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Comparative Study of using Different Types of Bracing Systems in Mid-Rise Steel Structures

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ABSTRACT

The structural systems used in mid-rise buildings are being developed quantitatively and qualitatively to increase their resistance against gravity and lateral forces. Also, extensive studies are being conducted regarding the introduction and application of new structural systems in mid-rise structures in order to improve the behavior of the structure and reduce the risks caused by the effect of lateral forces. In this regard, in recent years, the use of a structural system with a bracing system has attracted the attention of many engineers and researchers. On the other hand, sometimes due to architectural limitations and the inappropriate location of the building, there is a possibility of torsional irregularity in them, and this issue can be seen in most buildings. X, diagonal and chevron (V, inverted V, combination of V and inverted V and combination of X and diagonal) bracing systems have not been done in mid-rise structures. Therefore, in this study, the investigation and comparison of X bracing system, single diagonal bracing and chevron in mid-rise structures is discussed. In order to achieve the goals of this project, a 10-story structure with a combined system of moment frame and X, diagonal and chevron bracing is modelled in ABAQUS software. The obtained results showed that FM10-V-Λ-bracing and FM10-Λ-bracing models have the best performance in displacement and base shear, respectively in comparison with a reference model. The higher the stiffness of a structure, the less likely it is to damage and destroy its non-structural components due to less plasticity and displacement; But in case of failure, the destruction will be sudden and severe.

Keywords:

Seismic behavior, X brace, Diagonal brace, Chevron brace, Mid-rise structure.

1. Introduction

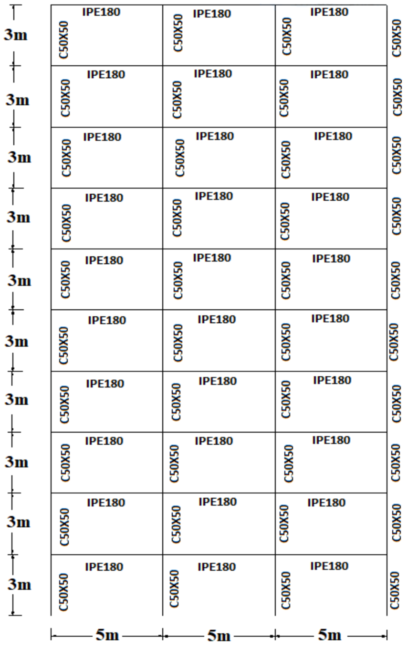
The behavior and reaction of structures during an earthquake is not exactly known. Structures that are designed for areas with high seismicity can provide a more controlled seismic behavior for the structure. They must have two criteria. First, it must have sufficient stiffness to control lateral displacement in order to prevent any structural and non-structural damage during moderate but frequent earthquakes, and secondly, the structure must have sufficient strength and ductility to withstand severe earthquakes to prevent its collapse, in this case limited structural and non-structural damage is allowed. Braces are one of the well-known systems for the resistance of frames against lateral loads. If a limited length of the ductile member in the bracing system has inelastic behavior, conventional systems such as concentrically braced frames (CBFs) and moment frames cannot simultaneously satisfy the needs of ductility and stiffness. CBFs usually have high stiffness, but due to buckling of compression members, they have low ductility. On the other hand, regular frames have an acceptable formability and energy dissipation capacity in the beams due to bending yielding, but they have limited stiffness. Therefore, due to the necessity of increasing the ductility and the level of energy consumption of a structure located in seismic areas, it has been discussed that it has the ability to absorb energy in two different levels [1-4]. In the following, the background of this research is presented.

Chao and Goel (2006) investigated a seismic design method for CBFs in order to increase the performance of these frames. They designed a single-span frame using nonlinear dynamic analysis by applying two methods of elastic design and plastic design based on energy method. They showed that design by code method (SCBF) results in very poor response and premature failure of braces. It also leads to structural instability and unacceptably large relative displacements. Meanwhile, energy design meets all the goals of the designer, including the desired yielding mechanisms and the relative displacement of floors, and prevents the failure of braces under different levels of risk [5]. Rai and Goel (2003) addressed the seismic evaluation and improvement of eccentrically braced frames (EBFs). They studied and evaluated a 4-story CBF building located in North Hollywood that was subjected to the Northridge earthquake (1994) and did not experience serious damage. They used non-linear analyzes for seismic evaluation, such as non-linear static analysis and non-linear dynamic analysis (time history) and showed that filling the CBF bracing tubes with plain concrete improves the seismic performance of the building [6]. Dicleli and Mehta (2007) investigated the effect of near-field earthquakes on single and multi-storied one-span steel braced structures with and without fluid viscous dampers (FVD). By performing a nonlinear time history analysis, they showed that the seismic performance of frames with CBF without FVD is very weak and is sensitive to the pulse frequency and intensity of earthquakes. Also, by installing FVD on structures with CBF, it significantly improves the seismic performance of the brace by maintaining its elastic behavior [7]. Systani et al. (2008) investigated the performance of steel structures with CBF based on the plastic design method. They showed that steel frames with CB designed based on the plastic method have higher reliability levels against total destruction compared to frames [8]. Abdollahzadeh and Mohammadi (2013) investigated the reduction factor of double steel frames with large-scale CBs. Large-scale CBF refers to bracing that connects both floors in a cross manner. They examined 3 structures of 8, 10 and 12 stories using nonlinear static and nonlinear incremental dynamic analyses and obtained the reduction factor of the studied structures [9]. Mahin et al. (2014) investigated the seismic performance of braced frame systems resistant to buckling. They showed that the conducted tests show the good behavior of braces [10]. Rahgozar et al. (2016) investigated the seismic performance of self- centering brace frames. They showed that the main patterns of self-centering braces for low and mid-rise steel structures can create a sufficient margin of safety against seismic loads [11]. Gholhaki and Ahmadi investigated the effect of thin steel sheet filler on the behavior of eight CBs [12]. Canxing et al. (2018) used shape memory alloys (SMAs) in frames with CBs, compared their performance with buckling restrained braces (BRBs). The results of this research showed that it is better to use CBF equipped with SMAs instead of BRBs [13]. Nazarimofrad and Shokrgozar (2019) used SMAs in the core of the BRB in 4 and 8-story structures. Then, by performing incremental dynamic analysis, their seismic performance was evaluated under 6 earthquake records. The results of this research indicated the improvement of the studied seismic responses [14]. Pachideh et al. (2020) conducted an experimental and numerical study of the effects of the type of core steel and the distance between the core and the shell on the buckling behavior of the brace. The results show that the use of softer steel with lower yield stress and with equal thickness in the core reduces the bearing capacity and resistance of the brace [15]. Pachideh et al. (2020) introduced and investigated the experimental performance of the new bracing system and its combination with the yielding damper. This system, which has been proposed and reviewed in order to increase plasticity, absorb higher energy and cover the weaknesses of the existing systems [16]. Saberi et al. (2020) evaluated the effect of material type, thickness, and perforation of the side plates on the cyclic performance. For this purpose, in addition to using side plates of soft steel (ST37) and high strength structural steel (ST52), nickel-titanium-shaped memory alloy (SMA-Ni-Ti) was also used to investigate the superelastic effect of this alloy on the connection performance. Modeling and analysis were performed in finite element software under cyclic loading. The results showed that the increased capacity and ductility of the side plate connections with shape memory alloy [17]. Sadeghi et al. (2020) modeled and analyzed 4, 8, and 12-story 3D steel moment frame structures with special ductility under nonlinear static and incremental dynamic analysis, and finally used fragility curves to investigate their collapse capacity. The results show that the collapse capacity of 4, 8, and 12-story structures is the highest under far fault earthquakes and the lowest under near fault earthquakes with pulses, and among them, the low-rise 4-story structure has a lower collapse capacity [18]. Hashemi et al. (2021) studied the seismic behavior of frames with BRB’s and the effect of utilizing SMAs. The selected models are three frames with 3, 6 and 9 story, which in different openings have BRBs in two states with and without applying SMAs. By reviewing the results, it is clear that improvements in the 6 and 9-story frames compared to the 3- story frame is more tangible. Also, the analysis results showed by equipping the frames with SMAs, the energy dissipation concentration pattern has been changed [19]. Hashemi et al. (2023) investigated the reliability of steel BRB frames equipped with intelligent materials by considering the existing uncertainties in material properties, loading and geometry of members. Evaluation of sensitivity and reliability analyses based on kriging meta-model of BRB frames with and without SMAs under artificial near-fault earthquakes are conducted. The results of this research showed that in the studied frames, the random variables of the length of SMA and the cross-sectional area of the BRB were the most effective variables in calculating the probability of failure in BRB frames with and without intelligent materials, respectively [20].

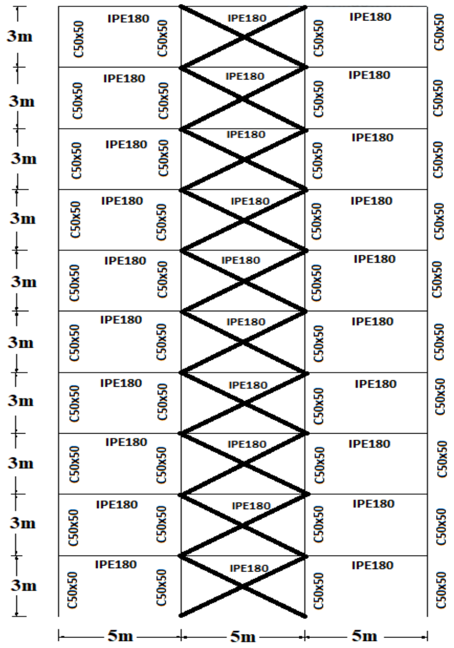
In this paper, as a novelty, the investigation and comparison of X bracing system, single diagonal bracing and chevron in mid-rise structures is discussed. In order to achieve the goals of this project, a 10-story structure with a combined system of moment frame, X, diagonal and chevron bracing is modelled in ABAQUS software [21]. Finally, the best performance of bracing systems is analyzed and specified under seismic records.

2. Modelling process

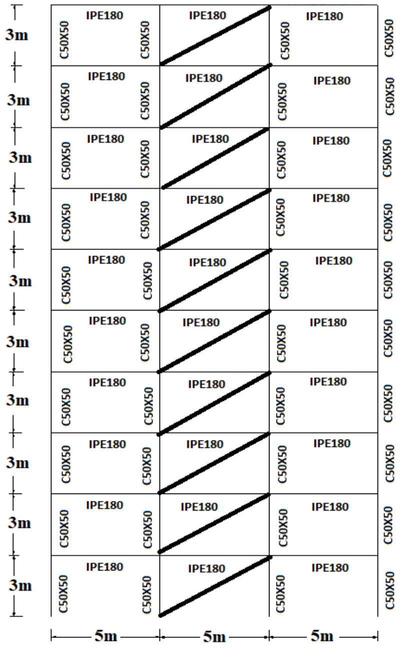
In this research, seven steel residential buildings are designed with a steel moment frame and different types of bracing systems with the number of 10- story by considering the design codes [22-24]. Also, the height of each story is 3 m. The total height is 30 m. The structures are designed by ETABS software [25]. The side frame of these structures will be subjected to nonlinear dynamic time history analysis in ABAQUS software and the nonlinear dynamic time history analysis results will be used to evaluate their seismic behavior of below models. Figure 1 indicates the side frames of 10- story structures and their cross sections.

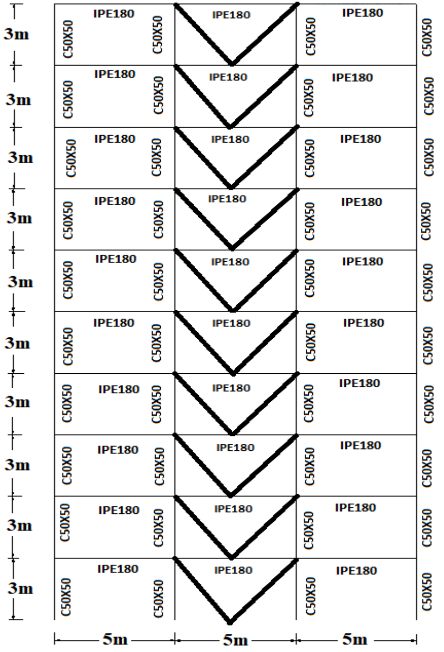


a) Moment Frame (FM10-IMF)



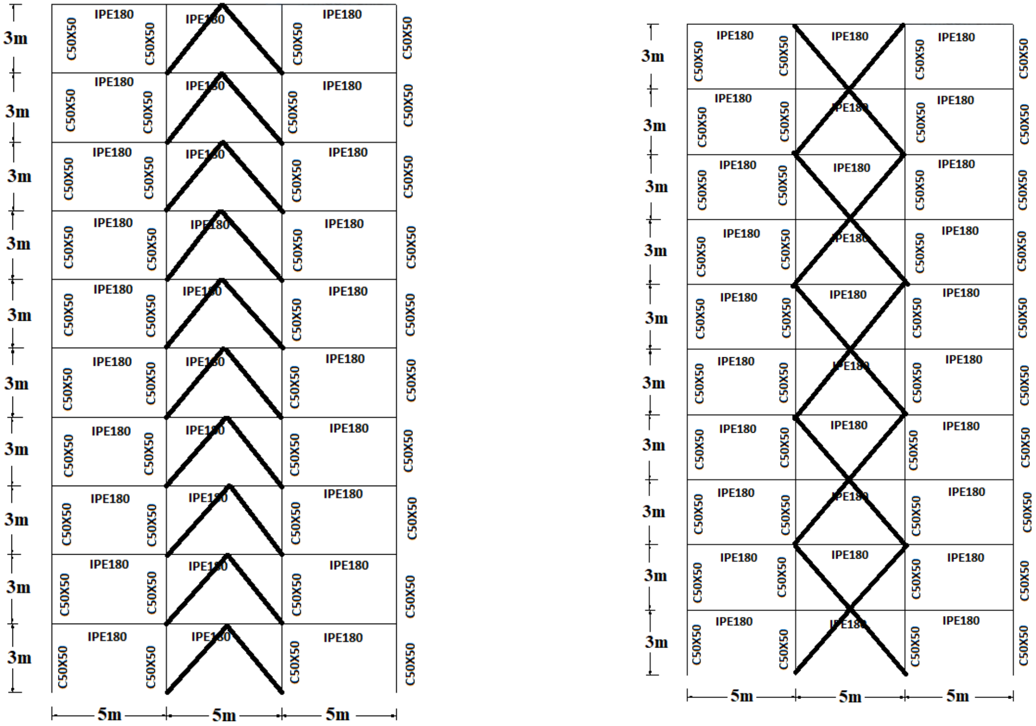
b) X Braced Frame (FM10-X-Bracing)





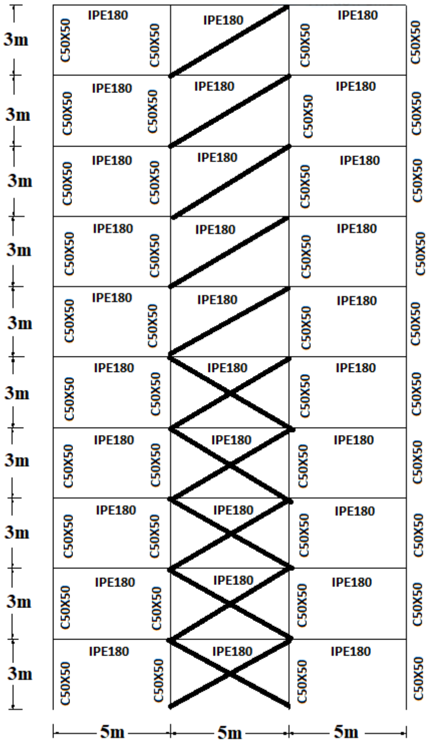
c) Diagonal Braced Frame (FM10-Diagonal-Bracing)

d) V Braced Frame (FM10-V-Bracing)



e) Inverted V Braced Frame (FM10-Λ-Bracing)

f) V and Inverted V Braced Frame (FM10-V-Λ-Bracing)



g) X and Diagonal Braced Frame (FM10-X-Diagonal-Bracing)

Figure 1. The elevation and cross section of elements of side frame of *10*- story models.

In the selected frames, the dead and live loads on the beams are considered equal to 1500 kg/m and 600 kg/m, respectively. Also, the materials used in beams and columns are all of ST37 type with modulus of elasticity equal to 200 GPa, yield stress and ultimate stress are assumed to be 240 MPa and 370 MPa respectively. In addition, for plastic features, Johnson-Cook criterion is used in the current research. In the following, in order to study the behavior of the desired frames with different bracing systems, three near fault earthquake records have been used according to Table 1. The mentioned earthquakes are adapted from the PEER database [26].

Table 1. The details of studied earthquake records.

No.	Earthquake	Country	Year	Magnitude	PGA (g)
R1	Tabas	Iran	1978	7.1	0.54
R2	Elcentro	Japan	1995	7.3	0.62
R3	Manjil	Iran	1990	7.3	0.62

3. Results and discussion

The results of the studied models are presented for three earthquake records in three sections.

3.1. Tabas earthquake record

The maximum Von Mises stress contour and the maximum displacement of the model moment frame are shown in Figures 2 and 3. It can be seen that the stress distribution in the moment frame with intermediate ductility is well seen, the maximum stress value is 156.80 MPa. Also, according to Figure 3, the concentration of the responses is more at the top of the frame, the maximum value of which is equal to 29.35 mm.

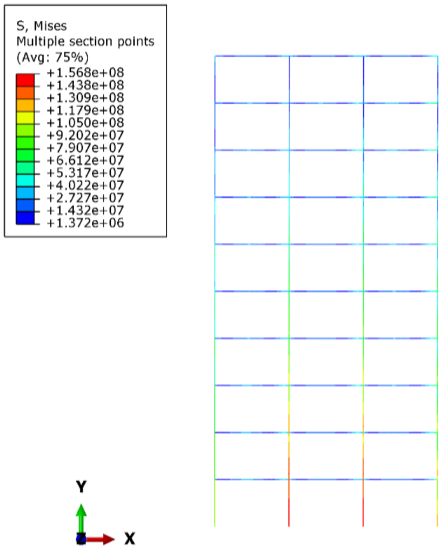


Figure 2. Von-Mises stress contour of FM10-IMF.

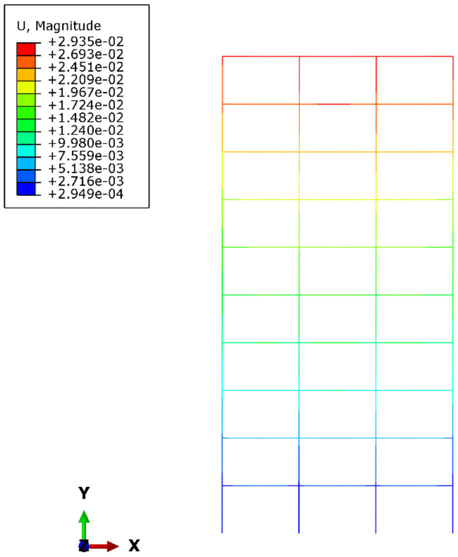


Figure 3. Displacement contour of FM10-IMF.

Then, for X braced frame model, the maximum Von Mises stress and the maximum displacement are 145.70 MPa and 16.90 mm, respectively. Figures 4 and 5 are shown the Von Mises stress and displacement contours, respectively.

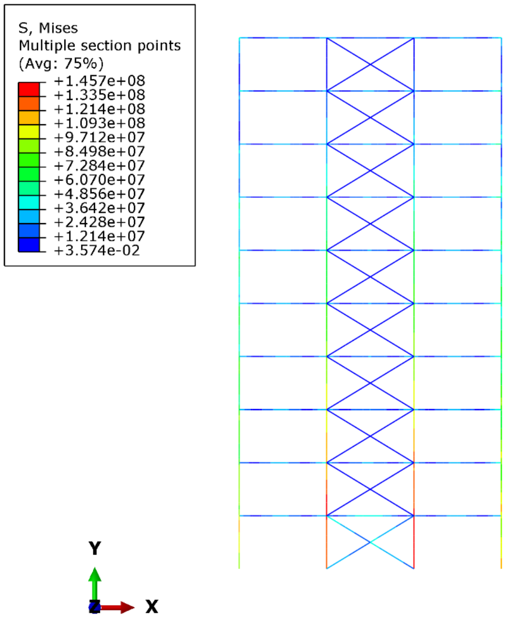


Figure 4. Von-Mises stress contour of FM10-X-Bracing.

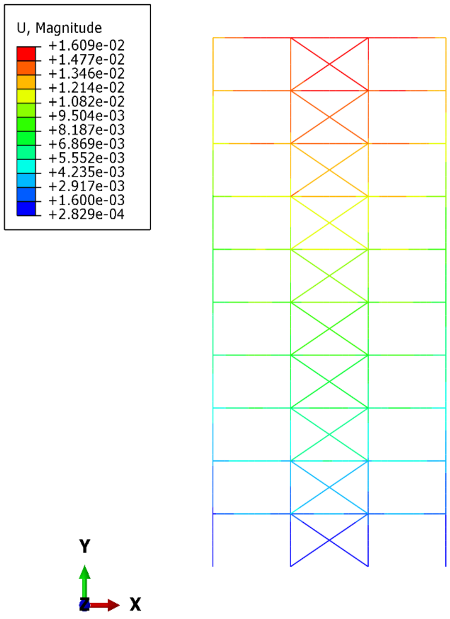


Figure 5. Displacement contour of FM10-X-Bracing.

Based on Figures 6 and 7, the maximum Von Mises stress and the maximum displacement for diagonal braced frame are 230.20 MPa and 36.11 mm, respectively.

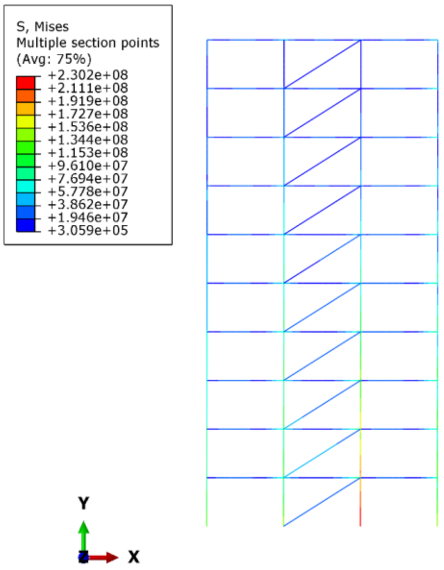


Figure 6. Von-Mises stress contour of FM10-Diagonal-Bracing.

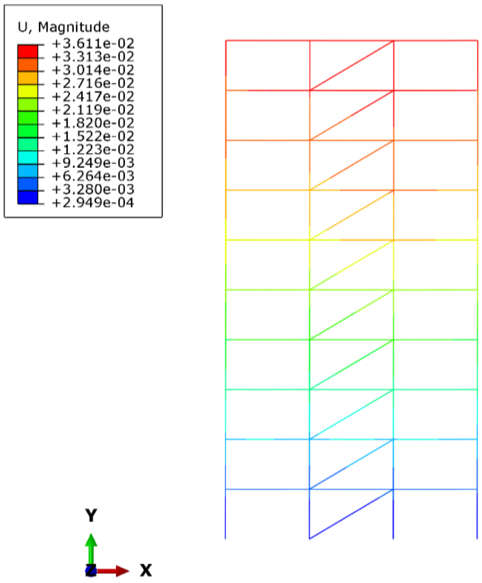


Figure 7. Displacement contour of FM10-Diagonal-Bracing

For V braced frame, the maximum Von Mises stress contour the maximum displacement, contour are shown in Figures 8 and 9. These values are 190.20 MPa and 12.93 mm, respectively.

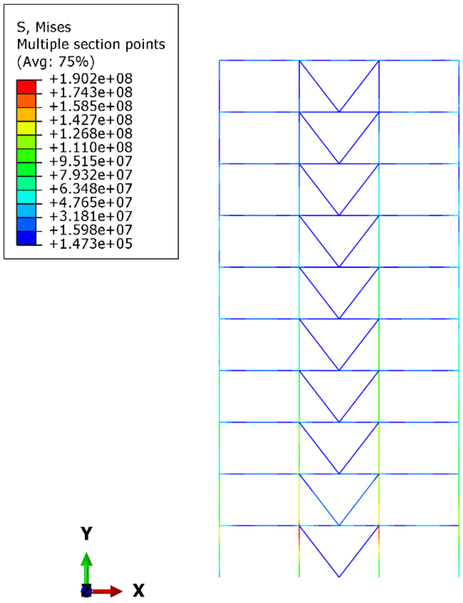


Figure 8. Von-Mises stress contour of FM10-V-Bracing.

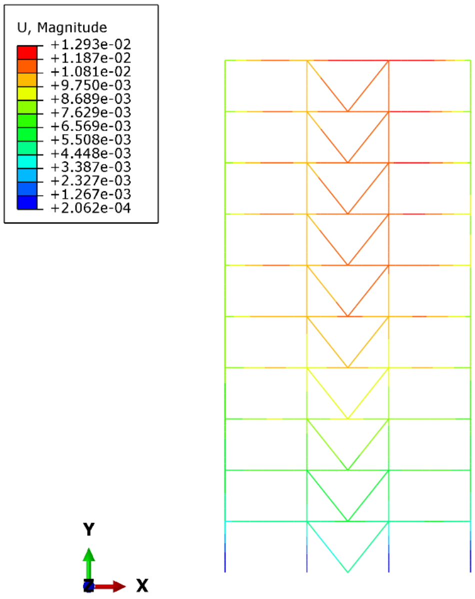


Figure 9. Displacement contour of FM10-V-Bracing.

Based on Figures 10 and 11, the maximum Von Mises stress and the maximum displacement for inverted V braced frame are 270.40 MPa and 34.60 mm, respectively.

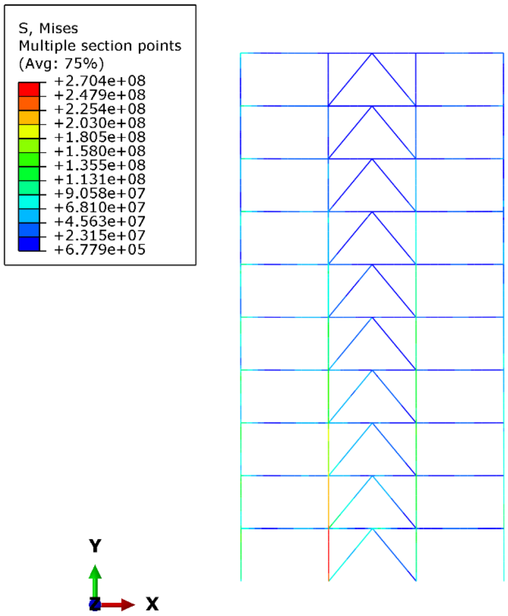


Figure 10. Von-Mises stress contour of FM10-Λ-Bracing.

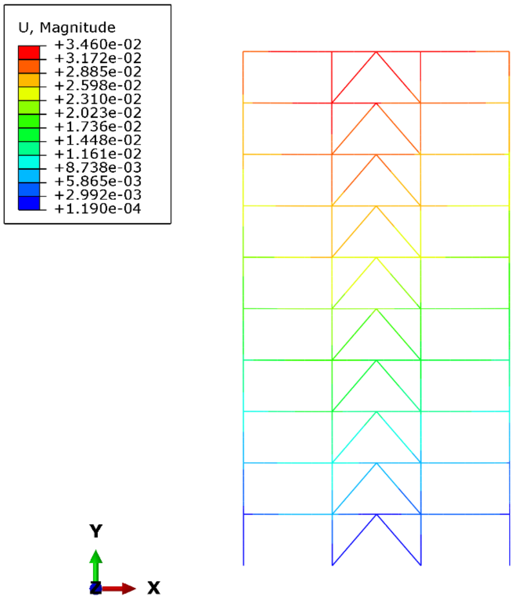


Figure 11. Displacement contour of FM10-Λ-Bracing.

According to Figures 12 and 13, the maximum Von Mises stress and the maximum displacement are 135.60 MPa and 19.74 mm for combined V and inverted V braced frame, respectively.

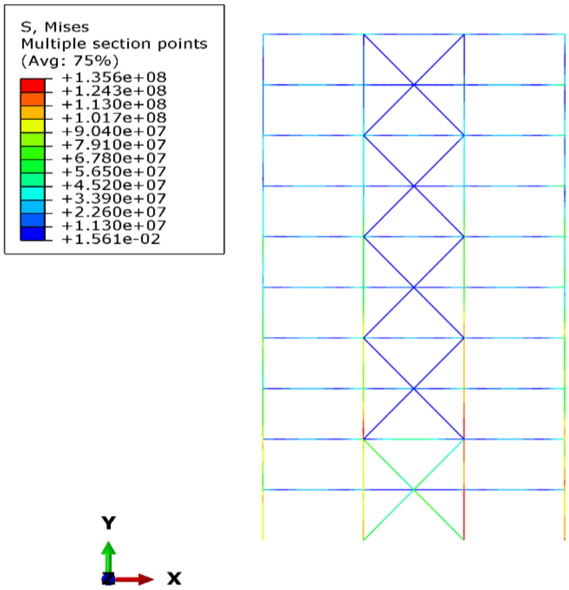


Figure 12. Von-Mises stress contour of FM10-V-Λ-Bracing.

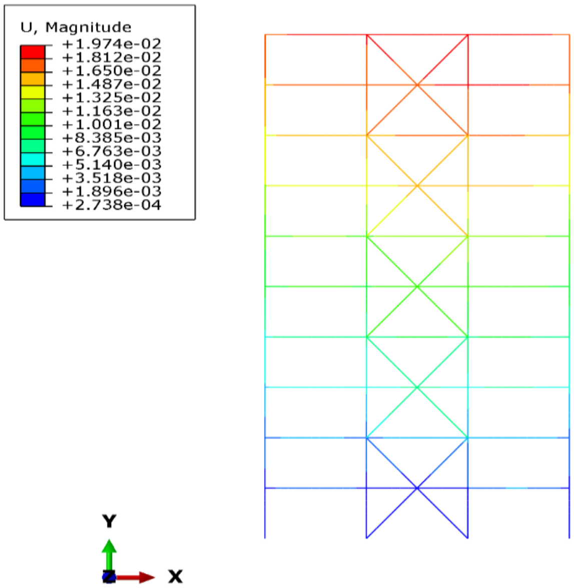


Figure 13. Displacement contour of FM10-V-Λ-Bracing.

The maximum Von Mises stress contour and the maximum displacement contour are shown in Figures 14 and 15. These values are 189.30 MPa and 49.85 mm for combination of X and diagonal braced frame.

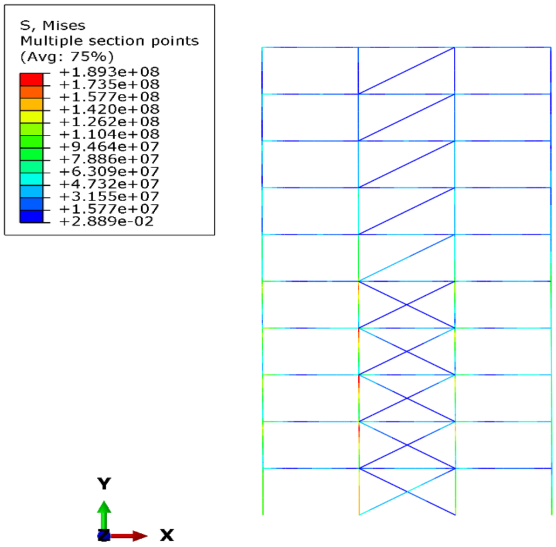


Figure 14. Von-Mises stress contour of FM10-X-Diagonal-Bracing.

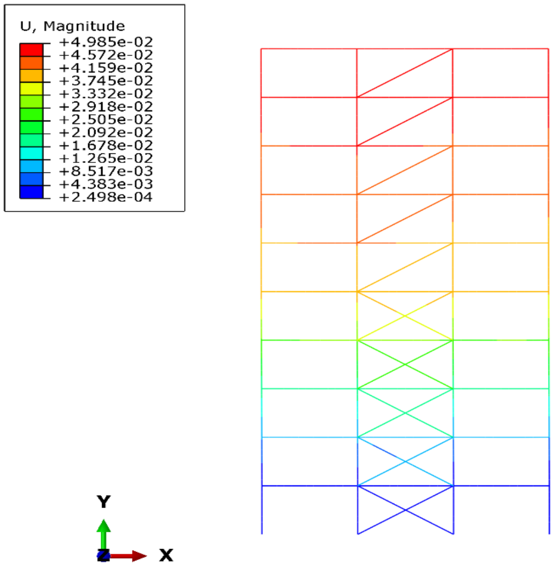


Figure 15. Displacement contour of FM10-X-Diagonal-Bracing.

In this part of the research, the results of maximum displacement and base shear are extracted from Figures 16 and 17. According to the Table 2, the displacement value of FM10-V-Λ-Bracing model is 54.85 mm. By comparing the displacement values, FM10-V-Λ-Bracing model has the best performance with a 46% reduction compared to the reference model. Also, by comparing the base shear values, FM10-Λ-Bracing model has the best performance with a 42% reduction compared to the reference model.

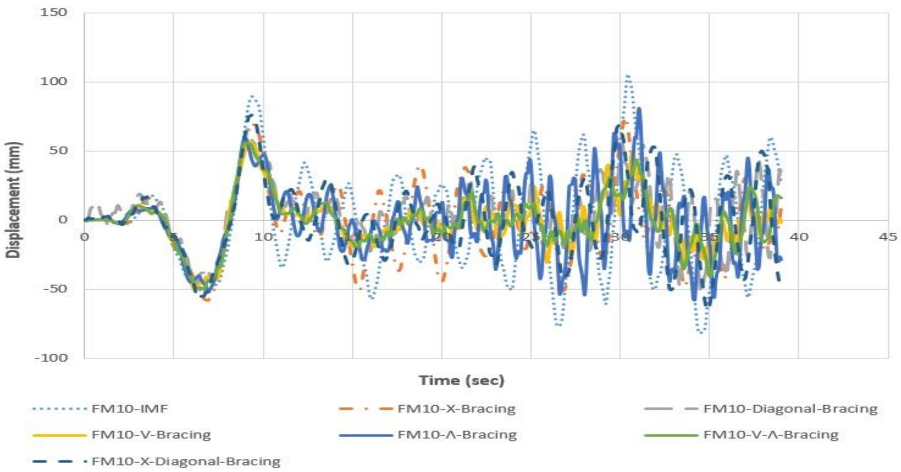


Figure 16. Displacement time history of models under Tabas earthquake record.

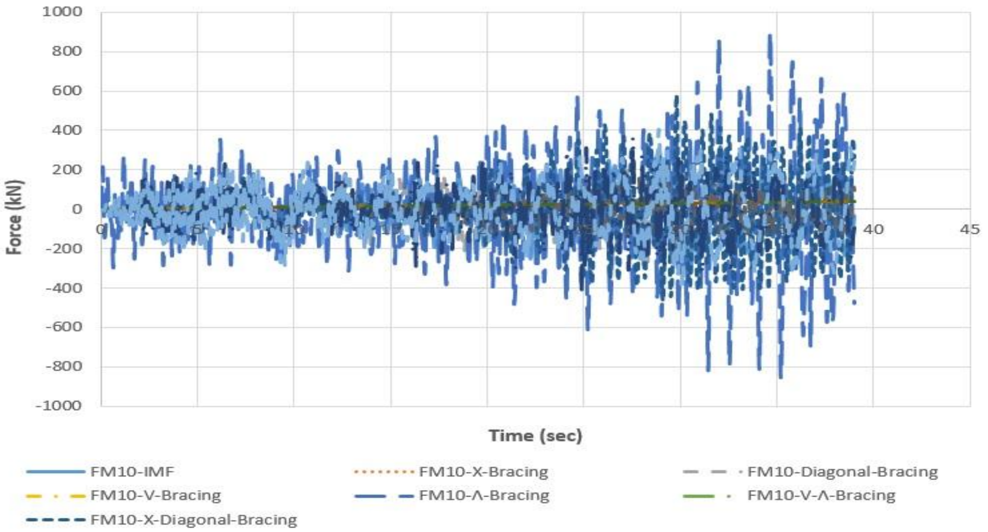


Figure 17. Base shear time history of models under Tabas earthquake record.

Table 2. The details of outputs of studied models under Tabas earthquake record.

Models	Base shear (kN)	Displacement (mm)
FM10-IMF	315.56	102.17
FM10-X-Bracing	222.19	72.58
FM10-Diagonal-Bracing	896.26	63.76
FM10-V-Bracing	579.41	55.90
FM10-Λ-Bracing	183.58	81.34
FM10-V-Λ-Bracing	364.02	54.85
FM10-X-Diagonal-Bracing	400.25	74.91

3.2. Elcentro earthquake record

According to the Figures 18 and 19, the time history of displacement and base shear are plotted. Based on Table 3, FM10-V-Λ-Bracing model has the best performance with a 47% reduction in displacement compared to the reference model. Also, FM10-Λ-Bracing model has a significant performance with a 64% reduction in base shear compared to the reference model.

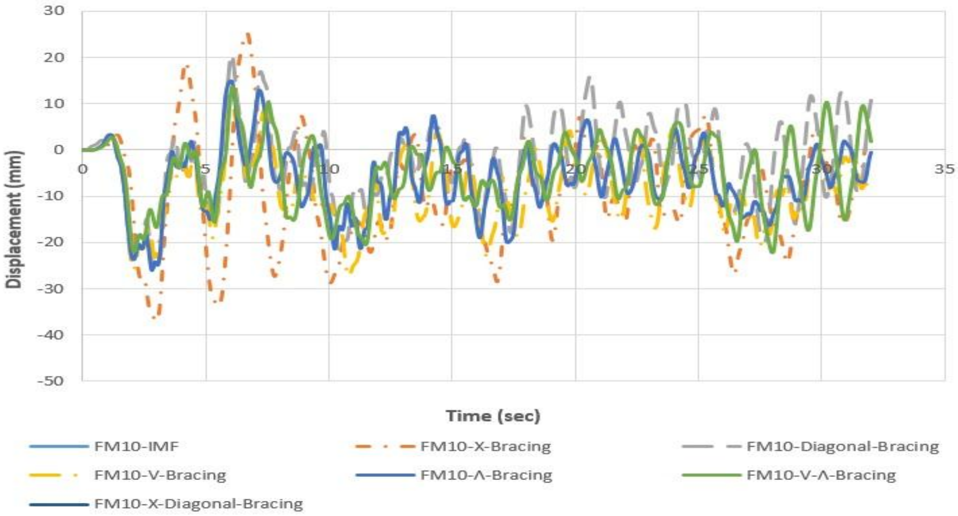


Figure 18. Displacement time history of models under Elcentro earthquake record.

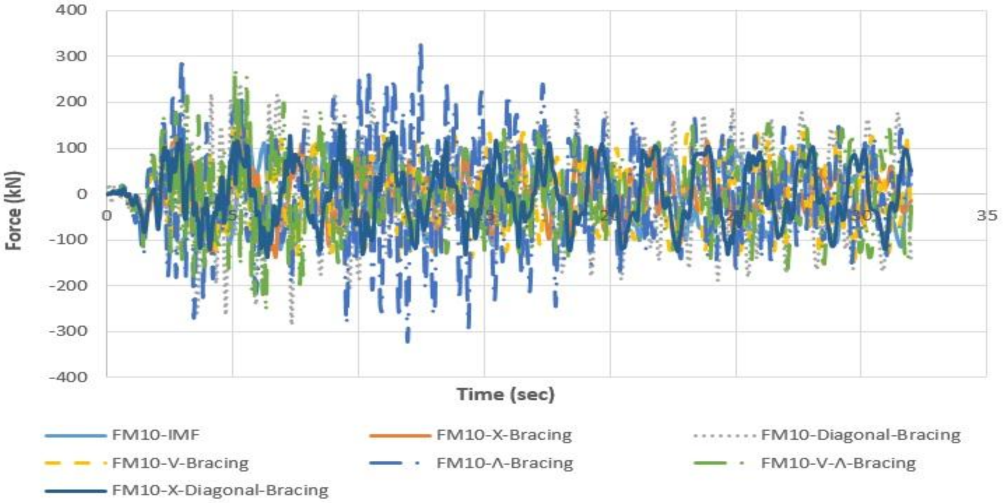


Figure 19. Base shear time history of models under Elcentro earthquake record.

Table 3. The details of outputs of studied models under Elcentro earthquake record.

Models	Base shear (kN)	Displacement (mm)
FM10-IMF	330.37	25.06
FM10-X-Bracing	161.82	21.93
FM10-Diagonal-Bracing	240.15	20.67
FM10-V-Bracing	158.78	10.57
FM10-Λ-Bracing	116.33	14.74
FM10-V-Λ-Bracing	273.75	13.27
FM10-X-Diagonal-Bracing	152.51	20.72

3.3. Manjil earthquake record

The results of maximum displacement and base shear are extracted from Figures 20 and 21. According to the Table 4, the displacement value of FM10-V-Λ-Bracing model is 23.03 mm. FM10-V-Λ-Bracing model has the best performance with a 53% reduction in displacement values compared to the reference model. Also, FM10-Λ-Bracing model has the best performance with a 60% reduction in base shear values compared to the reference model.

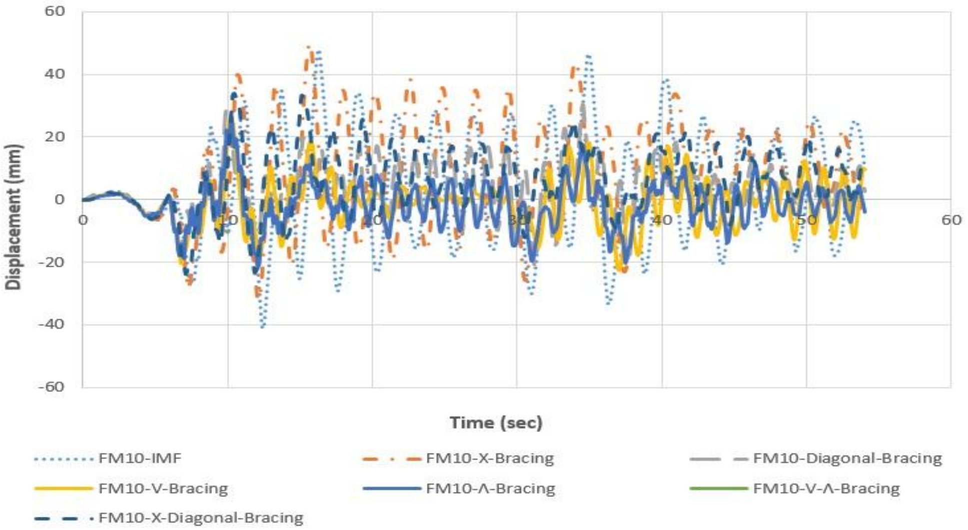


Figure 20. Displacement time history of models under Manjil earthquake record.

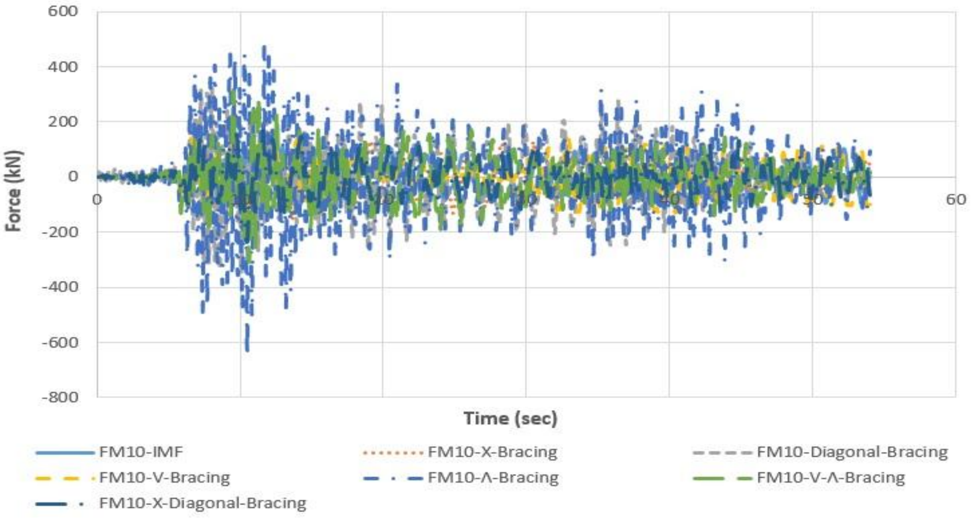


Figure 21. Base shear time history of models under Manjil earthquake record.

Table 4. The details of outputs of studied models under Manjil earthquake record.

Models	Base shear (kN)	Displacement (mm)
FM10-IMF	323.34	49.41
FM10-X-Bracing	175.67	48
FM10-Diagonal-Bracing	155.51	30.28
FM10-V-Bracing	149.43	26.45
FM10-Λ-Bracing	129.28	26.59
FM10-V-Λ-Bracing	313.08	23.02
FM10-X-Diagonal-Bracing	176.04	34.02

4. Conclusion

In this study, 7 models of steel frames with X, diagonal and chevron braces are investigated in mid-rise structures under 3 earthquake records. By examining and comparing the seismic responses of the studied models, the following results have been obtained:

1. According to the obtained results of Tabas earthquake record, FM10-V-Λ-bracing and FM10-Λ-bracing models have the best performance with 46% and 42% reduction in values of displacement and base shear compared to the reference model.
2. According to the obtained results of Elcentro earthquake record, FM10-V-Λ-bracing and FM10-Λ-bracing models have the best performance with 47% and 64% reduction in values of displacement and base shear compared to the reference model.
3. According to the obtained results of Manjil earthquake record, FM10-V-Λ-bracing and FM10-Λ-bracing models have the best performance with 53% and 60% reduction in values of displacement and base shear compared to the reference model.
4. The higher the stiffness of a structure, the less likely it is to damage and destroy its non-structural components due to less plasticity and displacement; But in case of failure, the destruction will be sudden and severe.

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