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Research Note

An investigation into the seismic behavior of single-story concrete frames equipped with metallic yielding dampers

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Abstract. Two one-story, single-span concrete frames with different bay to height ratios ($B/H < 1$ and $B/H > 1$) are considered in order to evaluate the vulnerability of concrete structures equipped with metallic Yielding Elements (YE) against earthquakes. The nature of damages in structures is based on the rate of absorbed energy. Therefore, investigating the behavior of structures based on energy concept is considered as one of the most important methods toward the designed structures against earthquake load. It requires to concentrate the absorbed energy on some yielding elements in order to reduce and/or avoid damage to the main elements. One powerful technique to retrofit existing structures and seismically design new concrete structures is the use of metallic yielding dampers. The metallic dampers function similar to a fuse by deforming during earthquake, which subsequently can be replaced by new ones. In this study, parametric studies based on static analysis are carried out to determine the best place and angle of these elements in the frames. Furthermore, the responses of these frames against three earthquakes are presented and comparison of results is performed. It is revealed that yielding element can dissipate up to 60 percent of earthquake energy in a concrete reinforced structure.

1. Introduction

In order to provide seismic resistance against earthquake and reduce damage in the main elements, it is required to minimize the absorbed energy in these elements. One way is to concentrate input energy into another element. Moreover by entering these elements into nonlinear region, they can dissipate a large amount of energy. By using yielding elements, the main elements such as beams and columns are prevented from entering into nonlinear region, even in severe earthquakes.

The more rigidity in concrete structures, the less ductility in them and this prevent their ability to effectively dissipate energy. Consequently, dissipating energy in concrete structures seems more challenging than it in steel structures. Yielding dampers function similar to a fuse by deforming during severe earthquakes and then being replaced by new ones.

Many authors have investigated the application of steel braces in concrete frames. One of the cases a designer may decide to use steel braces in a reinforced concrete frame is for retrofitting purposes. However, a number of engineers may use it in a new design as well. Massumi and Absalan [1] have investigated two experimental models of reinforced concrete frames. Both frames are designed according to old traditional codes, but one of them is strengthened by steel X-bracing. The finite elements model of both frames is

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made and analyzed as well. The experimental results show good interaction effects between reinforced concrete frame and steel bracing, especially in increasing system damping. Dominguez et al. [2] have presented the analytical results of two-dimensional reinforced concrete frames strengthened by chevron steel braces. They have concluded that when a proper design for these frames is performed considering the requirements of related codes, suitable ductility and over-strength demands are obtained.

The effect of eccentric bracing system on seismic fragility of mid-rise reinforced concrete frames is presented by Ozel and Guneisi [3]. They have obtained the improvement in seismic performance of mid-rise reinforced concrete frames from retrofits by different types of eccentric steel braces through the formulation of fragility reduction. Fu [4] have used a three-dimensional finite element modeling technique for analysis of the progressive collapse in multi-story reinforced concrete frames retrofitted by steel braces. He has recommended some measures to mitigate their progressive collapse.

Metallic yielding dampers have been considered in this study. They have several advantages as follows. No complicated technology is needed to manufacture them, they can easily be integrated in structures, they show stable behavior in earthquakes, and no environmental factors (temperature, humidity) affect their performance. In this research, responses of the single-story, single-span concrete frame equipped with yielding elements are investigated. Two concrete frames with different bay-to-height ratios ($(B/H) < 1$ and $(B/H) > 1$) are selected. In each frame, metallic dampers are connected to the intersection points of beam and column through appropriate steel brace elements. Linear static analysis is primarily performed. By dislocating the yielding element with different sizes along the width and height of frame, the best size and location of yielding element will be obtained in accordance to its performance.

In cases where the yielding elements are attached to the beam, different connection angles are investigated to find the best connection angle of YE to frame [5]. The stiffness ratio of concrete frames equipped with YE to a similar moment frame without any braces is utilized as a criterion to compare different locations and angles. Based on the results from static analysis, five models have been selected to perform nonlinear dynamic analysis. In this section, comparison of the maximum displacement along with base shear among frames equipped with the YE and ordinary moment-resisting frames is made to further demonstrate effective performance of the YE. Finally, the last section of this study is devoted to investigation of the ratio of dissipated energy by the YE to the total entering energy of structure. This ratio can show the efficiency of YE to dissipate the input energy.

2. Yielding steel dampers

The eccentrically-braced frames represent a widely accepted concept, where energy dissipation can be concentrated primarily on shear links. These links represent a part of the structural system which is likely to suffer from damage in severe earthquakes. The ability of braced frames to dissipate energy over extended periods is questionable because the repeated buckling and yielding of braces can cause degradation of their stiffness and strength.

Several devices which function as an integral part of the seismic isolation systems have been developed; one of these devices is referred to as Added Damping and Stiffness (ADAS) consisting of multiple X-shaped steel plates which was introduced by Bechtel Power Corporation [6].

Another example of such dampers is friction damper which has been proposed by Pall and Marsh [7]. This is a device which can be located at the intersection of cross bracings in the frame. When loaded, the tension brace induces slippage at the friction joint. Consequently, the four links force the compression brace to slip. In this manner, energy is dissipated in both braces even though they are designed to prevent slippage under normal service loads. Filiatrault and Cherry [8] and Aiken et al. [9] show the effectiveness of these devices in providing a substantial increase in energy dissipation capacity and reducing inter-story drifts in comparison to moment resisting frames without such devices. Filiatrault and Cherry [10] have developed a design method to estimate the optimum slip load distribution for the pall friction dampers. Moreover, these devices have been used in several buildings in Canada.

YE element as a part of bracing system was first used at Rome University, Italy in 1989. In the experimental test that was carried out, it showed very good energy dissipation properties [11]. Tajammolian and Mofid have used these elements in one-story steel structures. They have investigated the best location of these elements in the frame as well as seismic responses of the frames in different earthquake records. Their study has revealed that YE can dissipate up to 60 percent of input energy in a three-story steel braced structure.

3. Model properties

In this study, two types of frames have been considered. The first type of frames has 4 m of span and 5 m of height which represents the frames with $B/H < 1$ and the second type of frames has 5 m of span and

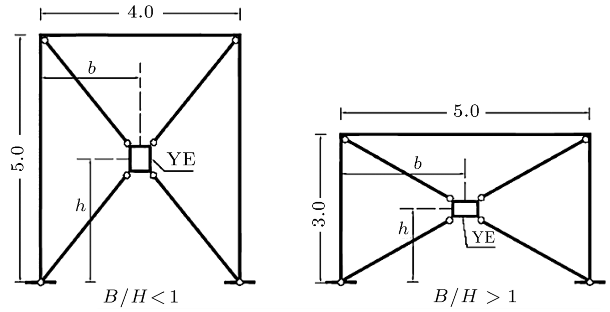


Figure 1. Investigated frames [5].

3 m of height. The second type represents the frames with $B/H > 1$ (Figure 1). The used concrete in this research is C30 with 30 MPa cylindrical strength after 28 days and 27000 MPa modulus of elasticity. The steel martial used for braces in YE elements is ASTM A36 with 25 and 37 MPa of yield and ultimate strengths, respectively.

The frames are parts of a three-dimensional structure with 8 m distance between adjacent frames and the Dead and Live loads are considered to be 5.5 kN/m^2 and 2.00 kN/m^2, respectively. The main structural system is moment resisting frame and the yielding elements have been added to the main structure by means of the bracing system. The seismic coefficient of frames is calculated according to ASCE 7 code [12] and the concrete design is performed based on Building Code Requirements for Structural Concrete [13]. The steel braces are proportioned according to specification for structural steel buildings [14] as well.

The designed sections dimensions are presented in Table 1. Note that the box-type steel elements have been used as brace and yielding elements, while the concrete beams and columns are typically rectangular sections. The required reinforcement of each section

Table 1. Designed sections.

Element	**Dimensions (mm×mm)**	
	$B/H<1$	$B/H>1$
Column	350×350	350×350
Beam	300×300	300×300
Brace	60×60×4	60×60×4
YE	40×40×4	40×40×4

has been calculated and used in linear as well as nonlinear analyses of the models.

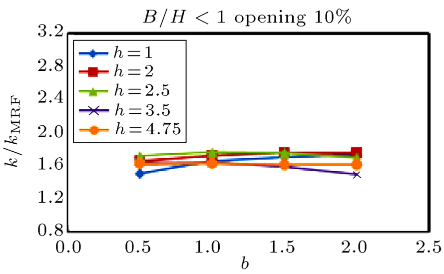
The important point is that the dimensions of yielding elements have to be appropriately proportional to the dimensions of the main frame; otherwise, the added part to the main frame can encounter instability and may practically play no role in suffering of lateral loads. At the preliminary design stage, the dimensions of yielding elements are selected as 10% of the dimensions of the main frame. Hereafter, we will denote the size of yielding element with respect to the main frame dimensions and will call it X% opening which means that the YE size is X% of the main frame dimensions. It should be noted that openings with 10, 20, 30, 40, and 50 percent of the main frame dimensions are utilized in this analysis.

4. Linear static analysis

4.1. Effect of YE location on frame stiffness

The parameters '**b**' and '**h**' are used to show the location of yielding element in the frame; '**h**' represents the distance of the center of yielding element from the ground surface; and '**b**' represents the distance of the center of yielding element from the left column, as it is indicated schematically in Figure 1. Evidently, due to symmetry, locating the yielding element at the left or right of the frame makes no difference. Consequently, we only consider displacement of the yielding element from the left column to the center of frame. In order to make a comparison and provide better understanding, the lateral stiffness of frames (k) is normalized to that of a similar moment resisting frame without any braces stiffness (kMRF). The results are presented in Figures 2 and 3 for frames with $B/H < 1$ and $B/H > 1$, respectively. Note that the trends of changes in all the models with different openings are very similar, therefore only the 10% and 50% opening graphs are presented.

It can be seen that the 10% opening YE has added 60 and 40 percent to the frame stiffness in $B/H < 1$ and $B/H > 1$ frames, respectively. This value is 30 and 10 percent in $B/H < 1$ and $B/H > 1$ frames for the 50% opening damper. So smaller YE causes more stiffness in the system. As Figures 2 and 3 denote, location of



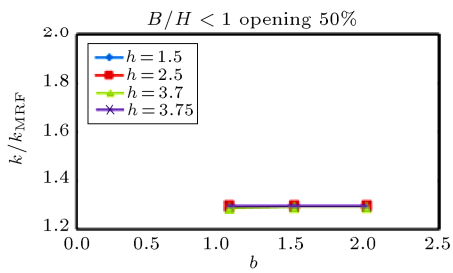


Figure 2. Normalized stiffness of frames with $B/H < 1$.

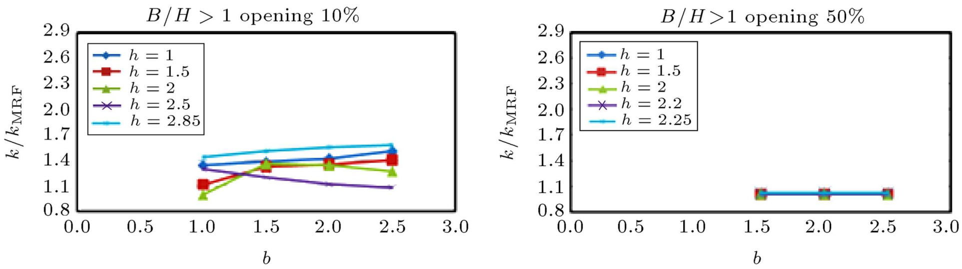


Figure 3. Normalized stiffness of frames with $B/H > 1$.

the yielding element has no role in the stiffness changes of concrete frames. This issue seems reasonable as in all cases the concrete frame plays the main role in stiffness of the whole frame. As a result, we will locate the YE at the middle of the frame for future analyses.

4.2. Effect of the connection angle of yielding elements on the frame's stiffness

In this section, effect of the connection angle of yielding elements on the frame stiffness is investigated. As can be seen in Figure 4, by decreasing the angle, the yielding element turns to a triangle element, and by increasing this angle, it turns to an isosceles trapezoid. In this section, we only use the models in which the yielding elements are connected to the beam.

Like the previous section, the stiffness of frames with different YE angels connected to the top beam

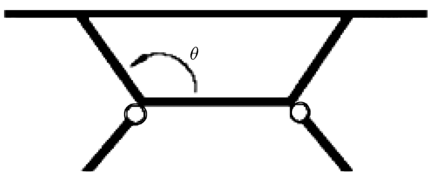


Figure 4. Connection angle [5].

of frame is normalized to the stiffness of a frame with no brace and YE. The results are presented for YE with 10 and 50 percent openings for $B/H < 1$ and $B/H > 1$ frames in Figures 5 and 6. It can be seen that the YE with a shorter connecting angle leads to more stiffness in the frame as it is similar to a chevron brace connecting to a top beam in a frame. We will select a triangle which has the most stiffening effect as well as trapezoidal YE with less stiffness for analyses in future sections.

5. Nonlinear dynamic analysis

In this section, the effect of yielding elements with different shapes, which are selected according to the previous section, on the real behavior of frames subjected to an earthquake is investigated. The elements, which are used in the nonlinear dynamic analysis, are listed in Table 2. Rectangular YE at the middle and top of the frame, triangular and trapezoidal YE connected to the top beam of frame, and a circular YE at the middle are investigated. The YE dimensions identified as the opening percent are varied from 10 to 50 percent of the main frame dimensions. Note that in triangular

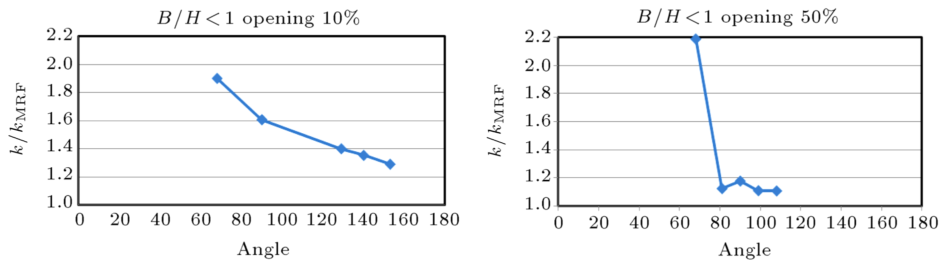


Figure 5. Normalized stiffness of frames with $B/H < 1$ for different connection angles.

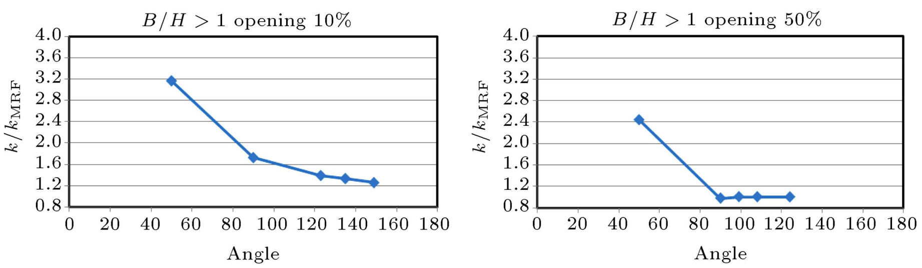


Figure 6. Normalized stiffness of frames with $B/H > 1$ for different connection angles.

Table 2. Different YE models in nonlinear dynamic analysis.

Model	YE location in frame	YE shape	YE section (mm)
Mid	Middle	Rectangular	Box 40×40×4
Mid cir	Middle	Circular	Box 40×40×4
Top	Top	Rectangular	Box 40×40×4
Top 68	Top	Triangular	Box 40×40×4
Top 153	Top	Trapezoidal	Box 40×40×4

and trapezoidal elements, the dimensions refer to their bottom width as well as their height. In the circular element, we refer to the rectangular element that is surrounded by the circle. After creating the models under consideration, nonlinear dynamic analysis is performed; the results will be presented in the next section. The maximum displacement and base shears of the models in different earthquakes are also shown.

The Newmark-Beta is a method of numerical integrations used to solve differential equations and is chosen to solve the governing differential equations in this research with $\beta = 0.25$ and $\gamma = 0.5$. The OpenSees program is utilized for nonlinear dynamic analysis of the models [15].

The elastic-perfectly plastic material is used to obtain axial force in braces. The related backbone curve is presented in Figure 7. Due to probability of buckling in compression, the yielding stresses in tension and compression differ from each other and are not equal.

To model the bending property of concrete beams and columns, a concrete material object with tensile strength and linear tensions softening is employed as indicated in Figure 8.

To define the bending property of yielding elements, a uniaxial bilinear steel material object with kinematic hardening and optional isotropic hardening, described by a non-linear equation, is used. This material is identified as steel01 in OpenSees (Figure 9).

The models are analyzed for three different earthquake records: Elcentro (1940), Gazli (1976), and Northridge (1994). In all cases, the interval of 0.01 second is used for nonlinear analysis and the analysis is continued up to the 50th second of records. The scaling of earthquake records is performed in accordance to DBE spectrum of ASCE 7-10 code.

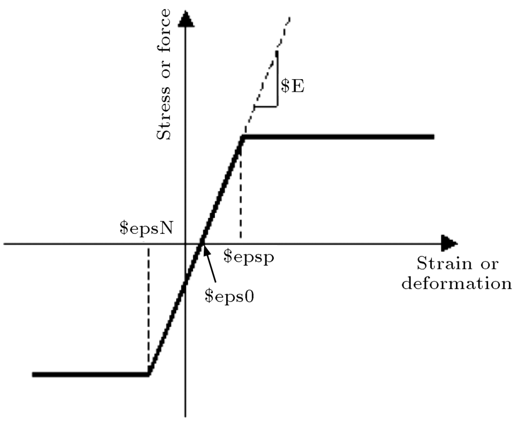


Figure 7. Elastic perfectly plastic material [15].

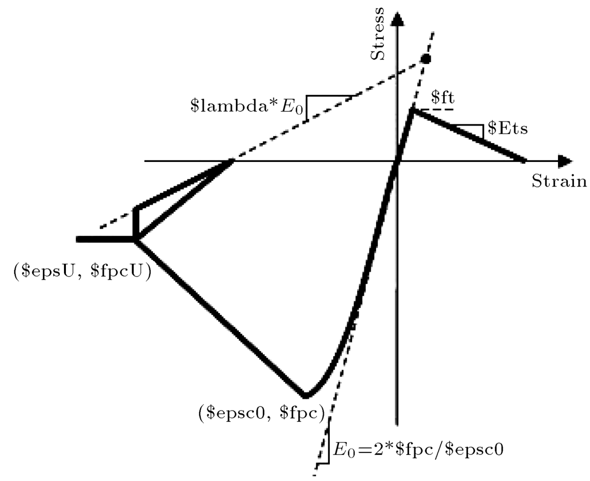


Figure 8. Concrete with tensile strength [15].

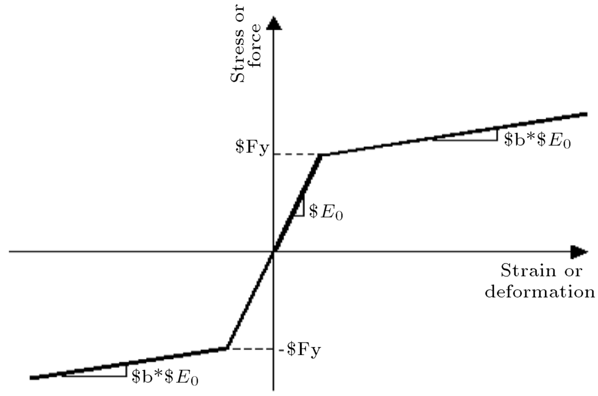


Figure 9. Uniaxial bilinear steel material (Steel01) [15].

Displacement of the frames with $B/H < 1$ and $B/H > 1$ in three earthquake records are illustrated in Figures 10 and 11. Figures 12 and 13 show the base shear of these frames as well.

As can be seen in the above-mentioned frames, the triangular model at the top of frame, identified as "Top-68", has the smallest displacement and the greatest base shear in all three earthquakes. The reason is the greatest stiffness of the frame which was discussed before. The frame with a circular YE in the middle has the least stiffness in comparison with other frames; therefore, it has the largest displacement and the smallest base shear. The characteristics and behavior of a frame with rectangular YE are very similar to those of a circular one.

Figures 10 to 13 denote that increasing the opening size of YE will increase the displacement, but has no effect on the base shear. Therefore, it can be

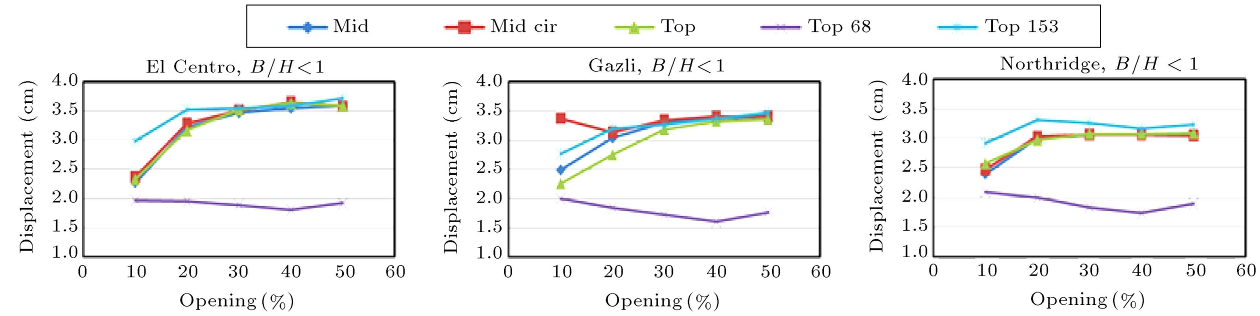


Figure 10. Displacement of frames with $B/H < 1$.

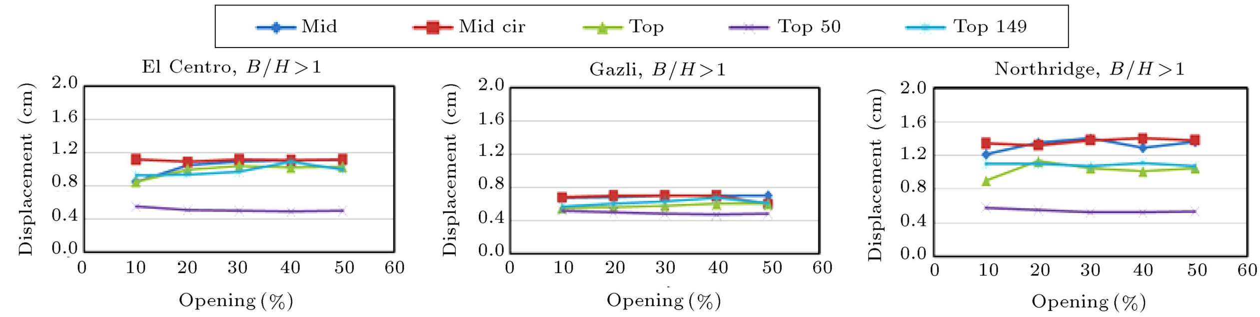


Figure 11. Displacement of frames with $B/H > 1$.

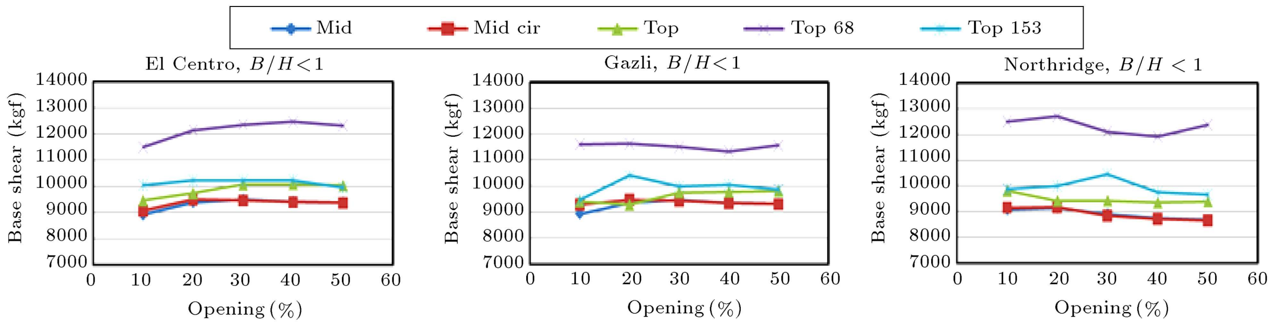


Figure 12. Base shear of frames with $B/H < 1$.

concluded that the elaborately smallest YE will have better performance in the reinforced concrete frame in addition to that it is more practical.

6. Investigation into the different types of energy in models

Energy balance in a structure can be written as follows:

$$E_I = E_K + E_E + E_P + E_x, \quad (1)$$

where E_I is earthquake input energy, E_K is kinematic energy, E_E and E_P are energies dissipated by elastic and plastic deformation of frames, respectively, and E_x is the dissipated energy by viscous damping [16]. The ratio between plastic deformation energy to the input one (E_P/E_I) is a good indicator that can reveal the ability of a yielding damper in dissipating the earthquake energy [17,18].

To obtain the amounts of different types of energy in the studied frame, a post-process code was used which can calculate the input and hysteresis energies of structure by integration. Hysteresis to input energies ratio is calculated as a criterion for nonlinear behavior of frames. In these analyses, only the results of YE with 10 and 20 percent sizes are presented. It was discussed before that larger YE is not so efficient.

Figures 14 and 15 show the ratio of hysteresis energy to input energy of the structures for each of the models after 50 seconds of loading in Northridge and Gazli earthquakes. These figures reveal that 10%-opening rectangular YE in the middle of frame has the most ratio of dissipated energy. It has dissipated near 60 and 30 percent of the input energies of Northridge earthquake in $B/H < 1$ and $B/H > 1$ frames, respectively. The triangular YE connected to the top beam of frame has the least amount of energy dissipation which is nearly zero in different earthquakes. In addition,

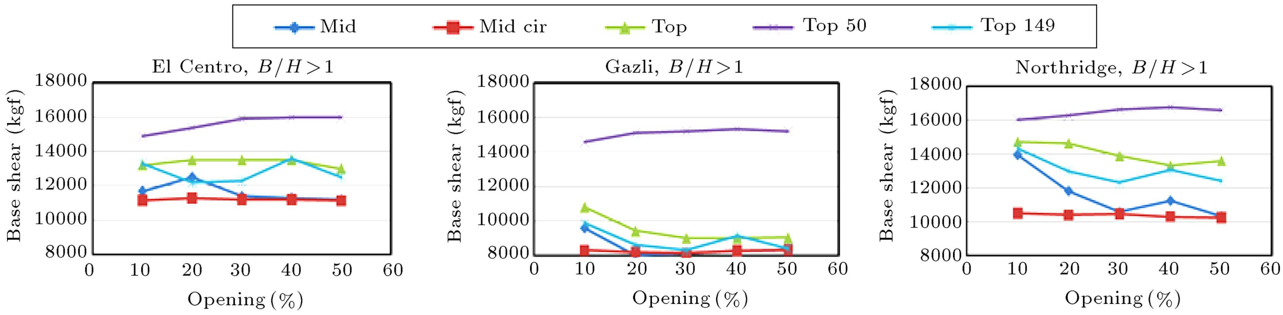


Figure 13. Base shear of frames with $B/H > 1$.

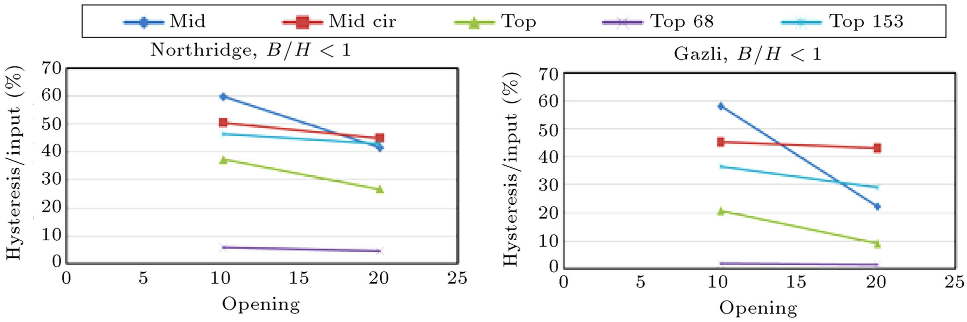


Figure 14. Ratio of the hysteretic to the input energy in frames with $B/H < 1$.

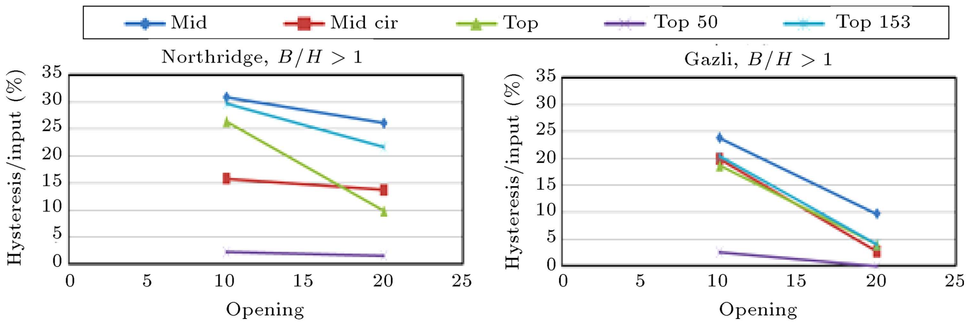


Figure 15. Ratio of the hysteretic to the input energy in frames with $B/H > 1$.

the results denote that the YE with a bigger size will dissipate less energy.

7. Conclusion

In this investigation, a parametric study was conducted to discover sensitivity of concrete frames to the location of metallic YE, which was attached through steel braces to the main frame. Then the responses of frames with different YE shapes, such as displacement and base shear, were investigated in three earthquake records. Finally the ratio of hysteresis to input energy of frames is calculated. In the following, a summary of the main results of this study is presented:

1. The effect of location of the yielding element along height and width of the frame is not noticeable.
2. The larger the dimension of yielding element becomes, the more the effect of such elements in stiffness of the frame decreases and the closer comes their performance to the performance of a moment resisting frame without yielding element. In the case of 10% opening, the presence of yielding element increases the stiffness of frame up to 1.7 times the stiffness of the simple case without yielding element.
3. By decreasing the connection angle and changing the shape of element to a triangle, the stiffness of frames dramatically increases. This effect is due to elimination of one element (turning to triangle) from an original shape of the yielding element. On the other hand, by increasing the angle, the stiffness of frame slightly decreases and it seems that it will have more effective performance against input earthquake energy.
4. Smaller YE causes more stiffness in frames and reduces displacements. The reason is that by increas-

ing the dimensions of yielding elements, the stiffness of frames decreases and the maximum displacement increases. In addition, in the frames equipped with each type of YE except the triangular one, base shear variations are not distinguished. Among all the aforementioned shapes, the triangular yielding element dramatically decreases the displacement and increases the base shear. This is interpretable when considering the noticeable effect of triangular element on the stiffness of frames.

5. The above tables and figures have a reasonable coincidence with the results of Section 4 regarding the behavior of main elements of the frames. As obtained from the charts, the triangular yielding element shows an unacceptable nonlinear behavior, thus its hysteresis absorbed energy is negligible. Using such an element as a yielding element is not advisable at all. By increasing the dimensions of yielding elements from 10% of the dimensions of the frame to 20%, the rate of the hysteresis absorbed energy decreases. Among all the models which are mentioned, the yielding elements with the dimensions of 10% in the middle of frame have the best performance.

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