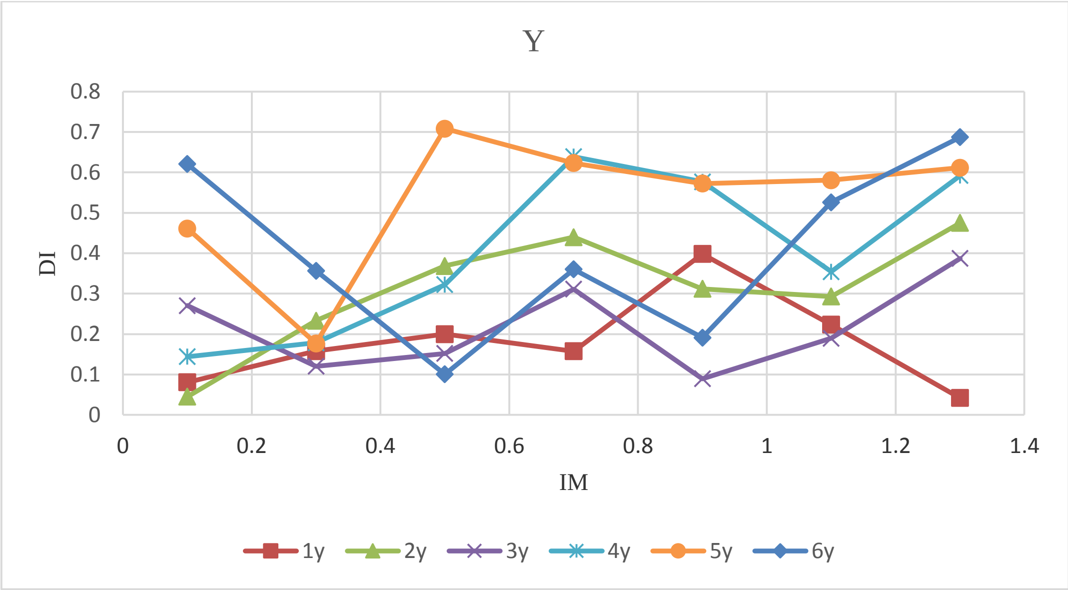

Figure 28. Average damage index in Y direction.

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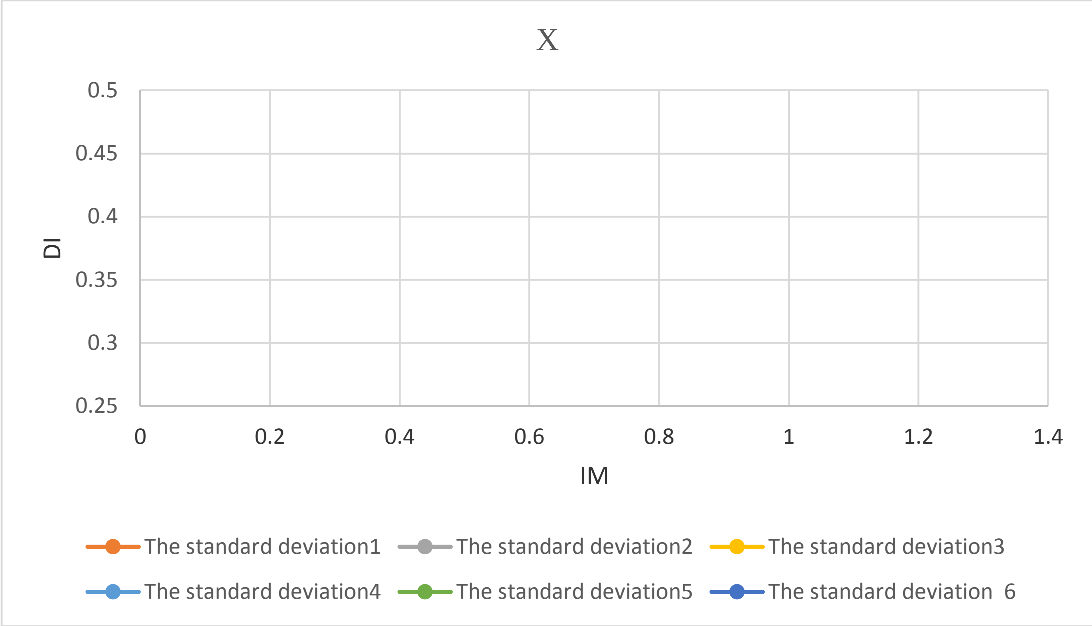

Figure 29. Standard deviation of damage indexes in X direction.

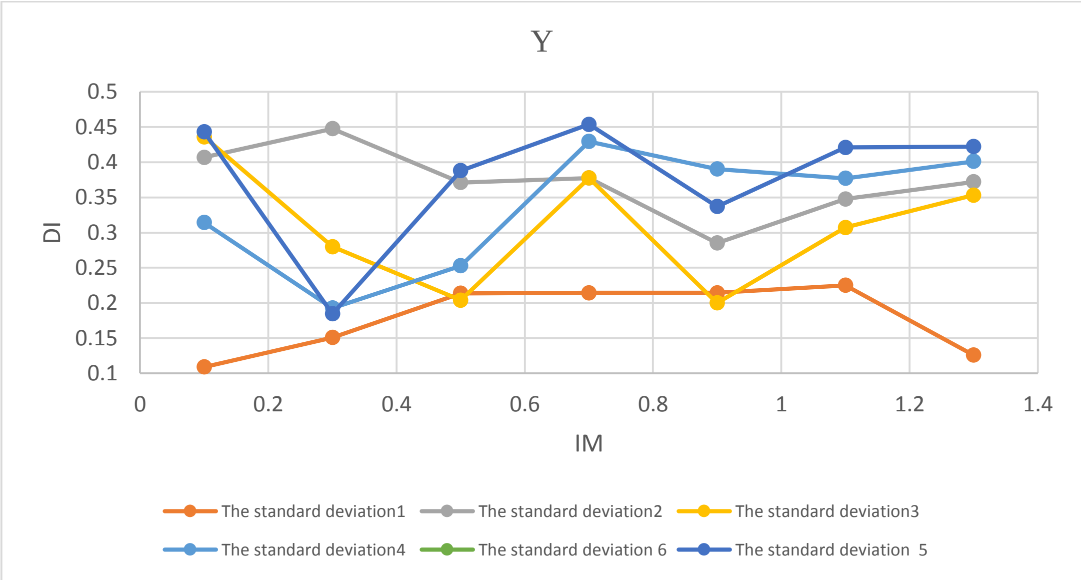

Figure 30. Standard deviation of damage indexes in Y direction.

3.5. Comparison of the average damage index

This section investigates the average damage indices for PGA values of 0.35 and 0.7, representing the base acceleration of Tehran city plan and twice the design level of the structure in both X and Y directions, respectively. The intensities of the earthquake are characterized by the degree of damage inflicted. The average graphs of the respective PGA values are analyzed to determine the level of damage incurred.

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3.5.1. Comparing the average damage index at PGA=0.35

This section places a great deal of political, social, and economic weight on Tehran because of its dense population and central location for governmental institutions. Due to the aforementioned factors, this city is full of twisted irregular constructions. Due to this city's tremendous seismic potential, the entire nation would suffer irreversible effects if an earthquake occurred there. The comparison of the average index at PGA=0.35 are shown in Figs. 31 and 32, which is equal to the base acceleration of the Tehran city according to standard 2800.

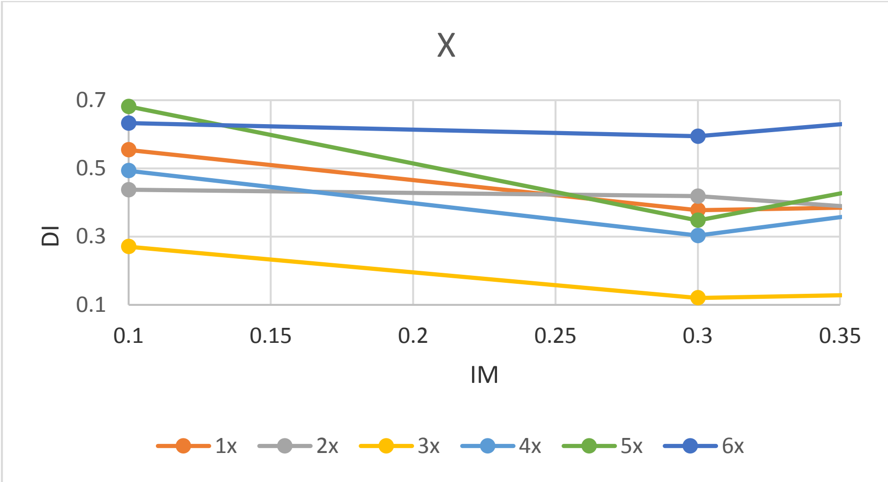

Figure 31. Average damage index at PGA=0.35 in X direction

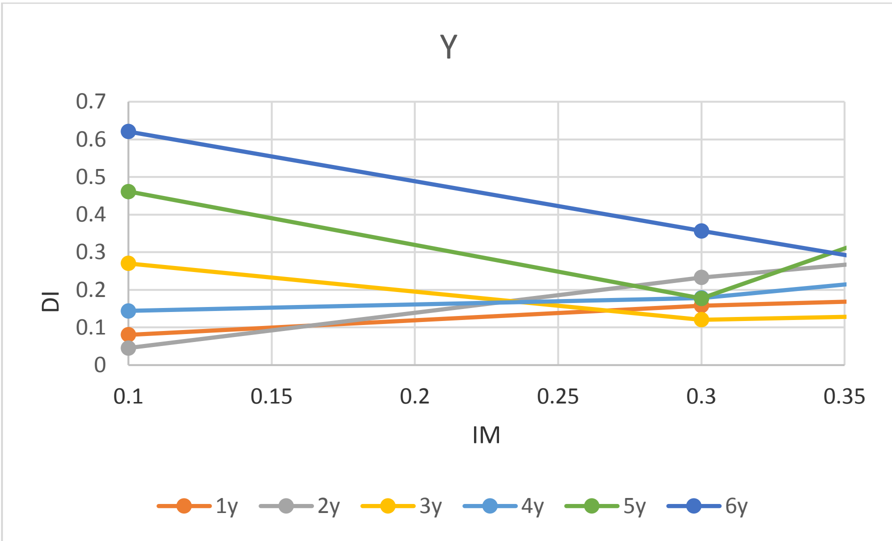

Figure 32. Average damage index at PGA = 0.35 in Y direction

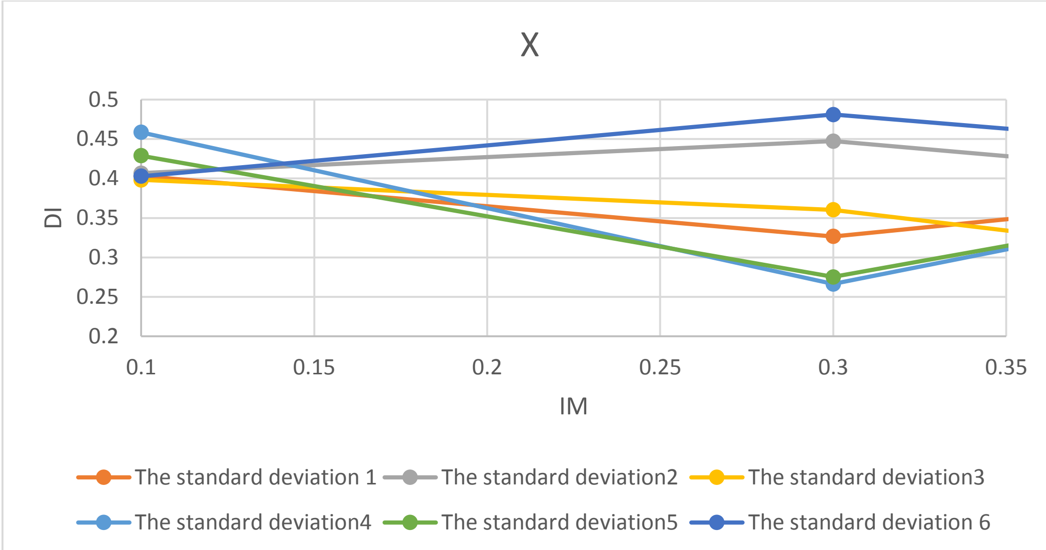

Figure 33. Standard deviation of damage indexes at PGA=0.35 in the X direction.

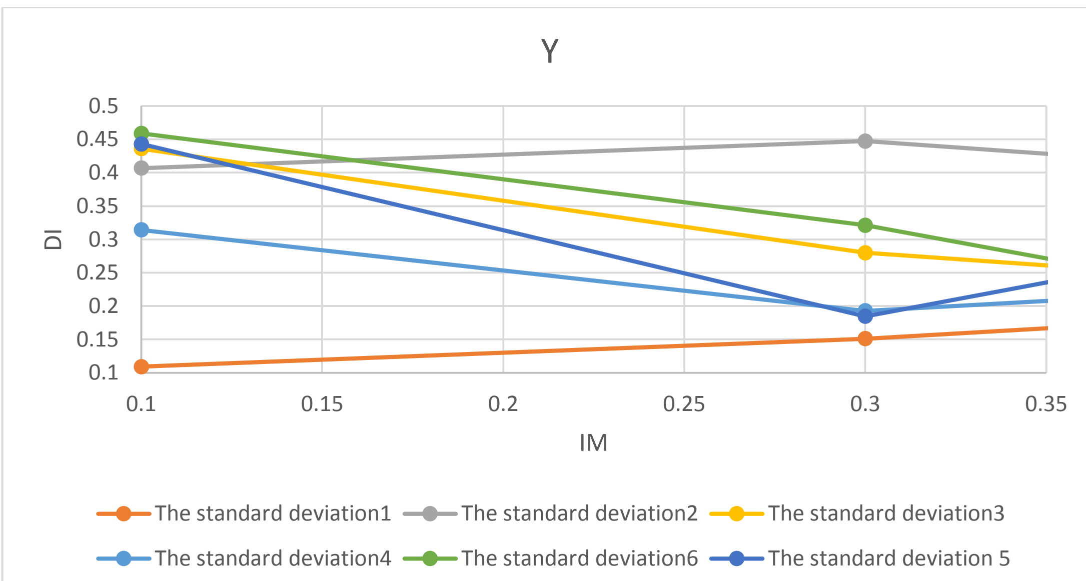

Figure 34. Standard deviation of damage indexes at PGA=0.35 in the Y direction.

As depicted in Fig. 31, the average damage index of all structures in the X direction at PGA=0.35 indicates that structures with higher degrees of irregularity are more vulnerable to damage when subjected to accelerations of less than 1g, during which the structure remains in a linear state. Specifically, the sixth structure, characterized by the highest degree of irregularity, incurred the greatest damage, while the regular construction, with the lowest degree of irregularity, suffered the least damage. This finding emphasizes the importance of taking into account the level of irregularity in structures when evaluating their seismic resilience. It should be noted that, despite its higher degree of regularity than the fourth structure, the second structure in Fig. 31 sustained greater damage. This observation can be attributed to the fact that the second structure had not yet entered the nonlinear phase at PGA=0.35 in the X direction, while the fourth structure had yielded and softened, but remained in a load-bearing position that decreased the separation between the center of mass and the center of stiffness to an even lower level than in its original state. This underscores the critical role that the nonlinear behavior of structures plays in their seismic response. Furthermore, Fig. 32 highlights the significant impact of Y-directional irregularity on the structural response to seismic loading. Specifically, the second structure exhibits much more Y-directional irregularity than the fifth structure, contributing to the observed damage. The presence of stiffness in the load-bearing components further complicates the structure's seismic response and increases its vulnerability to damage. These findings emphasize the need for effective seismic design strategies that take into account various forms of irregularity and nonlinearity to ensure the safety and resilience of structures in high-risk seismic regions.

3.5.2. Average damage index at PGA=0.7

In this section, we investigate the average damage index at PGA=0.7, which corresponds to twice the design level of the structure, and is equivalent to the maximum possible earthquake (MPE) level, as specified by the 2800 standard. The analysis of the average damage index at this level of seismic loading provides critical insights into the overall structural damage incurred by the examined structures. The structural response to seismic loading in both X and Y directions is considered in this investigation. Specifically, we examine the extent of damage incurred by the structures when subjected to accelerations that exceed their design level by a factor of two. Such extreme loading conditions can cause significant structural damage and compromise the safety and resilience of the affected buildings. Thus, analyzing the damage index at PGA=0.7 provides essential information for assessing the seismic performance of the examined structures under the worst-case scenario.

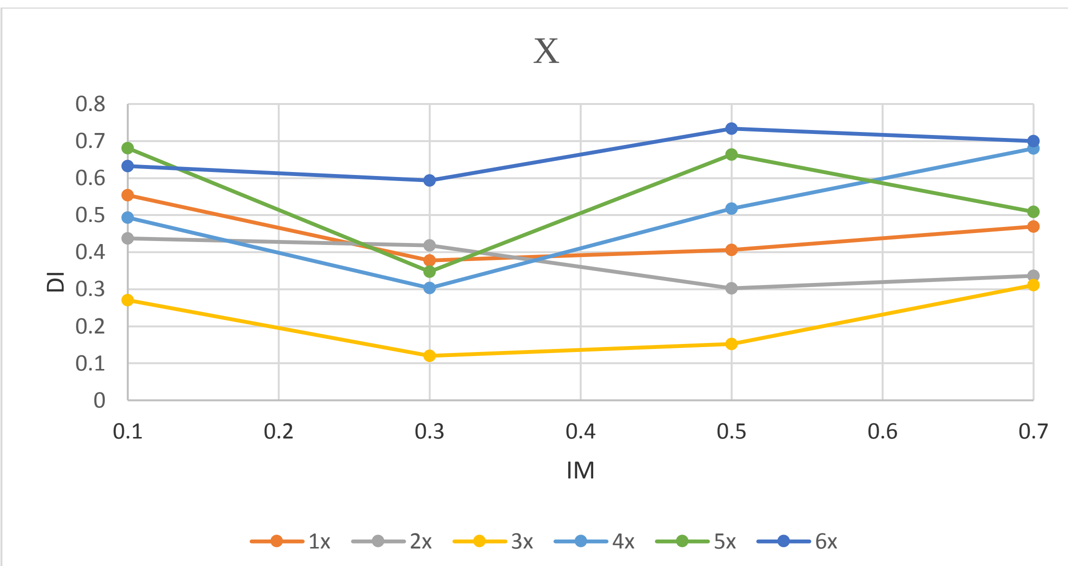

Figure 35. Average damage index in PGA=0.7 in the X direction.

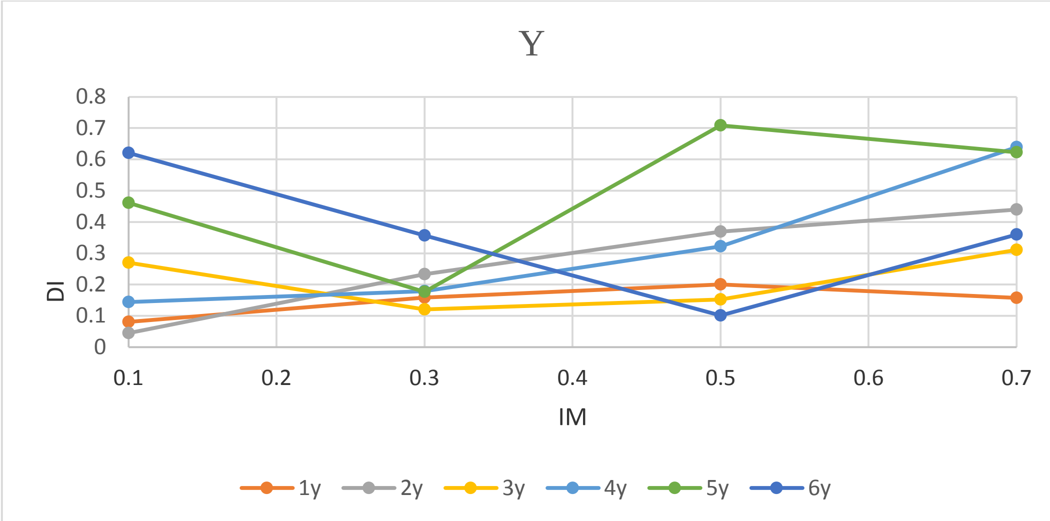

Figure 36. Average damage index at PGA=0.7 in Y direction.

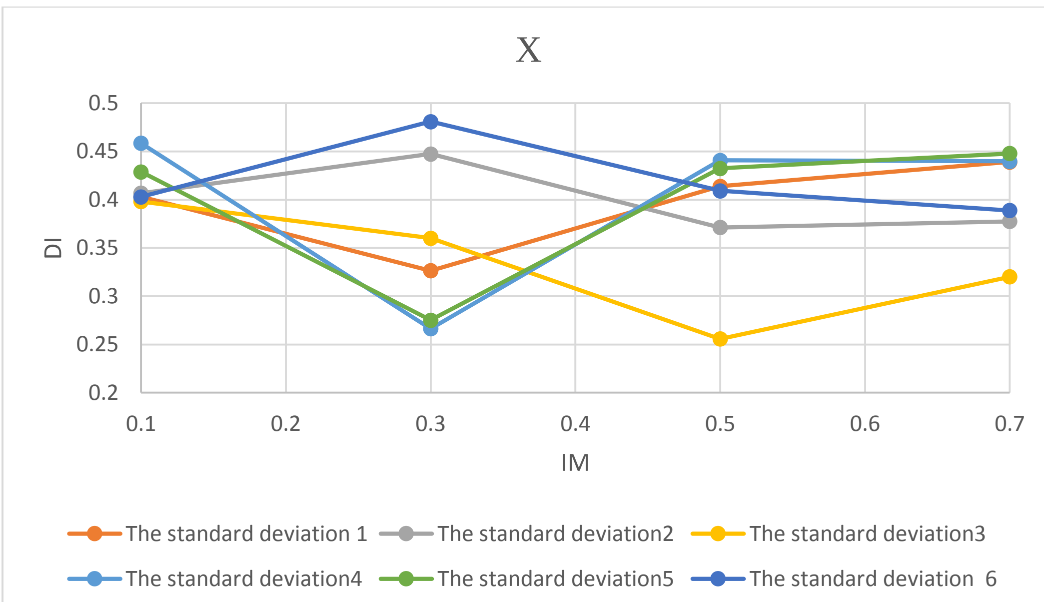

Figure 37. Standard deviation of damage indexes at PGA=0.7 in the X direction.

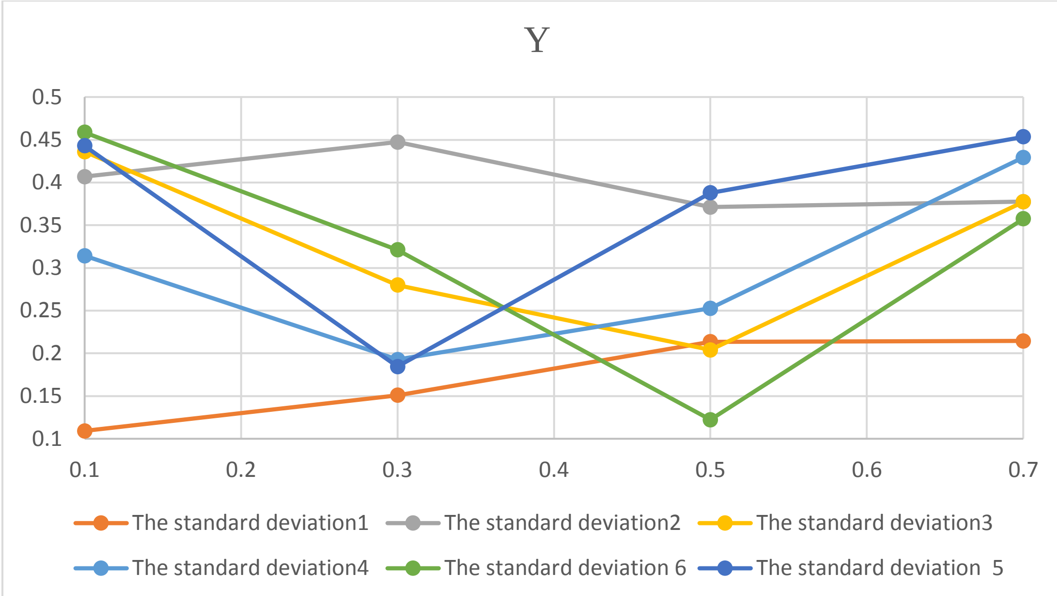

Figure 38. Standard deviation of damage indexes at PGA=0.7 in the Y direction.

The findings from this study indicate that the amount of damage during an earthquake is closely linked to the level of irregularity of the geometry. As the intensity of the earthquake rises, structures with more irregular geometry suffered less damage than those with more regular shapes, as evidenced by the average damage index in Fig. 35 at PGA=0.7g in the X direction. Specifically, the sixth structure, with the highest degree of irregularity, experienced the most damage, while the perfectly regular first structure sustained the second-highest amount of damage. However, in the Y direction, the most damage was sustained by the fifth and fourth structures, which have severe twisting irregularities in their geometry. It is noteworthy that the level of torsional irregularity in a structure is not solely determined by its geometric shape, but also by the point at which it enters the nonlinear phase due to an increase in acceleration. For instance, in Fig. 36, the fourth structure suffered less damage than the second structure because its load-bearing components were arranged in a different mode that reduced the distance between their centers of mass and stiffness even further from their initial condition. To provide a more quantitative analysis, Tables 9 and 10 present the numerical amount of damage sustained by each structure. As the level of irregularity increases, so does the amount of damage, confirming the close correlation between the two variables.

Table 9. The average amount of damage index of structures in the X direction.

PGA	Earthquake record	1st structure	2nd structure	3th structure	4th structure	5th structure	6th structure
0.1	1	0.554	0.437	0.435	0.493	0.681	0.632
0.3	2	0.377	0.418	0.396	0.303	0.347	0.594
0.5	3	0.406	0.303	0.239	0.518	0.663	0.734
0.7	4	0.469	0.336	0.31	0.68	0.509	0.7
0.9	5	0.402	0.28	0.414	0.477	0.455	0.564
1.1	6	0.33	0.498	0.304	0.3	0.664	0.296
1.3	7	0.445	0.483	0.379	0.608	0.599	0.518

Table 10. The average amount of damage index of structures in the Y direction.

PGA	Earthquake record	First structure	second structure	Third structure	Fourth structure	Fifth structure	Sixth structure
0.1	1	0.081	0.045	0.27	0.144	0.461	0.621
0.3	2	0.158	0.233	0.12	0.178	0.177	0.357
0.5	3	0.2	0.369	0.152	0.322	0.708	0.101
0.7	4	0.158	0.44	0.311	0.639	0.623	0.36
0.9	5	0.398	0.312	0.089	0.577	0.572	0.191
1.1	6	0.223	0.293	0.19	0.354	0.581	0.526
1.3	7	0.042	0.475	0.387	0.592	0.612	0.687

Furthermore, it is important to note that these findings have significant implications for seismic design and construction practices, particularly in regions with high seismic activity such as Tehran. The results suggest that structures with higher torsional irregularity are more vulnerable to earthquake damage, and therefore, additional measures may need to be taken to reinforce such structures. This may involve incorporating specific design and construction features that can mitigate the effects of torsional irregularity, such as the use of diagonal bracing or additional lateral support systems. Overall, this study provides valuable insights into the effects of torsional irregularity on the seismic performance of buildings, highlighting the importance of considering both the geometric arrangement of the structure and its level of nonlinearity. The findings underscore the need for continued research in this area to further refine our understanding of seismic design and construction practices and enhance the resilience of structures in earthquake-prone regions.

4. Conclusion

Based on the seismic design standards, it has been widely believed that structures with greater torsional irregularity would experience more severe damage during an earthquake. However, the validity of this assertion is dependent on various factors, including the strength and durability of the building materials as well as the magnitude of the earthquake. Moreover, the relationship between the degree of irregularity in the structural plan and the resulting damage is only applicable when the structures are still in the linear phase and have not yet experienced complete failure. In other words, the correlation between the torsional irregularity and the damage index weakens as the level of nonlinearity in the structure increases, and the distribution of seismic activities in the members becomes more independent of the initial plan geometry. In the event of high seismic acceleration levels, the asymmetric structure will gradually yield, exiting the linear phase and entering the non-linear phase. Under these circumstances, no harm would come to the structure from the torsional irregularity. Hence, in high seismic intensities, structures with torsional irregularity can better withstand damage than those with regular geometrical forms. It can be inferred that a structure's torsional irregularity is influenced not only by its geometric shape but also by the seismic intensity that caused its nonlinearity and deformity. The findings from the present study indicate that structures with higher torsional irregularity have sustained the most damage at accelerations of less than 1g when the structure still remains in its linear condition. The cause for this observation is that irregular structures will enter the nonlinear phase at an earlier stage with an increase in acceleration, and the arrangement of load-bearing elements that still possess significant stiffness will change in such a way that the separation between the center of mass and the center of stiffness is closer to its initial state. Thus, it is evident that emphasis on torsional irregularity should be drawn not only from the geometric arrangement of the structure but also from the level of seismic intensity that caused the transition from the linear to the nonlinear phase. The degree of torsional irregularity is undeniably influenced by the magnitude of the earthquake and the degree of structural nonlinearity.

5. Data availability statement

Some or all data used are available from the corresponding author by request.

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