Seismic performance assessment of special concentrically mega braced frames with different spans ratio

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ABSTRACT

Special concentrically braced frames achieve good seismic performance in earthquake, these frames maintain the stability of the structure with linear behavior in weak to moderate earthquakes and with nonlinear behavior in extreme earthquakes. The design of structures is often based on linear analysis, so it is necessary to study the performance of mega braced frames with different spans ratio, by nonlinear analysis. In this study the seismic performance of special concentrically mega braced frames with different spans ratio is investigated. For this purpose, eight configurations of four and eight-story structures with special concentrically braced frame were designed in three dimensions, with conventional X and mega brace configurations with different spans ratio, then a braced frame of them was modeled in OpenSees in two dimensions, taking into account the second-order effects of the removed gravitational section, through a leaning column. Finally, in order to investigate the seismic performance of structures and perform incremental dynamic analysis, 14 far field earthquakes were selected according to the characteristics of the construction site. Evaluation of analysis results according to NIST GCR 10-917-8 report and Hazus Technical Manual in maximum inter story drift ratio, comparison of fragility curves and comparison of period and weight of structures, indicates that in special concentrically mega braced frames, if the spans are equal, mega braces has a suitable and economic performance, and if the ratio of spans is different, the use of mega braces has a better performance than conventional X braces and is much more economical. For example, in eight-story structures with a span ratio of 1.5, the weight of the structure with mega brace is about 20% less than the similar structure with conventional X brace. Also, the main period of frames with conventional X braces is about 20 to 30% longer than structures with mega braces, which indicates the higher stiffness of mega braces.

KEYWORDS

Incremental dynamic analysis, Special concentrically braced frame, Mega brace, Fragility curve, Far field earthquake.

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1. Introduction

Special concentrically braced frames are frames that dissipate seismic energy by yielding and buckling of the braces, so the configuration and design of these braces and their connections must be such that they can handle these deformations in a manner that the beams and columns remain elastic and can maintain the gravitational load of the structure [1].

In 2018, Momenzadeh and Shen studied the behavior of the columns in special concentrically braced frames designed by US seismic design provisions. The results showed that, yielding of the brace-intersected beams increases the braces ductility demand and leads to the early yielding of the columns, which is not expected in the SCBF by the current seismic design provisions [2]. In 2018, Kumar et al. studied the seismic response of multi-story SCBFs. The results showed that the performance of multi-story SCBFs in terms of lateral strength and ductility is almost equal to the conventional single-span brace arrangement, but the columns axial force is greatly reduced for multi-story brace arrangements [3]. To evaluate the seismic performance of low-ductility concentrically braced frames, in 2019, Sizemore et al. modeled 18 chevron and split-x frames with R = 3, 3.5 and 4 in OpenSees. After performing incremental dynamic analysis (IDA) and plotting fragility curves, the results showed that frames with R = 3.5 and 4 have good performance and frames with R = 4 are more economical [4].

In this paper, we investigate the seismic performance of special concentrically mega braced frames with different spans ratio. Special concentrically mega braced frames have lower steel weight and less welding compared to moment frames, due to the easier implementation of connections. In this study, after modeling the frames in OpenSees, incremental dynamic analysis is performed by far field ground motions and fragility curves are drawn.

2. Methodology

2.1. Design of Structures

Four 4-story structures and four 8-story structures with symmetrical square plans with 20 m length and 3.2 m height for each story and with fixed supports, were designed in three dimensions by ETABS based on the tenth topic of Iranian national building regulations [1]. To investigate the effect of spans ratio on the seismic performance of structures, two structures with spans ratio of 1, two structures with spans ratio of 1.5 and two structures with spans ratio of 2 were designed with special concentrically mega brace. Also, as control structures, two other structures with spans ratio of 1.5 were considered with special concentrically conventional X-brace.

2.2. Modeling of Frames

In this study, in order to model the nonlinear behavior of steel, the Steel02 material was used in OpenSees. Also, fiber section has been used in all members of the beams, columns and braces, which provides the possibility of including nonlinear effects in all components of the section. All members were modeled using nonlinear force-based beam-column element with distributed plasticity, i.e., forceBeamColumn element, and 7 integration points were considered for all elements. There must be an initial imperfection in the braces for their compressive buckling. Ten forceBeamColumn elements were used, to create this initial imperfection in middle of the bracing member in the form of a half sine wave, the amount of this initial imperfection based on previous researches was considered to be 0.002 of the brace length [5]. Seismic mass equal to DL + 0.2LL was applied to the main nodes of the columns.

A leaning column was used to account for the P-Δ effects of removed gravitational frames in converting three-dimensional models to two-dimensional. In the leaning column, the elasticBeamColumn element with a large cross-sectional area was used for stability in gravitational loads, which was connected to the main frame through truss elements. Low stiffness rotational springs were used in leaning column connections, to prevent increase stiffness. Also, due to the presence of two bracing frames in each direction, the tributary area of the leaning column is half of the tributary area of all gravity columns [6].

2.3. Incremental dynamic analysis

In incremental dynamic analysis (IDA), an earthquake record with a specific intensity measure (IM) is applied to the structure as the input of the analysis and for each IM, the response of the structure, i.e. the Damage Measure (DM) is obtained [7]. In this research, 14 far field earthquakes records were used according to the characteristics of the construction site and with shear wave velocity of 175 - 375 m/s.

Finally, to evaluate the results of IDA curves, the fifth chapter of NIST GCR 10-917-8 report was used, which estimated the collapse of SCBFs at 10% interstory drift ratio, and the Hazus technical manual was also used, which specified the slight, moderate, extensive and complete drift levels to plot the fragility curves [8, 9].

2.4. Verification

To verify the incremental dynamic analysis, two special concentrically braced frames with chevron and two-story X-bracing configurations were selected. These frames with leaning column, have been modeled in 2018 by Momenzadeh and Shen. Finally, according to the reference paper, Imperial Valley earthquake ground motion was used for single-record IDA [2].

The period of the modeled frames differs by about 1% from the reference paper, which indicates the correct modeling of the linear parameters of mass and stiffness. Finally, after incremental dynamic analysis, the Sa(T1, 5%) versus maximum interstory drift ratio diagram was plotted for each frame. As shown in Figure 1, the OpenSees output IDA curves are very match by the curves presented in the paper, which indicates the correct modeling of nonlinear parameters.

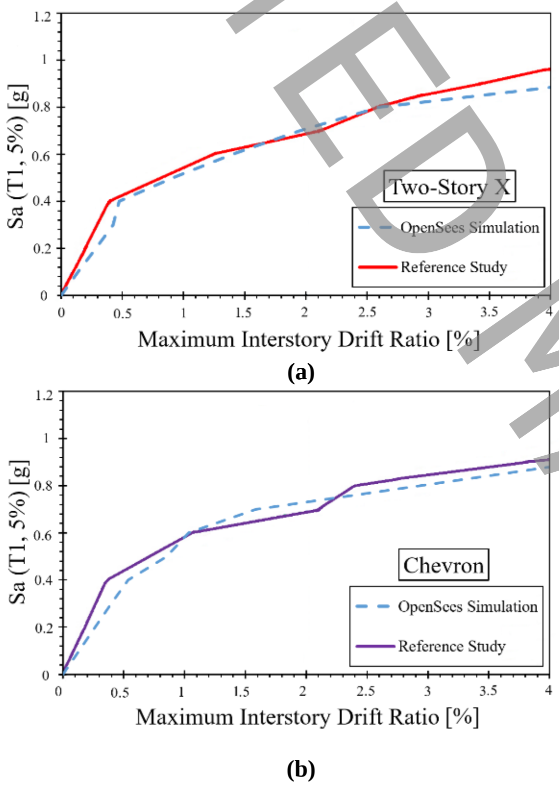

Figure 1. IDA verification (a) Two-story X-braced frame (b) Chevron frame

3. Results and Discussion

To compare the collapse probability of structures and for independence of the results from the first mode period, Sa(T1,5%) is divided into 1.5 times of the design spectra (Sa_{Norm} = Sa (T1, 5%) / 1.5AB×g), which is suitable for comparing the seismic performance of structures [10]. The normalized collapse fragility curves in 10% interstory drift ratio are shown in Figure 2.

According to Figure 2 (a), in 4-story structures, conventional X-brace frame has the best behavior at probability of less than 50% and performs worse than other models at probability of more than 50%. In the median and higher collapse probability, mega braces with spans ratio of 1 and 2 have almost the same performance and better than other models. According to Figure 2 (b), in 8-story structures, almost in whole of Sa_{Norm} range, mega brace with spans ratio of 1 has better performance than other frames, and with increasing the spans ratio to 1.5 and 2, performance of the structures has decreased. It is also observed that the performance of the eight-story structure with conventional X-brace is weaker than the mega braces.

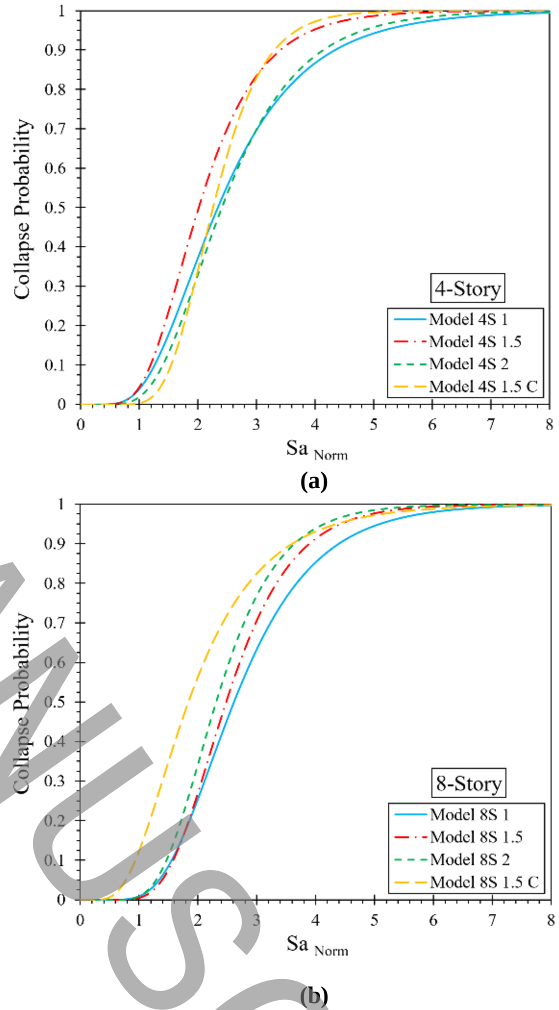

Figure 2. Normalized collapse fragility curves in 10% interstory drift ratio (a) 4-story frames (b) 8-story frames

Finally, in Table 1, according to the weight of the structures and the median of Sa_{Norm}, the performance of the structures in the 10% interstory drift ratio for collapse and the different levels of the Hazus technical manual are compared. Structural weight (W_T) is the weight of used steel for all members in three-dimensional structures. According to Table 1, in 4-story structures, the performance of mega brace with equal spans, is better than other structures, despite its lower weight. In the cases of unequal spans, and all performance levels of the Hazus except 10% interstory drift ratio for collapse, performance of mega braces is better than conventional X-brace frame.

Table 1. Comparison of weight and performance of the structures

Models	T_1 (Sec)	W_T (ton)	$Sa_{Norm50\%}$ 10% Drift	$Sa_{Norm50\%}$ Slight	$Sa_{Norm50\%}$ Moderate	$Sa_{Norm50\%}$ Extensive	$Sa_{Norm50\%}$ Complete
Model 4S 1	0.389	37.92	2.340	0.469	0.749	1.070	1.675
Model 4S 1.5	0.396	42.03	2.014	0.466	0.702	1.004	1.474
Model 4S 2	0.401	43.96	2.409	0.319	0.495	0.892	1.610
Model 4S 1.5 C	0.559	44.35	2.259	0.245	0.405	0.737	1.420
Model 8S 1	0.659	94.20	2.611	0.235	0.360	0.679	1.220
Model 8S 1.5	0.710	101.60	2.477	0.148	0.268	0.590	1.140
Model 8S 2	0.760	111.20	2.308	0.127	0.227	0.556	1.125
Model 8S 1.5 C	0.956	127.80	1.840	0.126	0.224	0.473	0.827

According to Table 1, In 8-story structures, mega brace with equal spans has the best performance at all performance levels and its weight much less than conventional X-brace frame. In eight-story mega brace frames, by increasing the middle to lateral spans ratio, the performance of the structures becomes weaker, but at all performance levels, they are better than conventional X-brace frame.

4. Conclusions

1. Among the four and eight-story special concentrically braced frames, by comparing the median of fragility curves, it was found that the mega brace frames with equal spans ratio, have the best performance and the lowest weight.

2. In four-story special concentrically braced frames with equal spans ratio, the performance of mega braces is better and more economical. Also, in different spans ratio, mega braces and conventional X-brace have almost the same performance, and each of them has its own advantages and disadvantages. But researchers believe that mega braces are better.

3. In eight-story mega brace frames, by increasing the spans ratio, the performance of the structures becomes weaker, but at all performance levels, they are better than conventional X-brace frame. In eight-story frames with spans ratio of 1.5, the weight of the mega brace frame is 20.5% less than the conventional X-brace frame.

4. In eight-story special concentrically braced frames with equal spans ratio, the performance of mega braces is better and more economical. Also, in different spans ratio, mega braces have a better performance than conventional X-brace and they are also very economical.

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