Comp. Meth. Civil Eng., Vol. 3, 1 (2012) 51-62

CMCE
Computational Methods in Civil Engineering

Parametric studies of seismic behavior of steel frames equipped with yielding elements

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Received 14 May 2012; accepted in revised form 17 August 2012

Abstract

Yielding elements (YE) are among those devices that not only help control structural damages, but make better seismic behavior by concentrating the frames in some removable part of the structures. YE are located at the intersection of Concentric Braced Frame (CBF) in a rectangular shape. In this paper, Seismic behavior of the frames with YE will be investigated. For this reason, 5 braced steel frames with different stories (3, 5, 7, 10 and 15) equipped with yielding elements and diverse opening percentages (10, 20, 30, 40 and 50) are modeled in the Opensees software. At first, through a linear static analysis, the stiffness of these frames is investigated, taking into account changes in the size of the YE and the increasing height of the frames. Subsequently, through some nonlinear dynamic analysis, an attempt is made to investigate their seismic behaviors including stiffness and resistance in different records of earthquake. Finally, the R factor of those optimized frames is calculated. The results show the efficiency of these elements in making a better seismic behavior.

Keywords: Seismic behavior; Yielding damper; Steel brace; R factor; Nonlinear dynamic analysis.

1. Introduction

In order to alleviate the earthquake related structural damages, it is required to minimize the absorbed energy in their main elements (i.e. beam and column). Distributing of input energy among different elements is the most commonly used method which is also being investigated in the current research. This energy distribution prevents beams and columns entering into nonlinear region, even in case of their exposure to severe earthquakes.

The behavior of Concentric Braced Frame (CBF) equipped with YE is another aspect being investigated in this paper. Here, the yield property of steel is used in the added central part of the bracing system to make their behavior better. YE are designed in such a way that these could get into nonlinear region and absorb the input energy due to earthquakes.

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In continuation, the paper investigates response of the aforementioned frames of different stories. Here, 5 types of 3 span frames with 3, 5, 7, 10 and 15 stories which are equipped with YE are chosen with different opening percentages (10, 20, 30, 40 and 50). Interestingly, through linear static analysis, changes in the frames stiffness are investigated by changing the dimension of YE as well as increasing the height of the frames after obtaining the optimized opening for YE. Also, it examines the nonlinear dynamic behavior of those frames against 4 given records of earthquakes. A comparison of drift of stories, shear forces and moment in beams and columns between frames shows the efficiency of the YE. Finally, considering the effect of increasing number of stories, the R factor of those frames is obtained.

2. Behavior of yielding element (YE)

The YE as a passive energy dissipater was first utilized at Rome University in Italy in 1989. It was part of a braced system that showed appropriate energy dissipation characteristics [1].
A concentric braced frame (CBF) has satisfactory lateral stiffness but it cannot dissipate energy very well. Further, due to the nature of its behavior in buckling the braces during severe earthquakes, the lateral load causes tension in one brace while compression in the other. In other words, the compressive brace buckles with the increasing lateral load. In the next cycle, the lateral load direction changes but the buckled brace is unable to bear tension (Figure 1). Consequently, it is not appropriately able to withstand tension unless the plastic deformation of the buckled brace is removed.

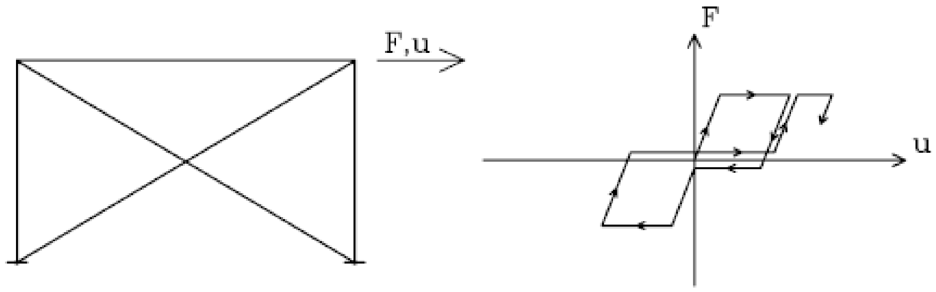

Figure 1. Behavior of frames with concentric brace.

On the other hand, although the moment-resistance frame (MRF) has reasonable capability on the energy dissipation behavior, it still needs big and heavy steel profiles to control the story drifts. As a matter of fact, its design is less economical [2].

The braced frame equipped with YE is similar to the frictional ‘Pall’ system [3], [4]. As the YE yields in a severe earthquake, it can pull back the buckled brace to its initial shape and help make it capable of withstanding tension in the next cycle (Figures 2 and 3). In addition, the YE yielding can dissipate the input energy through stable hysteretic loops caused by loading and unloading cycles. Therefore, the proposed system has advantages of both braced and moment frames. Moreover, any quake-related damage will be concentrated in the YE alone because it allows the main beams and columns to be intact in an intensive ground motion [5].

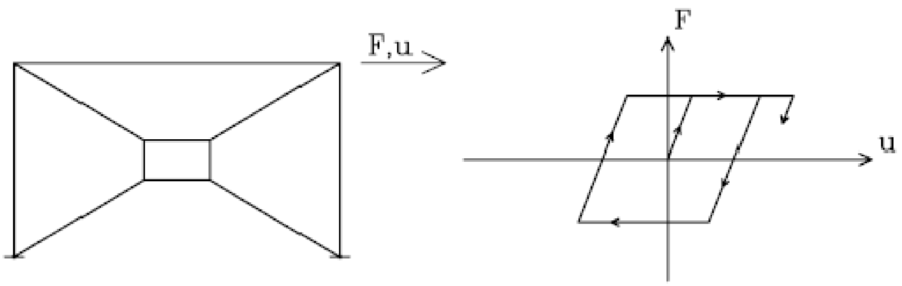

Figure 2. Behavior of frames with YE.

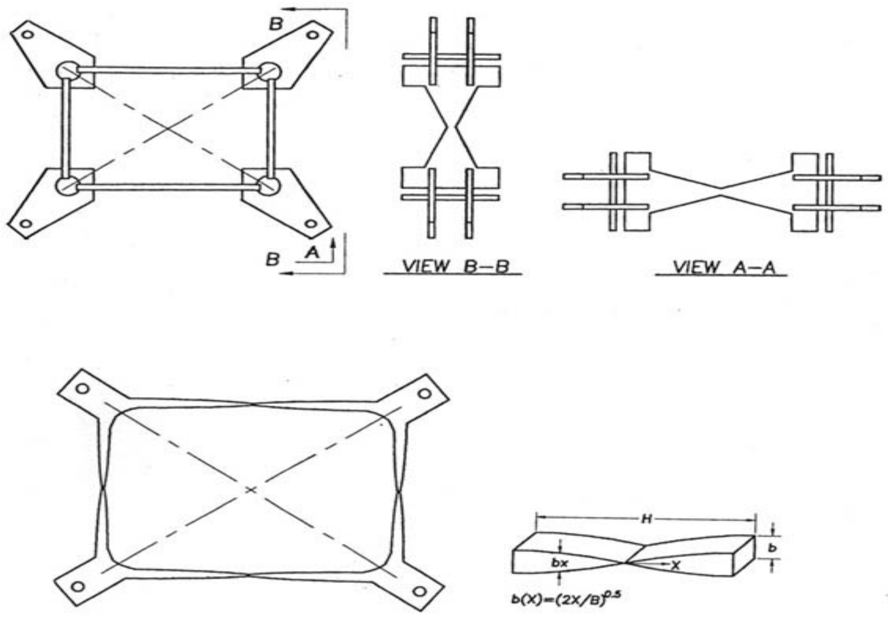

Figure 3. Two types of YE.

Following are the five steps showing the behavior of frames equipped with the YE against earthquakes (Figure 4):

1. Both braces are in elastic area hence, they are active in tension and compression forces.
2. An increasing tension force in Brace 1, a little compression force causes Brace 2 to buckle.
3. Brace 1 yield with an increasing tension force but before that phenomenon the YE is deformed. And that action leads Brace 2 that had buckled before, to change it to the smooth position.
4. When the direction of an earthquake loading is changed, Brace 2 is ready to suffer tension forces.
5. A cycle of hysteresis behavior is shown in this step.

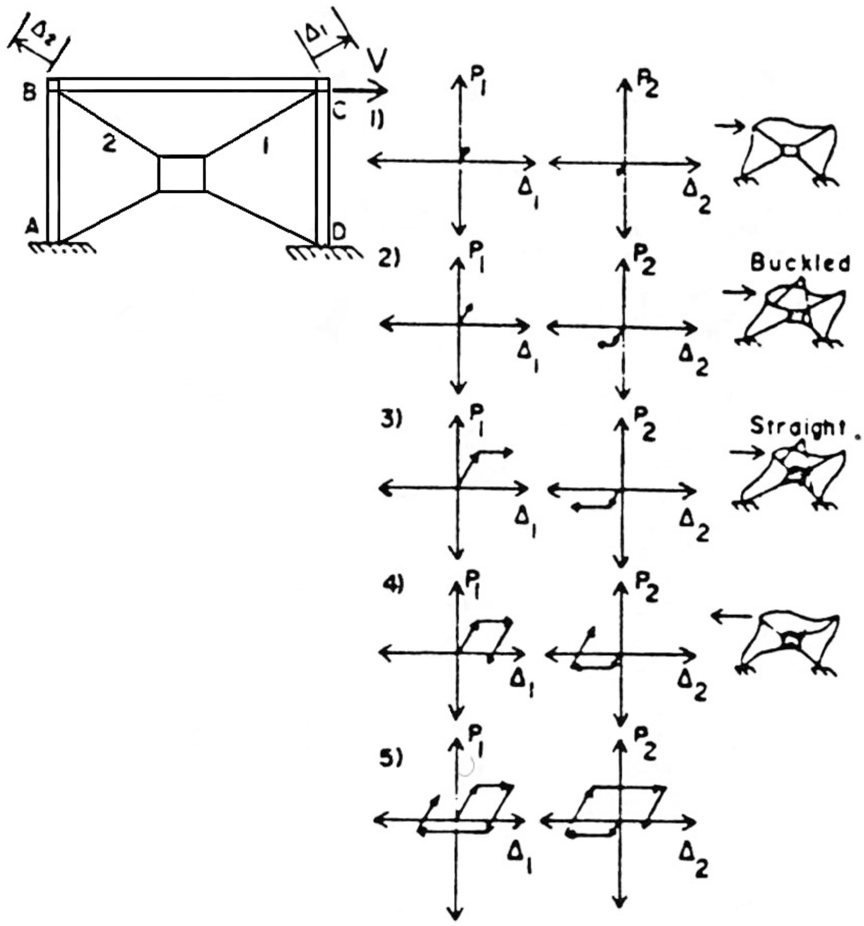

Figure 4. Behavior of frames with YE against earthquake loading.

3. Model properties

Figures 5 and 6 show 5 types of steel frames selected with different number of stories (3, 5, 7, 10 and 15). The frames have height equal to 9, 15, 21, 30 and 45 meter for 3, 5, 7, 10 and 15 story buildings respectively. In all frames the length of buildings is equal to 15 meter. Dead and live loads are 5.5 KN/m^2 and 2 KN/m^2 respectively. The moment resisting frame is the main structural system whereas the YE is added to the main system by bracing which has simple connections.

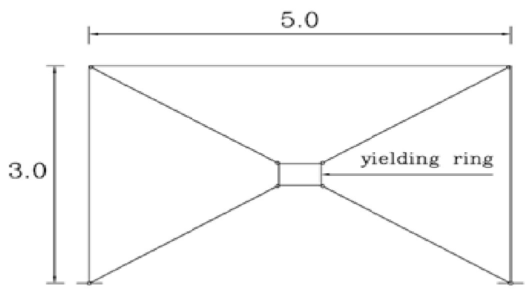

Figure 5. General types of the studied frames.

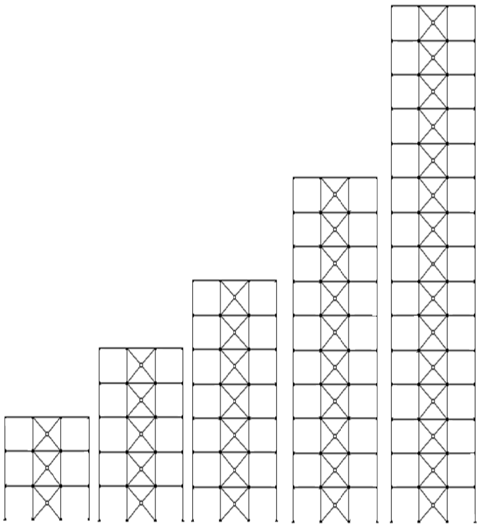

Figure 6. Different stories of studied frames with 10% opening.

The height and width of the YE must be appropriately proportional to the dimension of the main frame. In other words, (YE height/Frame story height) = (YE width/Frame span width) otherwise; the YE will be unstable and will hardly play any role in withstanding the lateral load [2 and 5]. For the initial design, the seismic loading is performed based on Uniform Building Code UBC-97 [6] and the base shear coefficient (C) is obtained equal to 0.125. AISC 2005 code [7] is used for designing the elements against loading.

4. Linear static analysis

In the first step, the variation of frames stiffness is investigated by considering changes in opening percentages and increasing in number of stories. The stiffness of each frame is calculated and normalized to the stiffness of the moment-resistance frame (MRF) with same dimensions and no bracings (K/K_{MRF}). In each frame, its stiffness is considered with the inverse roof displacement. The five different YE sizes in each frame are analyzed with 10%, 20%, 30%, 40% and 50% of the main frames dimensions, respectively. It means that the ratio of the YE frame area to the main frame area in each floor is 0.1, 0.2, 0.3, 0.4 and 0.5. The results indicate that this ratio is constant for all selected frames, which are highlighted in Figure 7.

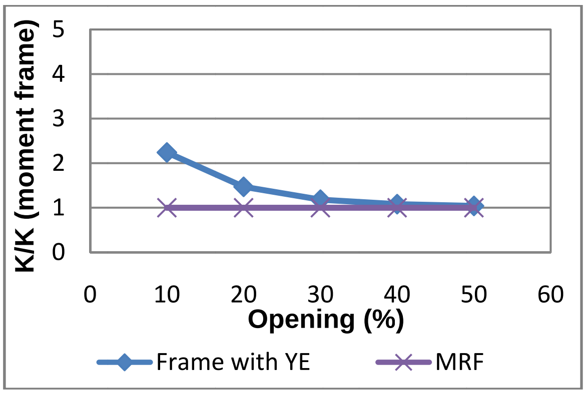

Figure 7. Normalized stiffness of frames with different openings.

5. Nonlinear dynamic analysis

The nonlinear dynamic analysis is performed via Opensees which is the finite element software and has enough capabilities to model the nonlinear behavior of differential elements. Table 1 presents the main periods of the frames.

Table 1. The main periods of the frames.

Frames	T (Sec.)
3	0.58
5	0.91
7	1.26
10	1.75
15	2.70

Flexural behavior of beams, columns and the YE is determined by bilinear diagram with 3% hardening in the second line. For its verification, some models are analyzed by SAP2000 software (a numerical analysis method) and the results show the correctness of the result. It means that the roof displacements are the same in both modeling. The inherent structural damping ratio is assumed to be about 5% of the critical value. The Newmark-β method with β=.25 and γ=05 is used to solve the governing differential equations. In the current research, four earthquake occurrences are selected for the time history analysis which includes:
1- El Centro 1940
2- Gazli 1967
3- Northridge 1994
4- Tabas 1978

Although, the study doesn't consider the interaction between soil and structure in its course, it tries to choose earthquakes in such way that it represents all four soil groups i.e. A, B, C and D included in USGS classification. PEER website proved helpful for references in choosing earthquake records (Pacific Earthquake Engineering Research, University of California, Berkeley). The PGA of all four earthquakes is scaled with 0.35g. Table 2 shows specifications of proposed four records.

Table 2. Specifications of applied records.

Earthquake	Year	M	Station	PGA(g)	Number of Point	dt(sec)	Duration (sec)	Scale
El Centro, Imperial valley	1940	6.95	El Centro Array #9	0.313	4000	0.01	40	1.118
Gazli, USSR	1976	6.8	Karakyr	0.718	3253	0.005	16.265	0.487
Northridge, California	1994	6.69	LA - Chalon Rd	0.225	3107	0.01	31.07	1.556
Tabas, Iran	1978	7.35	Tabas	0.852	1642	0.02	32.84	0.411

Figures 8 to 12 highlight the drift of the frames for 3, 5, 7, 10 and 15-story, respectively. And, Figures 13 to 16 show shear forces and moment in beams and columns.

Due to similarity in results of different records of earthquakes, only the outcome of frames against record of Electro has been shown. For better understanding and more comprehensive comparison, each quantity is normalized with a similar quantity in MRF. It means $(\mathrm{Drift})_{YE}/(\mathrm{Drift})_{MRF}$ and $(\mathrm{Shear\ force})_{YE}$ / $(\mathrm{Shear\ force})_{MRF}$ and $(\mathrm{Moment})_{YE}$ / $(\mathrm{Moment})_{MRF}$

charts are drawn for each frame with different stories against aforementioned record of earthquakes. The graphs show that YE have good behavior in decreasing the drift compared to the MRF. According to the same results, the YE also cause to decrease the shear force and the moment in the main structural elements (beams and columns). However, it is important to note that an increase in the dimension of YE increases the tension value in the main elements of frames to the extent that the YE with 10% opening percentages has the most effect on decreasing the tensions value there.

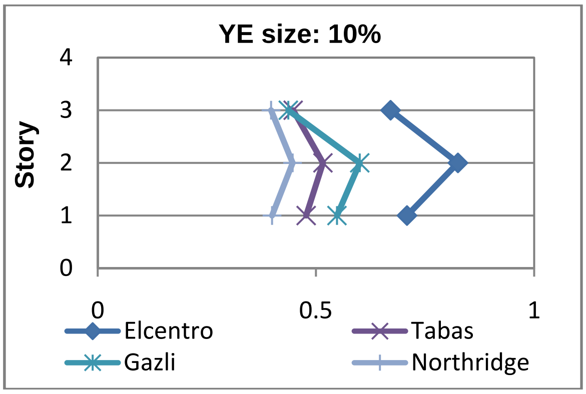

Figure 8. Normalized drift of frames with different stories in four earthquakes, 3-Story.

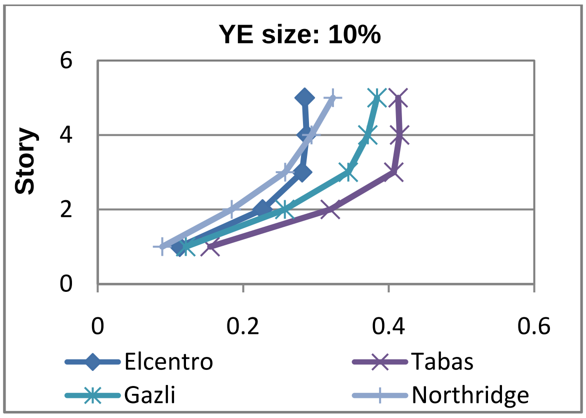

Figure 9. Normalized drift of frames with different stories in four earthquakes, 5-Story.

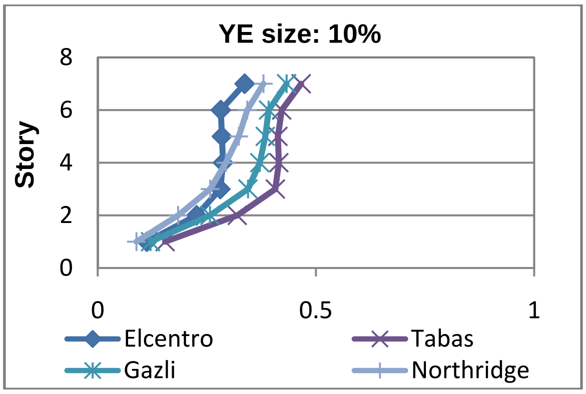

Figure 10. Normalized drift of frames with different stories in four earthquakes, 7-Story.

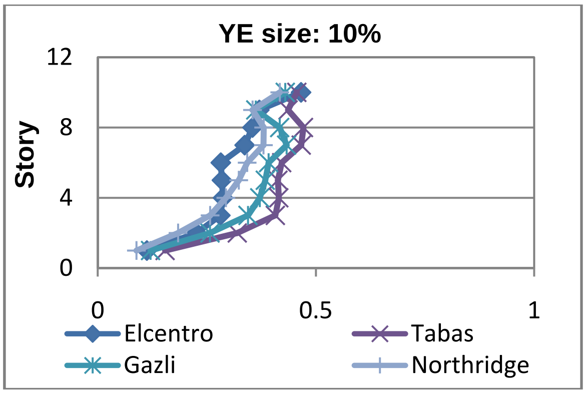

Figure 11. Normalized drift of frames with different stories in four earthquakes, 10-Story.

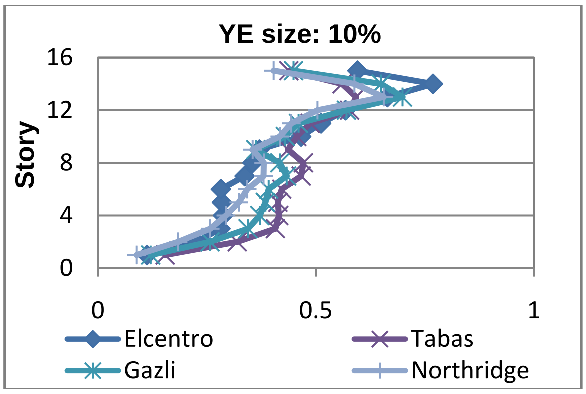

Figure 12. Normalized drift of frames with different stories in four earthquakes, 15-Story.

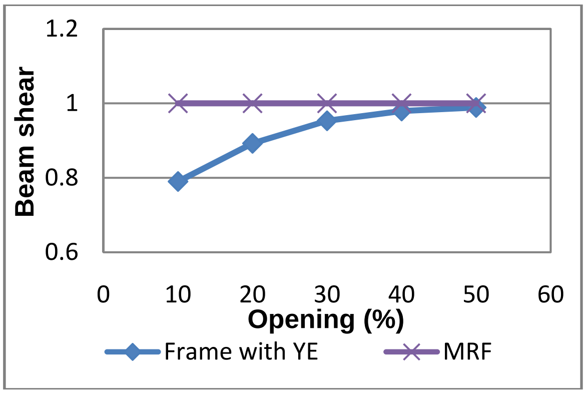

Figure 13. Normalized forces of beam (first floor and first span) with different opening in 3-story frame.

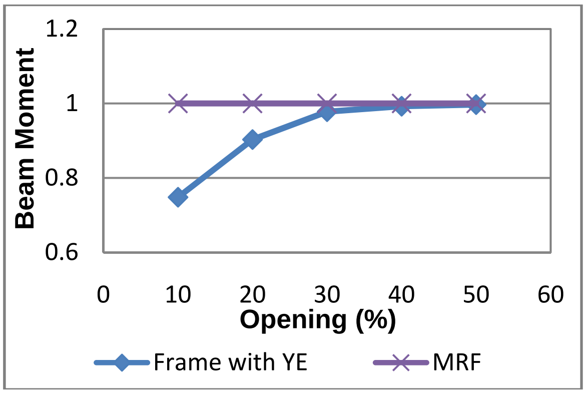

Figure 14. Normalized forces of beam (first floor and first span) with different opening in 3-story frame.

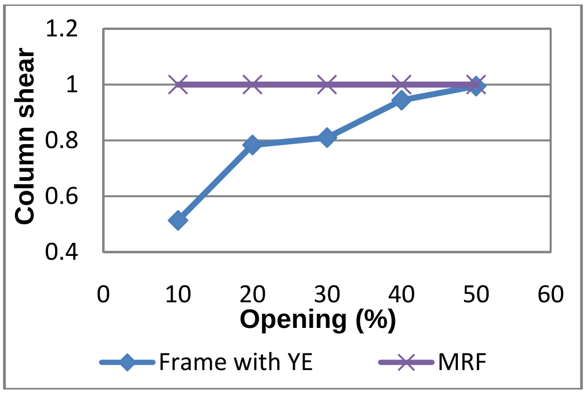

Figure 15. Normalized force of column (first floor and first span) with different opening in 3-story frame.

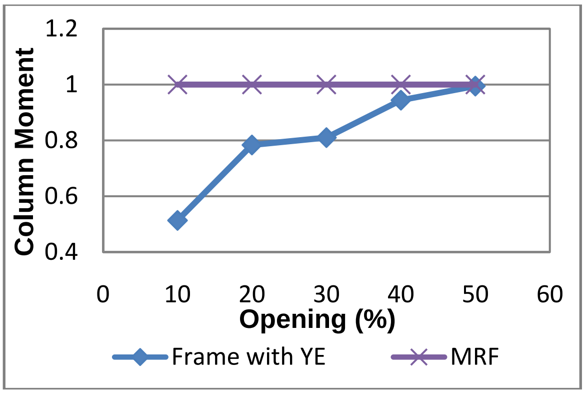

Figure 16. Normalized forces of column (first floor and first span) with different opening in 3 story frame.

6. Pushover analysis

6.1. Response modification factor

The elastic analysis of structures exposed to earthquake could create base-shear force as well as stresses which noticeably are bigger than the real structural response. In a structure, overstrength means the maximum lateral strength generally exceeds its design strength. As such, seismic codes reduce design loads, taking advantage of the fact that structures possess overstrength and ductility. In fact, the response modification factor includes inelastic performance of structure and indicates overstrength and structural ductility [8].

For computing the response modification factor, Mazzolani and Piluso [9] addressed several theoretical aspects such as the maximum plastic deformation, energy and low cycle fatigue approaches. As Figure 17 shows, the real nonlinear behavior is usually idealized by a bilinear elasto-plastic relation [10].

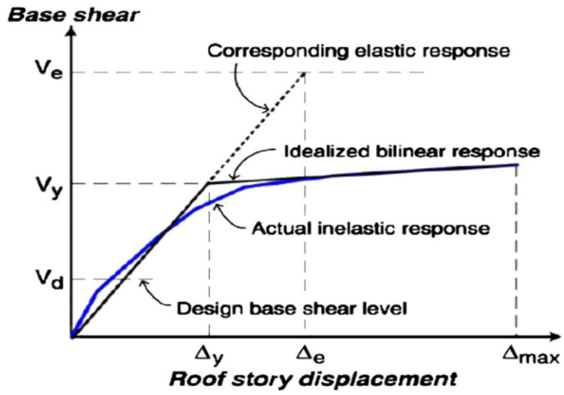

Figure 17. Lateral load-roof displacement relationship of structure [10].

Here, the yield force and the yield displacement of structure are shown by V_y and Δ_y, respectively. In this figure, V_e (V_{max}) corresponds to the elastic response strength of the structure [8]. Consequently, the response modification factor is determined as follows [11]:

$$R = R_{\mu} \cdot R_s \tag{1}$$

where, R_{μ} is a reduction factor due to ductility and R_s is the overstrength factor.

6.2. Reduction factor due to ductility

As mentioned, R_{μ} is a parameter to measure the global nonlinear response of a structure, due to the hysteretic energy. The maximum base-shear ratio is called force reduction factor due to ductility considering the elastic behavior V_e to the yield force of structure V_y :

$$R_{\mu} = \frac{V_e}{V_y} \tag{2}$$

Several proposals have been put forward for R_{μ}. In a complete version proposed by krawinkler-nassar [12], the reduction factor is written as:

$$R_{\mu} = (C(\mu - 1) + 1)^{\frac{1}{c}} \tag{3}$$

$$C = \frac{T^a}{T^a + 1} + \frac{b}{T}$$

Krawinkler's R_{μ} factor depends on fundamental period of system (T), ductility factor (μ) and strain hardening ratio (α). It is assumed that the value of strain hardening ratio equals to zero in this paper. According to Krawinkler's proposal, when α=0, the value of a, and b are equal to one and 0.42 respectively [12]. The μ is the structural ductility factor defined as:

$$\mu = \frac{\Delta_{max}}{\Delta_y} \tag{4}$$

where, Δ_{max} is the maximum displacement for the first life safety performance in structure and Δ_y is the yield displacement observed there.

6.3. Overstrength factor

As observed during some of the intermittent quake occurrences, it seemed building structures could take force considerably larger than they designed for. This phenomenon is explained by the presence of significant reserve strength that was not accounted in design [11].

To make it more lucid, overstrength could help structures stand safely not only against sever tremors but it reduces the elastic strength demand, as well. This object is performed using the force reduction factor [13]. Here, the design overstrength factor (R_s) is defined as [11]:

$$R_s = 1.15 \frac{V_y}{V_d} \tag{5}$$

where, V_d is the design base-shear in the building and V_y is the base-shear in relevance to the first life safety performance (Figure 17). In steel structure, the value of 1.15 is consider for difference between actual and nominal static yield strengths and increase in yield stress as a result of strain rate effect during an earthquake. Other parameters such as nonstructural component contributions as well as the variation of lateral force profile could be included once a reliable data is available [8].

In this paper, the R factor of aforementioned models is obtained through pushover analysis. The reverse triangular loading model is used for the lateral loading of the proposed frames. Figure 18 shows the R factor of these frames. Further, these values are compared with the R factor of the same MRF. Results show that the R factor decreases with the increasing of the height of the frames.

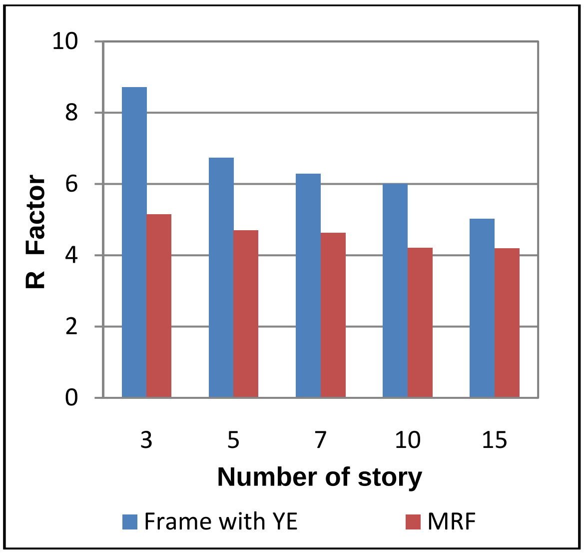

Figure 18. R-factor of optimum frames.

7. Conclusion

As mentioned, the yielding elements (YE) are among those devices that control the structural damages. Apart, they help make better seismic behavior by concentrating the frames in some removable part of structure. In this paper, 5 braced steel frames with different stories (3, 5, 7, 10 and 15) equipped with yielding elements as well as different opening percentages (10, 20, 30, 40 and 50) are modeled using the Opensees software. Finally, an attempt was made to evaluate the R factor for the structures equipped with those elements. The study summarizes the results as follow:

1. YE increase the stiffness and decrease the drift values.
2. As figures showed, the behavior of frames against different earthquake records is very similar. Consequently, it is assumed that the YE behavior is not sensitive to those records and the 10% opening percentages in YE is the optimized dimension.

3. R factor of frames decreases with the increasing of the number of stories or in the other words increasing of the height of structures.

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