



Comparison of Seismic Behavior of Buckling-restrained Braces and Yielding Brace System in Irregular and Regular Steel Frames under Mainshock and Mainshock-Aftershock

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ABSTRACT

Due to low stiffness of braces after yielding, the structures with buckling-restrained braces (BRBs) experience high residual drifts during an earthquake, which can be intensified by aftershocks and causes considerable damages to structures. Also, due to poor distribution of stiffness, this problem is exacerbated for irregular structures. Recently, the yielding brace system (YBS) has been introduced; which is an alternative to BRBs to solve this problem. YBS has a secondary stiffening part in its hysteresis behavior which can prevent excessive deformations. Therefore, structures with YBS are expected to show a better performance in seismic sequences compared to BRBs. However, the seismic behavior of the YBS system in irregular structures has not been studied so far. On this basis, this paper investigates the seismic behavior of frames with BRB and YBS in regular and irregular structures under seismic sequences. Twenty four 4-, 8-, and 12-story frames with these two systems were designed and evaluated. First, a nonlinear dynamic analysis was conducted on the frames under mainshocks, and the maximum interstory drift and the residual interstory drift of the frames were compared. Then, using incremental dynamic analysis and fragility curves, the behavior of the frames under mainshocks was investigated. Afterwards, using incremental dynamic analysis and fragility curves, the behavior of the structures under mainshock-aftershock in three performance levels was also investigated. The results showed that YBS bracing, especially in low rise structures, leads to far lower maximum drifts and maximum residual drifts than BRB braces, which can reduce the probability of the occurrence of soft stories in structures.

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1. INTRODUCTION

Centrically braced frames are one of the building systems, which are very popular because of their ease of implementation and their cost-effectiveness in dealing with earthquake forces. However, these systems have behaved well against the earthquakes in recent decades. They have lower ductility and energy absorption capacity as compared to the moment-resisting frames. The main problem with these braces is their buckling under

compressive forces leading to differences between compressive and tensile strengths of these braces and decreased strengths of them under compressive forces leading to differences between compressive and tensile strengths of these braces and decreased strengths of them under cyclic loading. Accordingly, buckling-restrained braces were introduced in 1989 for the first time, in which compression buckling of bracing could be avoided by its confinement [1]. Buckling-restrained braces yield in tension and compression, showed an ideal hysteretic behavior [2]. Therefore, the residual drift is unpredictable

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and depends on the excitation characteristics. Previous studies have shown residual drifts of greater than 0.005 rad on average for DBE and greater than 0.01 for MCE earthquake [3]. Sabelli et al. [4] investigated seismic response of two mid-rise BRB frames. They first discussed the properties of such braces and then reported the effect of structural configurations and proportions on response parameters. They observed that residual story drifts of the structures were 40 to 60% of the maximum drifts. Christopoulos et al. [5] investigated residual drifts of BRB and SMRFs. They designed structures with 2- to 12-stories according to ASCE7-05 and conducted pushover analysis on the structures. Their results showed that both systems experienced large residual drifts.

In vertically irregular structures, structural stiffness varies at different floors. Therefore, the distribution of forces is not uniform in height, which can intensify the problem of creating excessive residual drifts. Chen et al. [6] conducted a shaking table test and a numerical analysis on a vertically irregular frame. The results showed that earthquake influence coefficients for irregular frames are larger than values of the design code. Yuen et al. [7] investigated seismic performance of vertical irregular RC frames. They performed nonlinear dynamic analysis on 6 prototype buildings and concluded that the irregularity has a significant effect on the nonlinear response and lateral stability of the structures under earthquake. Seismic performance of vertically irregular steel moment frames were studied by Lee et al. [8]. Their results showed that presence of higher mass at higher stories can cause larger story drifts for the entire building. Mwafy and Khalifa [9] investigated the effect of vertical irregularity in tall buildings. They modelled and analyzed four 50-story buildings with different irregular configurations. They concluded that structures with geometric irregularities showed larger drift profile than the corresponding regular structure.

On the other hand, recently it is proved that seismic sequence (mainshock with aftershock) is a phenomenon that can cause more extensive damages in comparison to mainshock only. The key parameter for structures to withstand against aftershocks is residual drift under mainshock which can amplify the extent of damages due to aftershocks [10]. Li et al. [11] conducted mainshock-aftershock analyses on a typical steel moment frame. They carried out nonlinear time-history and fragility analyses and found out larger mainshock residual drifts can adversely influence the aftershock performance. Darvishan et al. [12] assessed aftershock collapse potential of BRB frames. Using Incremental Dynamic Analysis (IDA), they employed a probabilistic approach to estimate aftershock fragility and hazard curves. Results showed that considering aftershock in analysis yields more probability of collapse.

A study on the effect of multiple earthquakes on the seismic response of a testbed structure was carried out by

Ruiz-García and Aguilar [13]. By a postmainshock IDA analysis they observed that IDA curves under seismic sequence have less spectral acceleration compared to mainshock-only case.

Recently, Yielding Brace System (YBS) is proposed by Gray et al. [14]. This system features secondary hardening that prevents higher drifts. In addition, the bracing mechanism of YBS is simple without the complexities of the modeling and construction of other braces. Therefore, this bracing can be used as an alternative to BRB in regular and irregular structures to withstand against seismic sequences. However, the number of studies conducted on the seismic behavior of YBS is small, and the behavior of irregular frames and also mainshock-aftershock performance of these systems has not yet been investigated.

Accordingly, in the first stage, the behavior of regular and irregular structures equipped with CSY fuses and BRB braces under seismic loads has been investigated. Twenty four 4-, 8-, and 12-story frames have been modeled with irregularity in mass. Nonlinear and incremental dynamic time histories were analyzed for structures under mainshocks, and the structural responses such as interstory drift and the residual interstory drift were investigated. So, in the next step, in order to understand the effect of residual drifts resulting from mainshock on the behavior of the structures in aftershocks, the response of these structures under seismic sequence was also investigated.

2. BRB AND YBS BRACING SYSTEMS

Since most of the problems in concentric braced frames are due to the buckling of braces (the difference between compressive and tensile strength) as well as the reduction of the bracing strength under cyclic loads, numerous studies have been carried out by researchers to build bracings with ideal elastoplastic behavior in tension and compression. In fact, the bracing has a good behavior in tension, and if its buckling can be avoided by its restraining, the compressive strength of bracing is also increased, showing a completely symmetric hysteretic behavior. Although BRB bracing systems have resolved many problems of the concentric braces, there are also some weaknesses, a number of which are referred to in the following [15]:

Due to the presence of a metal shell around the bracing core, it is not possible to check and inspect it, and therefore, it is difficult to identify the failures in these braces. Also, another important issue in BRB braces is the dependence of the ultimate strength of bracing on its stiffness. Since, in a bracing span, the only parameter that can be changed by the designer is the BRB bracing cross-section, and in buildings with a large number of floors, it is important to observe the regulations on controlling the interstory drifts, BRB braces with higher cross-sectional

area must be inevitably used to meet the required stiffness. However, the system resistance will be higher than required in this case. Therefore, the design of the system will be regarded as non-economic.

Another approach to improve the bracing system behavior is to concentrate the structural damages to a single element or a bunch of elements, so that during an earthquake, the concerned elements can enter the plastic phase earlier than other members and protect other structural members from damage, while being easily replaceable. Such a member acts as a fuse, the performance of which is to prevent damages to other structural elements [16]. Researchers have recently developed a kind of steel fuse that can be used in concentric braced frames. This fuse is referred to as steel yielding fuse. This fuse attached to the end of the brace is designed to provide a non-elastic stable response through the bending of a series of fingers (see Figures 1 and 2). This fuse is named cast steel yielding fuse or CSY fuse. Also the system that equipped with CSY fuse is named yielding brace system or YBS.

As Figure 2 shows, at the end of the yielding fingers, there is a cylindrical protrusion on which there is a cavity to transfer the force to the bonding plates through the bolts and nuts. The bolts transmit the shear force at the end of the fingers to two bonding plates. If the cavity on the two plates is of a typical circular type, due to the large bending of the fingers, a second-order chainlike force is exerted on the bonding plates by the fingers [17]. To avoid this, the holes on the bonding plates are selected to be of long slotted hole type, which allows for higher

deformations at the fingers, such that as a result of the large bending, the ends of the fingers can move within the slot in a direction perpendicular to the braces, and prevent the creation of the second-order axial force within the fingers. However, when the fingers are bent excessively, their axial stiffness is also added to the stiffness of the entire system, which increases the stiffness of the system when subjected to high drifts. This behavior allows the fuse to even show a post-yield stiffening behavior even after yielding, and this will make its hysteresis cycle unique [18].

The elastic stiffness as well as the axial force triggering the yielding of fuse fingers is determined by the following equations [15]:

$$K = \frac{nb_0Eh^3}{6L^3} \tag{1}$$

$$P_p = \frac{nb_0h^2F_y}{4L} \tag{2}$$

In the above relations, n is the number of fingers, F_y and E are the characteristic yield stress of steel and its Young's modulus, respectively; L , b_0 and h are the length, width (breadth) and thickness (height) of the finger, respectively. Due to the series connection of the fuse to the end of the bracing, the ultimate stiffness of both elements is determined by serial summation of the fuse stiffness and bracing stiffness (E/AL).

Seismic energy is dissipated by the yielding fingers of the cast steel connector. At large deformations, the fingers yield in flexure and due to second order geometric effects, post-yield stiffness of the brace increases. Therefore, it can withstand larger forces in large drift. If P is equal to the force generated in the finger in the main direction of the fuse, and P_p is the shear force perpendicular to the main direction of the fuse fingers (this direction is perpendicular to the main direction of the fuse), for higher bending of fingers, one can associate the component perpendicular to the finger bending for any desired value of bracing drift (δ) with its axial load according to Equation (3):

$$P = \frac{P_p}{\cos(\frac{2\delta}{L})} \tag{3}$$

Gravity loads have been calculated in accordance with the National Building Regulations of Iran (Loads Imposed on Buildings) [19]. Seismic loading for designing the models examined in this study is based on Iran's 2800 Standard, Fourth Edition [20]. Therefore, given that the studied structures meet the mass irregularity requirements in elevation in accordance with the code, spectral analysis has been used for initial design and calculation of seismic force. The structures under study are located in Tehran, and are constructed on soil

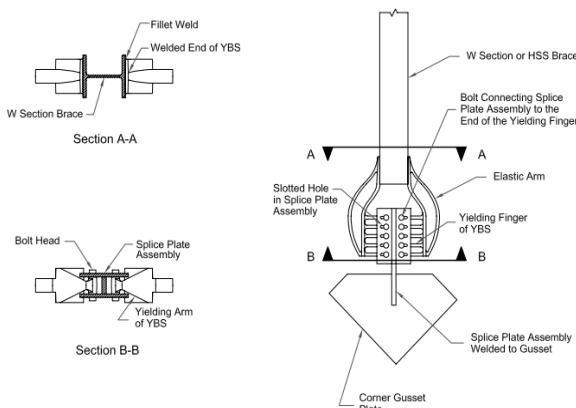


Figure 1. Bracing and fuse components [14]

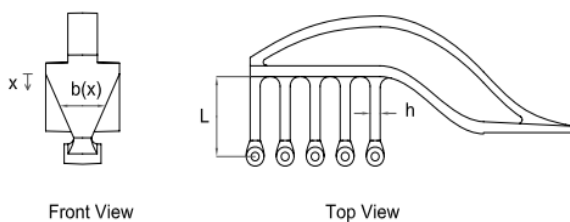


Figure 2. CSY fuse and its parameters [11]

type II. Also, according to the recommended values of the YBS system design guide, the initial behavior factor for designing structures is assumed to be $R=8$ [21]. The design of beam and column of frames has been in compliance with the National Building code (Edition 2014) [22], and seismic codes are also in compliance with the AISC 341-10 Code [23]. Given the fact that there is still no regulation introduced for the design of YBS braces, Both BRB and YBS systems were modeled with the same elastic stiffness and yield point, so that their behavior could be compared.

Using the above equation, one can plot the load-displacement diagram for the fuse (Figure 3). As the diagram shows, the fuse also exhibits a hardening behavior at higher ductility values after yielding.

Given the constant curvature of the bending fingers, using the second moment-area theorem, the strain within the fingers can be calculated for a given drift (δ), therefore, assuming the maximum strain of the flexural axis of ϵ_b within the finger, we have:

$$\delta = \Phi(L)\left(\frac{L}{2}\right) = \left(\frac{\epsilon_b}{h/2}\right)\left(\frac{L^2}{2}\right) = \frac{\epsilon_b L^2}{h} \tag{4}$$

$$\Rightarrow \frac{\epsilon_b}{\delta} = \frac{h}{L^2}$$

Thus, the drift of the end of the finger is associated with h and L^2 . Also, one can show the following relation:

$$K_{fuse} = \frac{P_p E}{1.5 F_y} \left(\frac{\epsilon_b}{\delta}\right) = \frac{P_p E}{1.5 F_y} \left(\frac{h}{L^2}\right) \tag{5}$$

3. DESIGN AND MODELING OF STRUCTURES

3. 1. Design of Structures All models are two-dimensional with three 6-meter spans. The frames are considered to be joined by pin joints, and also, the height of the stories is 3 meters. The bracing used in buildings are of Chevron type. Twelve frames have YBS fuse

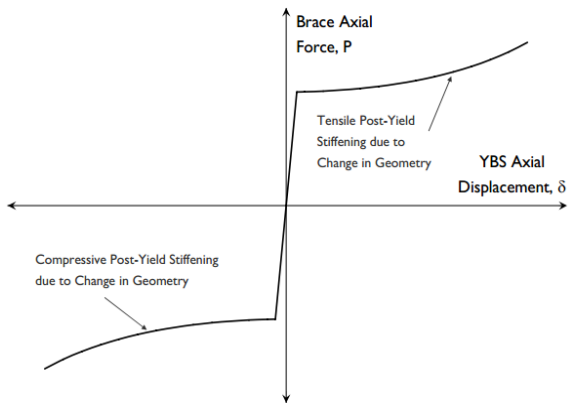
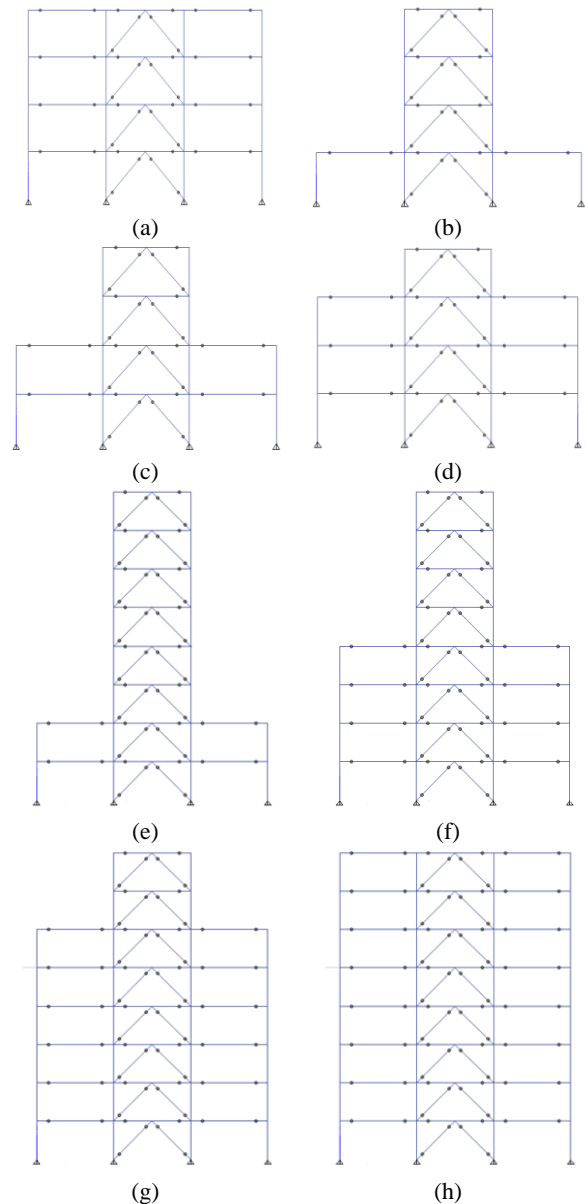


Figure 3. Load-displacement diagram for the fuse [14]

bracing system, and also, twelve frames have BRB bracing frames. There are four models of four-story structures, four models of eight-story structures, and four models of twelve-story structures. It should also be noted that in models of the same height, three models are considered to have mass irregularities in structural elevation, and one model is a regular frame (Figure 4). From left to right, irregularities occur at one quarter, one-half, and three-fourths of the height of structures.

3. 2. Structural Modeling In this study, OpenSEES software is selected because of its high speed and ability to perform heavy processing of time history analyzes. Due to the hinge joints, Beam and column stay linear. So these elements was modeled as “element elasticBeamColumn”.



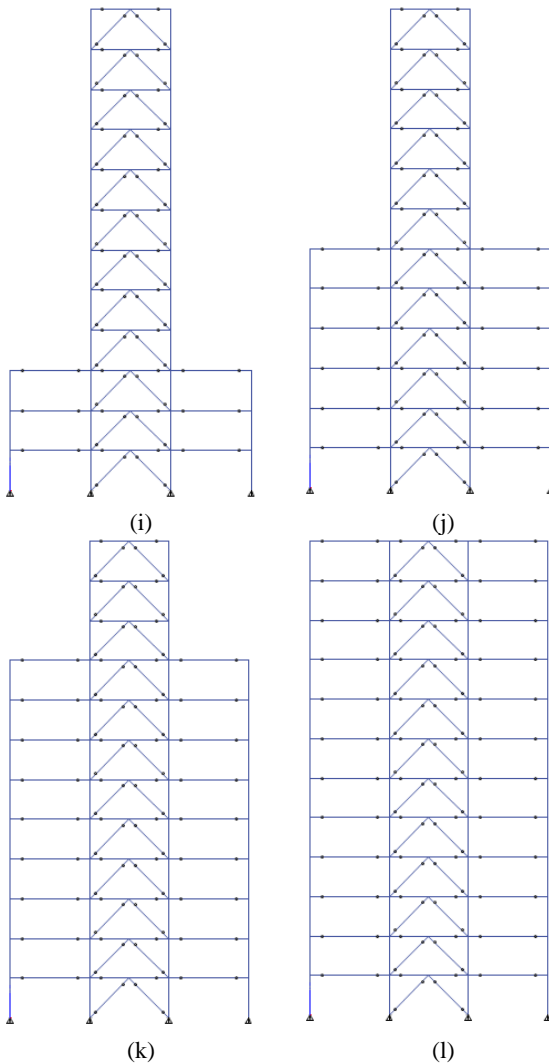


Figure 4. Regular and irregular structural models, (a) 4.1, (b) 4.2, (c) 4.3, (d) 4.4, (e) 8.2, (f) 8.4, (g) 8.6, (h) 8.8, (i) 3.12, (j) 6.12, (k) 9.12, (l) 12.12

Structural member mass, dead load plus 20% of live load, according to 2800 standard, are placed at the end nodes of each column elements. In nonlinear dynamic analysis Riley’s method is used to consider damping:

$$C = \alpha M + \beta K \tag{6}$$

Where C is the damping of the system, K and M are the stiffness and mass matrices, respectively. α and β are calculated from the following equations:

$$\alpha = \xi \frac{2\omega_1\omega_2}{\omega_1 + \omega_2} \tag{7}$$

$$\beta = \frac{2\xi}{\omega_1 + \omega_2} \tag{8}$$

In these relations ω_1 and ω_2 , the natural frequencies of the system, are assumed in the first and third modes.

3. 3. YBS Fuse Modeling

In order to model the

YBS fuse, the CastFuse materials were used in OpenSEES software with a yield strength of 3600 kg/cm² and a modulus of elasticity of 2000000 kg/cm² and the slope of the non-elastic region is estimated to be 2% according to Gray et al. [24].

The fuse is assumed to be about $\frac{1}{5}$ of the length of the bracing and also the remaining $\frac{4}{5}$ of the length is a conventional bracing designed for the fuse, and the two elements are connected to each other in series. Therefore, the elastic stiffness of the same set should be designed to match that of the elastic stiffness of the bracing. The point that should be noted is that the modeling of such a system acts appropriately in tension in OpenSEES, and the ultimate stiffness is equal to the serial summation of that for the bracing and the fuse, but when compressed, the joint connecting the brace and the fuse leaves its direction, and the system suffers convergence error. To overcome this problem, another point is defined in beam-column nodal points the coordinates of which are the same as those of the main point that is bound to the main node when moving in x and y directions, but it is rotationally independent of the main node. Two dummy column elements are defined between this node and the node between the fuse and the brace (as shown in Figure 5) with a high flexural rigidity, but the axial rigidity is extremely insignificant. For this purpose, the moment of inertia of the column should be extremely large, but the cross-sectional area should be extremely small.

To set the modeling parameters, the developed models should be verified by laboratory test results. Gray et al. [15] applied cyclic loading test on a CSY fuse. Fuse specifications and the method used to apply its cyclic loading are available in literature [21]. The laboratory hysteresis cycle and its calibrated numerical model are shown in Figure 6(a).

3. 4. Buckling Restrained Brace Modeling

In order to model the buckling restrained brace, the uniaxialMaterial Steel02 were used in OpenSEES software with a yield strength of 2400 kg/cm², modulus of elasticity of 2000000 kg/cm² and the slope of the non-elastic region is estimated to be 2%. Since only axial force acts on the brace, and it is pin-ended, a corotational truss element is used, which is a pin-ended element. The materials used in the bracing core are assumed to be of the st-37 type. The strain limit is assumed to be in

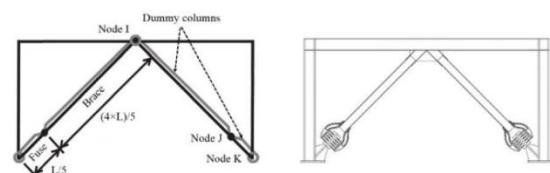


Figure 5. Modeling of YBS frame in OpenSEES

accordance with literature [25]. This limitation is imposed by using MinMax materials. This technique was also used by other researchers [26]. The laboratory hysteresis cycle and its calibrated numerical model are shown in Figure 6(b).

4. PERFORMANCE LEVELS FOR STUDYING THE BEHAVIOR OF THE STRUCTURES UNDER THE MAINSHOCK AND MAINSHOCK-AFTERSHOCK

One of the advantages of incremental dynamic analysis is the use of its results in determining the dynamic capacity of a structural system at various performance levels. In other words, after exposure to seismic loads, in terms of their behavior, the structures are classified as follows:

1. Immediate Occupancy (IO) Level: At this level, due to the occurrence of earthquakes, the strength and stiffness of the structural members do not change significantly, and it is possible for immediate use.
2. Life Safety (LS) Level: At this level, the occurrence of earthquakes imposes damages to the structure, but the extent of the damages is not enough to cause a loss of life.
3. Collapse Prevention (CP) Threshold Level: At this level, an earthquake imposes widespread destructions to the structure, but the building does not collapse and the

mortality rate is minimized.

4. Global instability (GI) Level: At this level, the structure is destroyed and its roof collapses.

In the following section, we introduced the performance levels for the YBS and BRBF systems: These four performance levels have been defined in this paper for the maximum engineering demand parameter to investigate the behavior of the structure under the mainshock and mainshock-aftershock. At first performance level, the difference between BRB bracing behavior and other bracing systems is negligible. Thus, for the BRB system, the same values recommended in FEMA-356 instruction are used for Immediate Occupancy performance level [27]. In this publication, for structures with conventional bracing, the maximum lateral interstory drift ratio is considered to be 0.5%. Also, a negligible value is considered for residual interstory drift ratio for this level of performance, which is equivalent to 0.25%. Christopoulos et al. [28] considered the threshold of the maximum interstory drift ratio of 1% as a failure criterion of structural elements in buckling restrained braced frames. Therefore, this criterion has been used as the second performance level. They also suggested the residual interstory drift ratio equivalent of this level as 0.5%. For the third performance level, the maximum interstory drift ratio of 2% is considered in accordance with the AISC 341-10 provisions. For this performance level, no value has been proposed for the residual interstory drift ratio. Therefore, the value of 0.75% was selected as the average of the two values of 0.5 and 1%; which were introduced by Christopoulos et al. [28] as the criteria for the initiation of structural failures and the collapse of the structures with buckling-restrained braces, respectively. At the fourth performance level, the structure actually loses its lateral load bearing capacity, and it collapses. This performance level can be found at a point of the IDA curve, where the failure intensity parameter of IDR_{max} (maximum interstory drift ratio) increases significantly in case of a slight increase in the seismic intensity of the maximum ground acceleration. To put it simply, the horizontal lines at the end of the IDA curve indicate the collapse of the structure. Because with a slight increase in maximum ground acceleration, IDR_{max} will dramatically increase, indicating the poor lateral structural strength. Also, Christopoulos et al. [28] introduced a residual interstory drift, such as 1%, as the collapse point in buckling-restrained brace frames.

Since the YBS system is a new structural system, no definite performance level is specified for it in former regulations and literature. Here, due to the great similarity of this system with the buckling restrained braced frames system, we have used the results of the studies conducted to define the performance level of the buckling restrained braced frames. So because of the failure to report the performance level values for the YBS bracing system so far, as well as comparing the

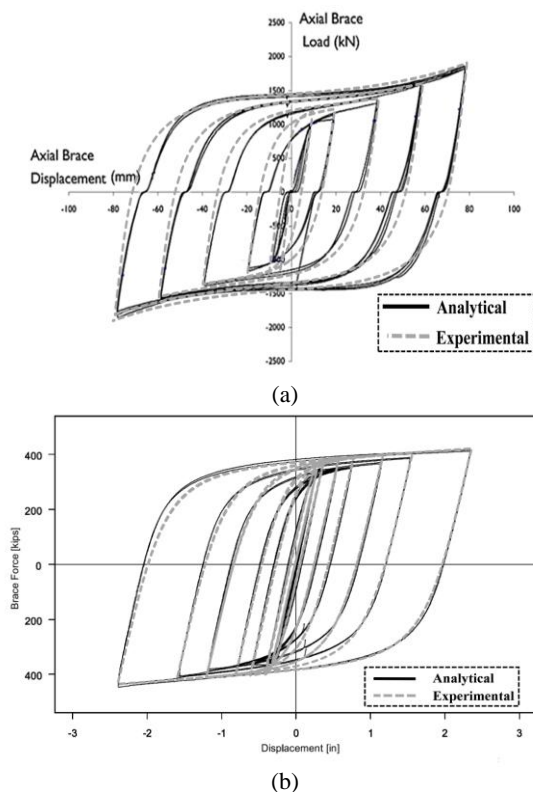


Figure 6. Modeled hysteretic load-deformation curves (a) YBS, (b) BRB

performance of both systems, the same values as the BRB system are also used for this system.

As it comes from IDA curves that derived from incremental dynamic analysis of frames under mainshock-aftershock, in this case, for most of these frames, initial interstory drift ratio is more than 0.5 and initial residual interstory drift ratio is more than 0.75. So the second, third and fourth performance levels have been used in this paper for the maximum failure intensity parameter of IDR_{max} to investigate the behavior of the structures under mainshock-aftershock. Also, the fourth performance level has been used for the maximum failure intensity parameter of $RIDR_{max}$ to investigate the behavior of structures under mainshock-aftershock.

Table 1 shows the performance levels values. In this table, IDR_{max} is the maximum interstory drift ratio, $RIDR_{max}$ is the maximum residual interstory drift ratio.

5. SELECTING THE SEISMIC RECORDS FOR THE STUDY OF BEHAVIOR UNDER THE COMBINED EFFECTS OF THE MAINSHOCK AND ITS AFTERSHOCKS

One of the most important factors in incremental dynamic analysis is determining the records imposed on the structure; because the analysis results are all conveying and resulted by the effect of the records imposed on the structure. Selecting the type of record is not a matter of taste, because this should be done in such a way that the results obtained from the structural analysis include all (elastic, plastic, and complete failure) behavioral states of the structure.

Another point that should be noted is the appropriate number of records, because the large number of records caused the analysis process to take much longer time. However, if the number of seismic records is low, the results cannot represent a complete structural response.

For this purpose, FEMA-P695 [29] far-field ground motions are used for analysis. This category of records includes 22 seismic events during the years 1971 to 1999. It is necessary to note that only the component with the maximum PGA value of these earthquakes is used for IDA analysis in this study. For time-history and mainshock IDA analyses, 22 ground motions of this bin are used. However, for mainshock-aftershock analysis, since the analysis is time-consuming, seven records

TABLE 1. Proposed performance levels for the YBS system for mainshock

Performance level	1	2	3	4
IDR_{max}	0.5	1	2	Horizontal lines of the IDA curve
$RIDR_{max}$	0.25	0.5	0.75	1

among the bin were selected as the mainshocks (Table 2), and three records were selected as aftershocks (Table 3).

For MainShock-AfterShock analysis, there is not a widely accepted criterion for utilizing real MS-AS sequence (Figure 7), probably due to the uncertainty and complexity associated with the selection of real MS-AS sequences [30]. Moreover, as stated by Ruiz- García [31] and Goda [32], in general, record characteristics of mainshock and aftershocks within the same sequences are different. On this basis, many studies have used a randomized approach using the same bin of ground motions for mainshock and aftershock [33-35]. Therefore, a randomized artificial approach is used here and AS records are selected randomly from the bin.

6. TIME HISTORY ANALYSIS OF THE MAINSHOCK

Firstly, nonlinear time history analysis has been used in order to determine the average distribution of interstory

TABLE 2. List of the mainshocks

	NAME	PGA
mainshock 1	DUZCE/BOL0 ¹	0.82
mainshock 2	LOMAP/CAP000	0.53
mainshock 3	LOMAP/G030 ¹ 0	0.56
mainshock 4	NORTHR/MUL00 ¹ 1 ¹	0.52
mainshock 5	KOBE/NIS000	0.51
mainshock 6	CAPEMEND/RIO ¹ 10	0.55
mainshock 7	CHI-CHI/TCU045.N	0.51

TABLE 3. List of aftershocks

	NAME	PGA
aftershock 1	KOCAELI/ARC000	0.22
aftershock 2	KOBE/SHI000	0.24
aftershock 3	LANDERS/YER270	0.24

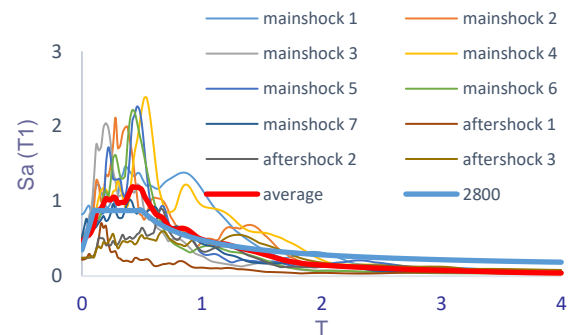


Figure 7. The spectra of seven mainshocks, three aftershocks and the spectrum of Iran's 2800 Standard

drifts in structural frames. In this analysis, 22 far-field earthquake records recommended by FEMA P695 [29] have been used. Figure 8 shows the spectrum of the 22 selected records. In this figure, the dash line represents the mean spectrum, and the continuous solid line indicates the spectrum of Iran's 2800 Standard.

Figure 9 shows the residual and the maximum interstory drift profiles for the Frame 4-1, as an example. As the figure shows, in four-story frames, the maximum interstory drift has occurred on the first story. Also in irregular structures with BRB system, the maximum interstory drift of the first story is much higher than that of the structures with YBS system, so that in structure 4.1, this parameter in BRB systems is 2.6 times that of YBS systems. One can also observe that the distribution of interstory drift in different stories in the frame with the YBS system is more homogeneous than that of the frame with the BRB system. The same trend is also observed for residual interstory drifts, so that the maximum value of this parameter occurs on the first story, and its value for the frame with the BRB system is more than that of the frames with the YBS system.

Table 4 also shows the values of structural response for other frames. In this table, IDR_{max} is the maximum interstory drift ratio, $RIDR_{max}$ is the maximum residual interstory drift ratio, and Range is the difference between the maximum and the minimum interstory drifts. In 4-story frames, the maximum interstory drift of the YBS system is much less than that of the BRB system. This phenomenon is especially evident in Frames 4-1 to 4-3. The Range values are also lower in these frames, which indicate the better distribution of nonlinear deformations at the height of these structures. For 8-story frames, it can be said that the maximum interstory drifts of the two systems, i.e. YBS and BRB, do not differ significantly. However, the maximum residual interstory drift of the eight-story frames with the BRB system is more than that of the eight-story frames with the YBS system. In Frames 8-2, 8-4, 8-6 and 8-8 with BRB system, this parameter is 2.07, 1.9, 1.35, and 1.2 times the same frames with the

YBS system, respectively. This can also be due to the secondary hardening of the YBS system. It can be clearly seen that the secondary hardening of the YBS system in most of stories prevents the occurrence of large residual interstory drifts, but due to the lack of this feature, the BRB system works poorly in reducing this parameter. Also, the interstory drift difference in the YBS frame is far less than that of the BRB frame, which indicates better distribution of nonlinear behavior in elevations in YBS structures. In frames with 4 or more stories, this phenomenon is significant, so that in the Frame 4-1, the difference in residual interstory drift in the BRB frame is 2.6 times the YBS frame.

7. INCREMENTAL DYNAMIC ANALYSIS UNDER THE IMPACT OF THE MAINSHOCK

Incremental Dynamic Analysis (IDA) includes a large number of nonlinear dynamics analyses under the impact of seismic records, and these records are scaled in such a way that they can cover the linear and nonlinear behaviors and eventually the collapse of the structure. The main goal of this method is to obtain structural responses for different values of the seismic intensity, and the results of this analysis are presented as IDA curves. To achieve a general state of structural behavior

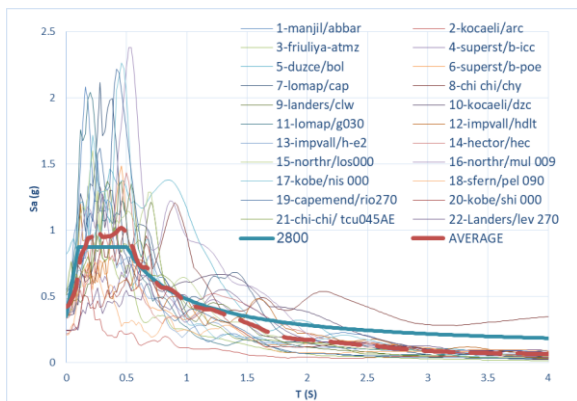
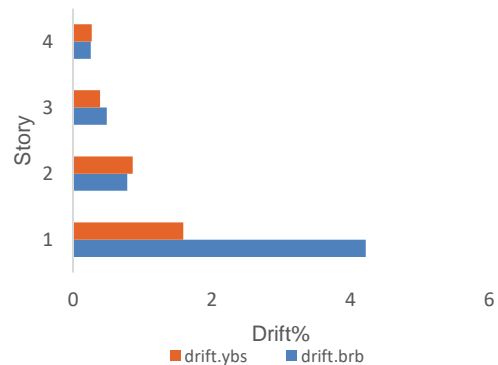
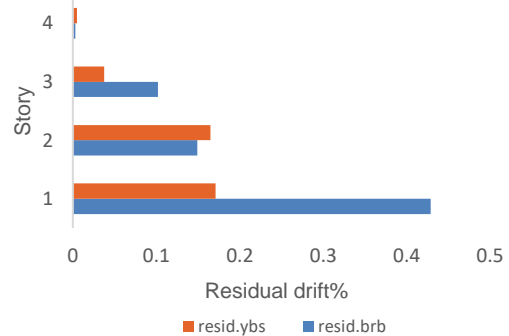


Figure 8. The spectrum of a set of 22 selected records along with the spectrum of Iran's 2800 Standard



(a) The maximum interstory drift



(b) Residual interstory drift

Figure 9. Interstory drift profile of the structure 4.1

TABLE 4. Summary of structural response under nonlinear dynamic analysis

frame	4.1	4.2	4.3	4.4	8.2	8.4	8.6	8.8	12.3	12.6	12.9	12.12
BRB												
IDR_{max}	4.25	4.75	4.85	2.1	1.37	1.35	1.12	1.09	1.12	0.84	1.13	1.08
RIDR	0.43	0.55	0.65	0.47	0.27	0.40	0.23	0.21	0.17	0.20	0.27	0.17
Range_{IDR}	4.00	4.50	4.60	1.60	0.97	0.96	0.72	0.54	0.62	0.34	0.63	0.45
Range_{RIDR}	0.43	0.55	0.65	0.42	0.27	0.40	0.22	0.17	0.15	0.19	0.25	0.13
YBS												
IDR_{max}	1.60	2.20	1.70	1.90	1.19	1.20	1.05	1.09	1.12	0.84	0.96	1.10
RIDR	0.17	0.24	0.26	0.25	0.18	0.21	0.16	0.17	0.14	0.19	0.22	0.14
Range_{IDR}	1.35	1.95	1.45	1.60	0.79	0.82	0.66	0.59	0.56	0.30	0.45	0.47
Range_{RIDR}	0.16	0.24	0.26	0.20	0.18	0.21	0.15	0.14	0.12	0.18	0.20	0.11

and to reduce information dispersion, we can summarize the IDA curves using statistical methods. For this purpose, the concept of median is used in this section. The median values of IDA curves are plotted for different frames; which is shown in Figure 10. A close look at these curves can clearly show that the YBS system collapses in higher seismic intensities than those of the BRB system. This can be attributed to the ability of this system to withstand large drifts. In 4-story frames, at higher stories more irregularly occurs; the performance difference between these two systems would be low. In the YBS system, the performance of irregular Frame 4-1 and 4-2 is also better than that of the regular frames; while, this is not the case in the BRB system. In 8-story frames, the more irregularly occurs at higher stories, the greater difference exist in their performance; therefore, the differences in seismic intensity of collapse for the two mentioned systems for Frame 8-2, 8-4, 8-6, 8-8 are 0.3, 0.5, 0.7, and 1g, respectively. In general, in eight-story frames with the YBS system, the more irregularly occurs at higher stories, the better the structure performance will be. However, this is not the case in the same frames with the BRB system, and the frames with irregularities at the upper and middle parts have weaker performance.

The results obtained for eight-story frames also apply to twelve-story frames, and as more irregularities occur at higher stories, the difference between the performances of the two systems increases, so that the differences in seismic intensity of collapse for the two systems for the Frame 12-3, 12-6, 12-9, and 12-12 are 0.4, 0.8, 0.9 and 1.3g, respectively.

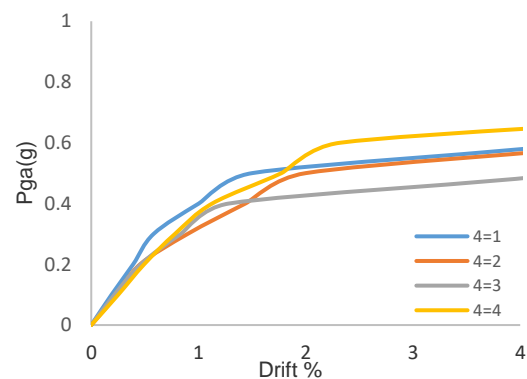
It can be clearly seen that the secondary hardening of the YBS system prevents the occurrence of large residual interstory drifts in most of stories, but due to the lack of this feature, the BRB system acts much weaker in reducing this engineering performance parameter.

It should be noted that the large residual drifts make the structure unsuitable for living, and, on the other hand, they make the structure more vulnerable to aftershocks.

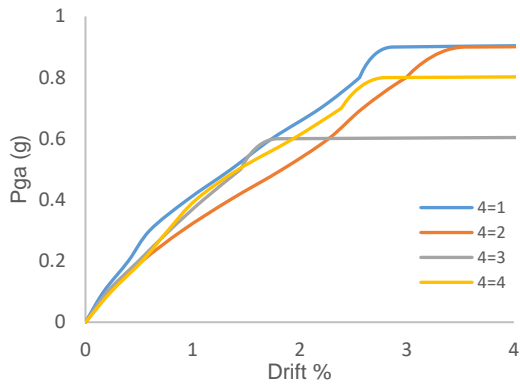
8. FRAGILITY CURVES UNDER THE IMPACT OF THE MAINSHOCK

In this section, the fragility curves have been studied in four performance levels. In these curves, the studied engineering demand parameter is the maximum interstory drift. Then, the fragility curves are presented for the engineering demand parameter of the maximum residual interstory drifts. Table 5 presents the structural exceedance probability for interstory drift at the spectral acceleration of 0.8g, which is approximately equal to the risk level of 10.15%, for brevity.

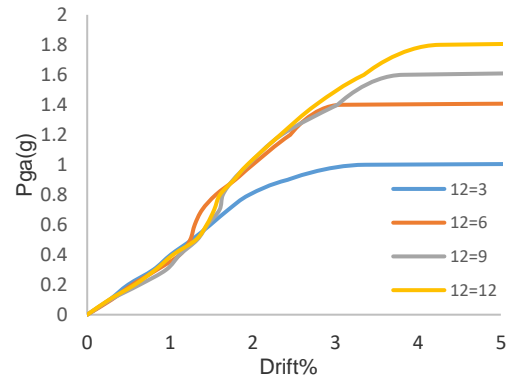
According to the Table 6, the two systems do not differ much from one another at low performance levels (such as IO and LS), and the exceedance probabilities of



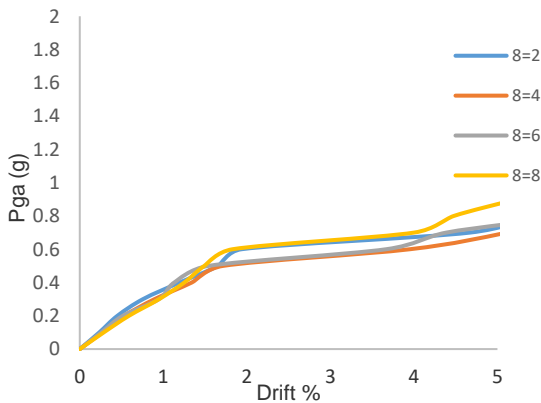
(a) 4-story structures with BRB system



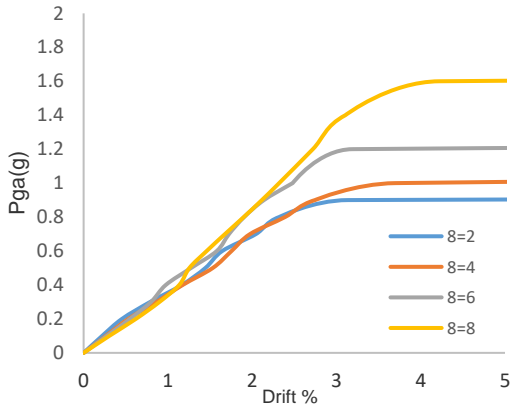
(b) 4-story structures with YBS system



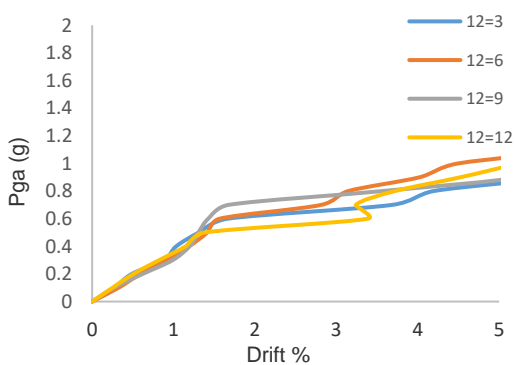
(f) 12-story structures with YBS system



(c) 8-story structures with BRB system



(d) 8-story structures with YBS system



(e) 12-story structures with BRB system

Figure 10. Median IDA curves for the structures under the impact of the mainshock

their maximum interstory drift are nearly the same. However, at higher performance levels (such as CP and GI), the YBS system shows a far lower exceedance probability. Especially, for the third performance level (CP), the exceedance probability in 12-story BRB frames is up to 20 times the YBS frame, indicating a much better performance than the YBS frame. This phenomenon is more evident in 12-story frames, which is clearly visible in both regular and irregular frames. However, at the fourth performance level (GI), the two systems act similarly, indicating that both systems are on the verge of instability.

As already mentioned, the behavior of the structure and its amount of residual drift under the mainshock has great impact on its performance under the aftershocks. So to better understand the residual drifts for both systems under seismic loads, the fragility curves of the frames for the third performance level (CP) for residual interstory drifts are shown in Figure 11. As shown in the figure, for all spectral accelerations, BRB frames exhibit a much higher exceedance probability. The YBS frames show a slight exceedance probability for spectral accelerations below 0.3g. However, BRB frames show a significant exceedance probability for the accelerations above 0.1g. BRB frames are likely to reach the exceedance probability of 1 at spectral accelerations above 1.5 g, but YBS frames reach their final capacity at accelerations of about 3g, and 12-story frames still have higher capacity in the same acceleration. In addition, it can be said that BRB frames with the same number of stories show almost the same behavior, however, in YBS frames, the structure is of more dispersed behavior. In 4-story frames, the structures with irregularities in lower stories show higher exceedance probability. On the contrary, 12-story frames with irregularities in upper stories are more vulnerable. Finally, in general, one can see that irregular structures have higher exceedance probability than regular structures.

TABLE 5. Structural response exceedance probabilities for acceleration of 0.8g

structure	4.1	4.2	4.3	4.4	8.2	8.4	8.6	8.8	12.3	12.6	12.9	12.12
BRB												
First performance level (IO)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Second performance level (LS)	0.98	0.99	0.98	0.97	0.97	0.97	0.98	0.98	0.95	0.95	0.99	0.95
Third performance level (CP)	0.80	0.84	0.93	0.70	0.70	0.78	0.77	0.64	0.68	0.70	0.63	0.79
Fourth performance level (GI)	0.84	0.90	0.92	0.75	0.71	0.78	0.80	0.68	0.70	0.75	0.70	0.80
YBS												
First performance level (IO)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Second performance level (LS)	0.98	0.99	0.97	0.93	0.97	0.96	0.95	0.98	0.94	0.94	0.98	0.92
Third performance level (CP)	0.27	0.34	0.64	0.51	0.36	0.33	0.16	0.15	0.37	0.12	0.05	0.04
Fourth performance level (GI)	0.68	0.88	0.66	0.70	0.61	0.61	0.47	0.45	0.51	0.29	0.33	0.31

TABLE 6. mainshocks leading to the collapse of the frames

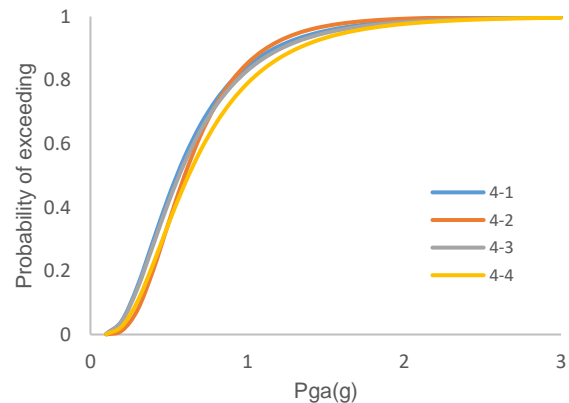
Frame	YBS	BRBF
4.1	---	Mainshock 1,2,4,6,7
4.2	---	Mainshock 1,4
4.3	Mainshock 4	Mainshock 1,2,4,7
4.4	Mainshock 4	Mainshock 1,4
8.2	---	Mainshock 4
8.4	---	Mainshock 4
8.6	---	Mainshock 4
8.8	---	Mainshock 4

9. INCREMENTAL DYNAMIC ANALYSIS UNDER THE COMBINED EFFECT OF THE MAINSHOCKS AND AFTERSHOCKS

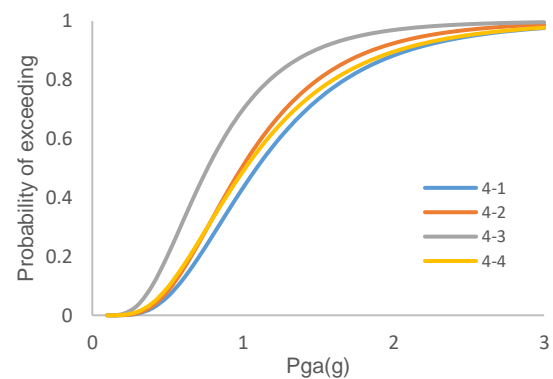
In this study, the incremental dynamic analysis of the aftershocks was carried out in such a way that first the main earthquake, which is scaled to the standard 2800 design spectrum, was applied. Then structure has a 30 second free vibration to be able to come back to the rest condition. Next, the aftershock with different PGA values is applied. for each intensity of the aftershock a certain amount of IDR and RIDR was achieved.

From the incremental dynamic analysis as well as the fragility curves obtained for both of the YBS and BRB systems in various irregularity and regularity conditions under the mainshocks, it can be stated that the YBS system behaves much better than the BRB system in creating drifts and residual drifts under the mainshocks, and also, given that the drifts and residual drifts resulting from the mainshocks are very effective in the behavior of structures under aftershocks, the YBS system is expected to have a better behavior under the combined effect of the mainshock and the aftershock as compared to the BRB

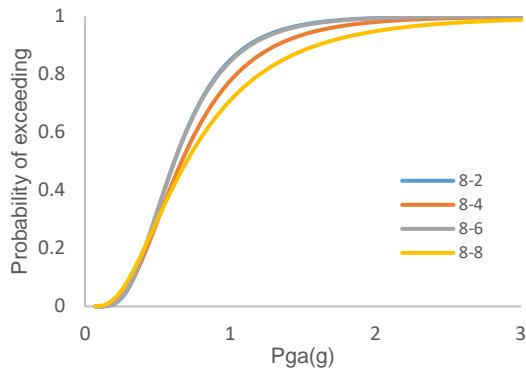
system. For this purpose, the main goal of this section is to obtain structural responses for different aftershock intensities, and the results of this analysis are presented as IDA curves. Figure 12 shows the median of the IDA curves for four- and eight-story frames with the YBS and BRBF systems under mainshock-aftershock, and compares the performance of both systems in different irregularity and regularity conditions.



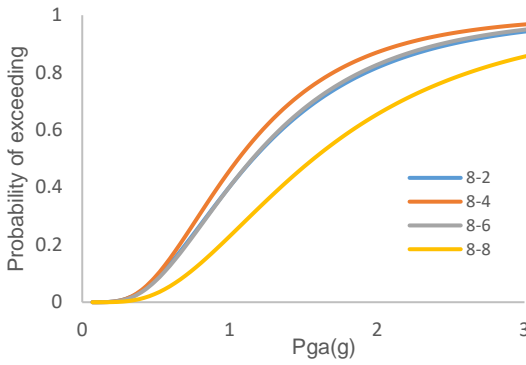
(a) 4-story structures with BRB system



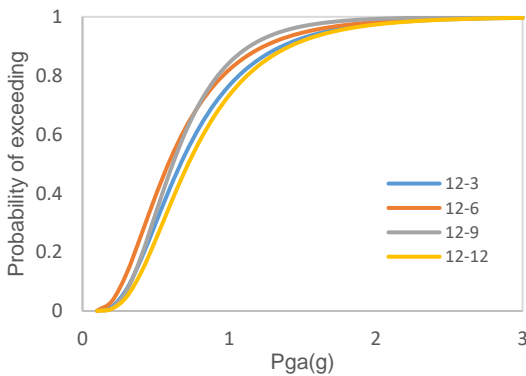
(b) 4-story structures with YBS system



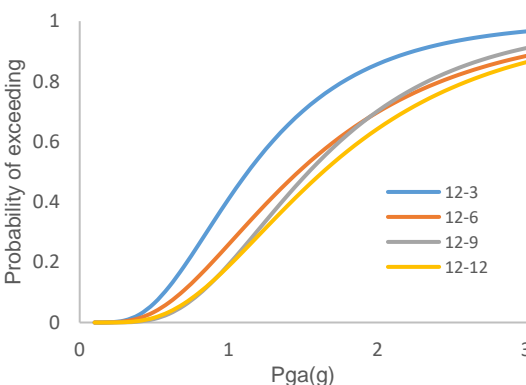
(c) 8-story structures with BRB system



(d) 8-story structures with YBS system

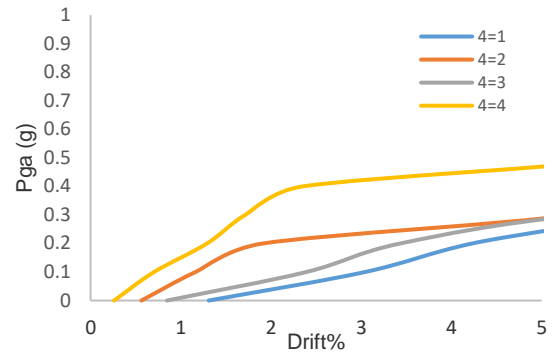


(e) 12-story structures with BRB system

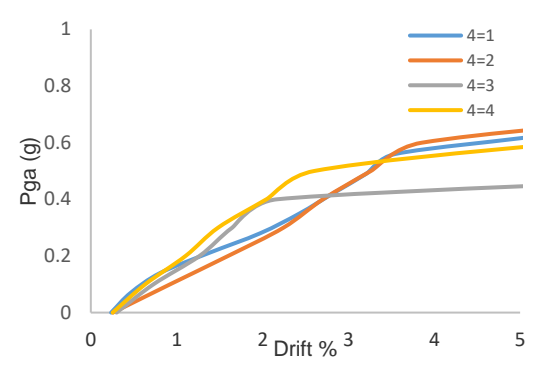


(f) 12-story structures with YBS system

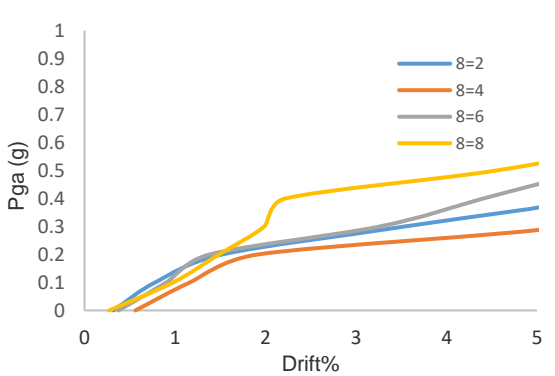
Figure 11. Fragility curves of structures for residual interstory drift for the third performance level under the impact of the mainshock



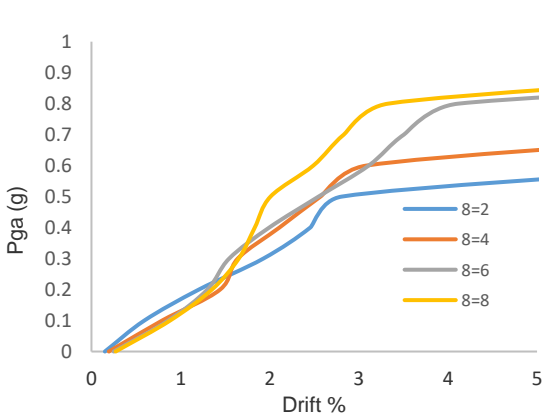
(a) 4-story structures with BRB system



(b) 4-story structures with YBS system



(c) 8-story structures with BRB system



(d) 8-story structures with YBS system

Figure 12. Median IDA curves for the structures under the impact of the mainshock and aftershocks

Given the IDAs medians, it can be seen that irregularities in the lower and middle sections of the four-story frame equipped with CSY fuse do not have much effect on the seismic intensity of their collapse compared to regularities. The irregularity at the top of the four-story frames equipped with CSY fuse reduces its collapsing PGA by 20%.

Among the four-story irregular frames with the BRBF system, the frame with irregularity in the middle section has a better performance than other irregular frames. This is also true for the four-story frames with the YBS system to some extent. It is also observed that the regular four-story frame with the BRBF system performs much better than irregular frames with the same number of stories. However, this is not the case for the four-story frames with the YBS system. In general, for 4-story structures, it can be said that the performance of the BRB and YBS systems in regular structures is almost the same. However, the regular frame with the YBS system will collapse at a higher PGA (approximately 0.1g) compared to the same frame with the BRB system. In eight-story frames with the YBS system, the more irregularities occur in the lower stories, the lower the PGA at which the structure collapses will be, so that the Frame 8-8 tolerates 60% more seismicity than the Frame 8-2. According to the final diagram of this figure for eight-story frames with the BRBF system, it becomes clear that all eight-story irregular frames collapse at an almost the same PGA; while, the regular frame can withstand twice seismicity. Also, the eight-story frames with the YBS system collapse at higher seismic intensities than the same eight-story frames with the BRBF system. One can conclude from the above that the use of the YBS system in eight-story frames can improve the behavior of the irregular structure against the aftershocks to a great extent.

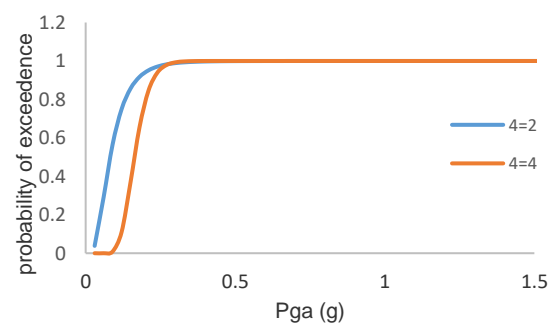
10. FRAGILITY CURVES UNDER THE COMBINED EFFECT OF THE MAINSHOCKS AND THE AFTERSHOCKS

In this section, the fragility curves are presented for regular frames and the frames with mass irregularities at different stories of the same height. For brevity, fragility curves have been investigated at the third performance level for the structures. In these curves, the studied engineering demand parameter is the maximum interstory drift. It should be noted that, as shown in the previous section, some frames collapsed when subjected to more than half the number of the mainshocks. Therefore, they are not much resistant to aftershocks. Thus, these records have been eliminated to obtain the fragility curves and compare the two YBS and BRBF systems. Table 6 lists the mainshocks leading to the collapse of the frames. As is clear from the table, the

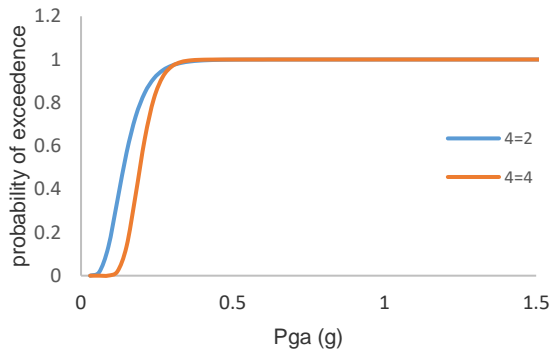
absence of secondary hardening in the BRBF system has made the system vulnerable to more mainshocks in comparison with the YBS system. Given that five mainshocks out of the seven mainshocks caused the failure of the Structure 4-1, and four mainshocks caused the failure of the Structure 4-3 with BRBF system, the fragility curve for these frames are not presented, because removing these records eliminates the possibility of a correct comparison between the two YBS and BRBF systems. On the other hand, it can be said that a four-story structure with an irregular BRBF system at the lower part of the structure will have the poorest performance followed by those with an irregularity at the top of the structure.

A close look at Figure 13 shows that at the second level of performance, the fragility of the irregular four-story structure is more than that of the regular 4-story structure in both systems. Also, the difference between the fragility of both regular and irregular four-story frames equipped with YBS is slightly lower than that for both frames in BRBF. It is also found that at the second performance level, the fragility of the four-story frames equipped with YBS is lower than that of the four-story frames equipped with BRB. One can also find that the difference between the fragility of the two systems is higher in the irregular Frame 4-2, such that the maximum of the difference in Frame 4-2 is 20%, and in Frame 4-4, it is 13%. Also, at this performance level, fragility of 8-story structures equipped with BRB is slightly higher than that of those equipped with YBS. According to Figure 13, it is clear that at the second performance level, the behavior of the eight-story frames equipped with both systems is dependent on the mass of the structure.

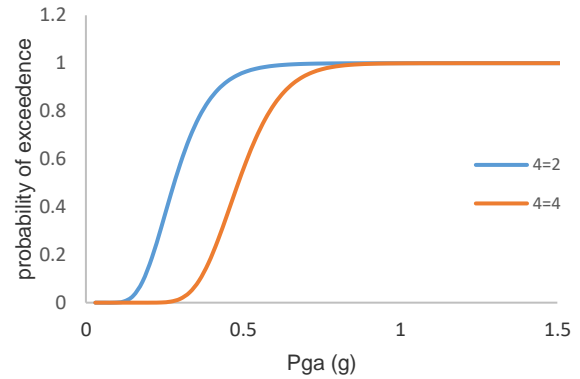
As Figure 14 shows, at the third performance level, despite an increase in engineering demand from interstory drift ratio of 1% to interstory drift ratio of 2%, the performance of the regular four-story frame is still better than that of the Frame 4-2. Just like the second performance level, the difference between the fragility of the regular and irregular frames is roughly the same in both systems. Also, as can be seen, at the third performance level, the fragility of four-story frames



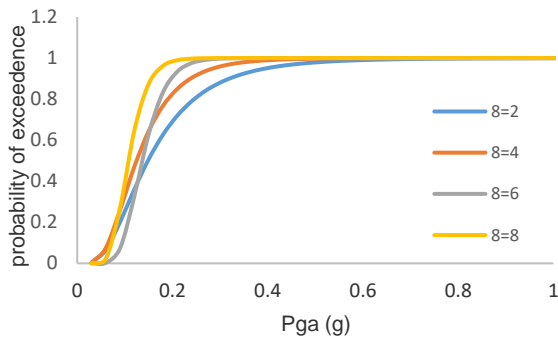
(a) 4-story structures with BRB system



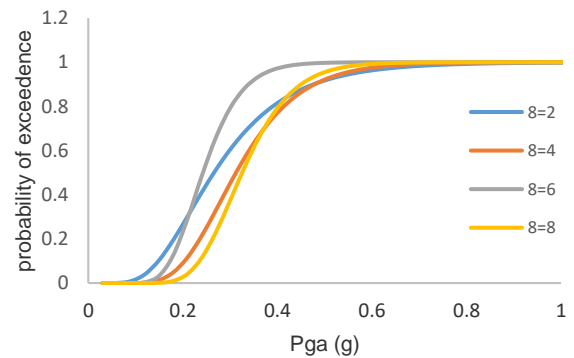
(b) 4-story structures with YBS system



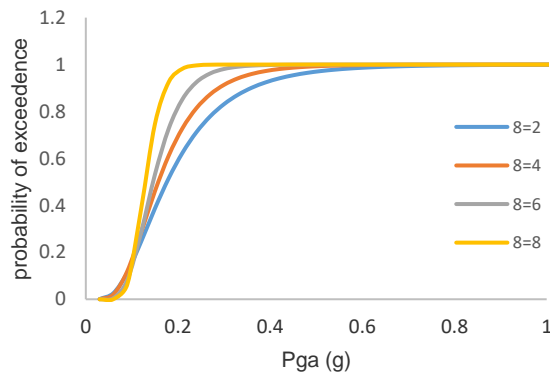
(b) 4-story structures with YBS system



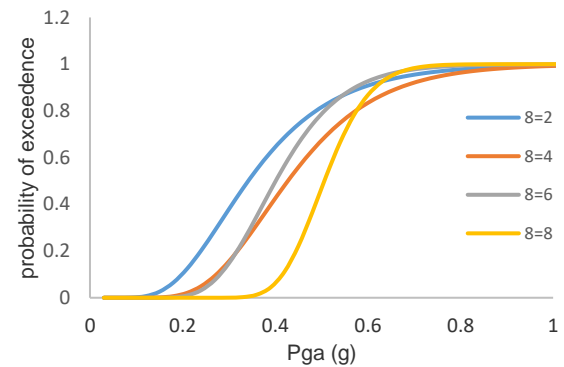
(c) 8-story structures with BRB system



(c) 8-story structures with BRB system



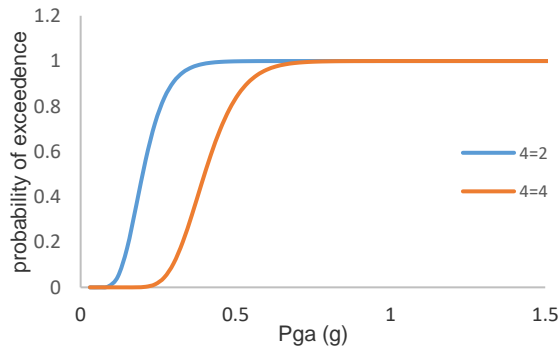
(d) 8-story structures with YBS system



(d) 8-story structures with YBS system

Figure 13. Fragility curves of structures for the second performance level for interstory drift under mainshock and the aftershock

Figure 14. Fragility curves of structures for the third performance level for interstory drift under mainshock and aftershocks



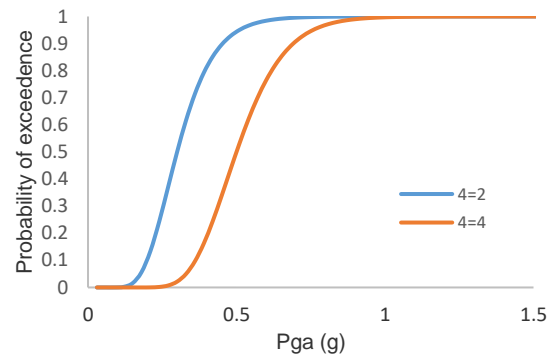
(a) 4-story structures with BRB system

equipped with BRB is also more than that of the frames equipped with YBS. The maximum difference in fragility of the two systems in Frame 4-2 is 21%, and in Frame 4-4, it is 15%. Also in 8-story frames, by increasing the engineering demand of the maximum interstory drift ratio from 1 to 2%, the difference between the fragility of the two frames equipped with BRB and YBS is also increased, and the YBS superiority is clear. Also, as shown in Figure 14, at the third performance level, the performance of the regular eight-story structure followed by that of the structure 8-4 in both systems are better than

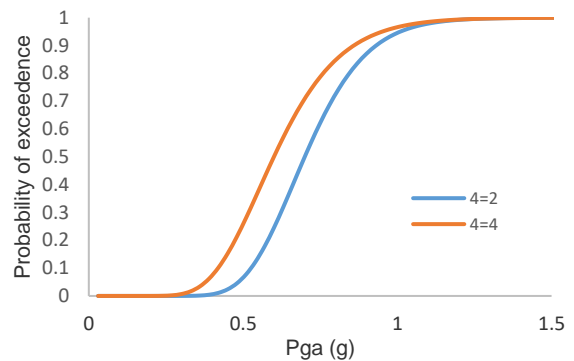
that of the other eight-story frames. Also in frames with the YBS system, the structures with irregularity in the lower part have the worst performance, while in a structure with a BRBF, the worst performance occurs for a structure with irregularity at the top of the structure.

However, at the fourth performance level corresponding to the collapse prevention (CP) threshold level of the structure, the situation is different. In fact, as shown in Figure 15, YBS causes the irregular Structure 4-2 to perform even better than the regular four-story structure, while the BRBF has failed to improve the performance of the irregular structure at the collapse prevention (CP) threshold level in comparison with the regular structure. Hence, it seems that YBS performs significantly better than BRBF in irregular four-story structures at the collapse level of performance. As can be seen, at the fourth performance level, which is corresponding to collapse prevention (CP) threshold level, the irregularity in the four-story frame greatly affects the difference between the fragility of the two systems. In a regular structure, the difference reaches 15% at the maximum. However, in Frame 4-2, this difference is 80% at most, indicating a significant difference in the performance of the two systems in this frame. Also, at this performance level in eight-story frames, the difference between the fragility of the two frames with BRBF and YBS is greater than the previous two performance levels, and as with the third performance level, one can clearly find the YBS superiority. At the collapse performance level of both systems, regular eight-story structures have the least fragility. Noteworthy is the status of the eight-story structure with an irregularity at the upper part. As can be seen, YBS has reduced the fragility of this frame as compared to other irregular frames. However, the BRBF has made this frame to have even weaker performance than other irregular frames. This has led to a significant difference in the performance of the two systems in the eight-story structure with irregularity at the upper part of the structure, so that the difference has reached around 100% at its maximum. In other words, this has led to about 100% better performance of YBS as compared to BRB at best in this 8-story frame with an irregularity at the upper part, which is subjected to the mainshock-aftershock.

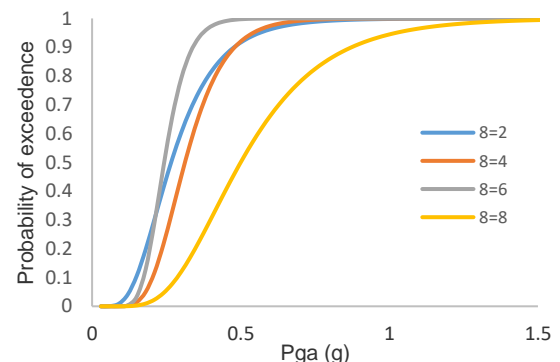
As can be seen, in almost all frames, YBS perform better than BRBF, which is due to the secondary stiffening of the system after its yield caused by large drifts. Since irregularities cause the structure to suffer further drifts, YBS has greatly improved the seismic performance of irregular structures. As already mentioned, the behavior of the structure and its amount of residual drift under the mainshock has great impact on its performance under the aftershocks. Given the post-yield stiffening feature of YBS, it was observed that under the mainshock, the structures equipped with



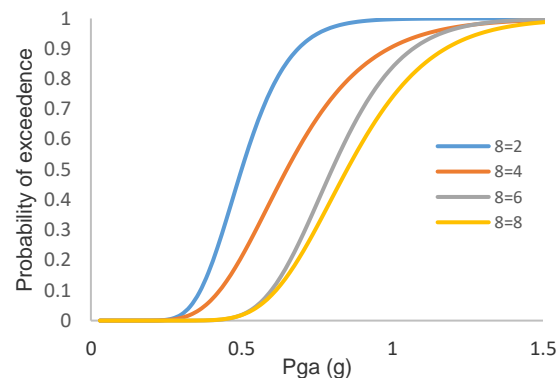
(a) 4-story structures with BRB system



(b) 4-story structures with YBS system



(c) 8-story structures with BRB system



(d) 8-story structures with YBS system

Figure 15. Fragility curves of structures for the fourth performance level for interstory drift under the impact of the mainshock and the aftershocks

this system have less residual drifts compared to the structures equipped with BRB. Hence, they show a better performance under the aftershocks. It was also observed that at the performance levels with higher interstory drift ratios, the difference in the effectiveness of these two systems is increased. This can be attributed to the fact that given the structure of CSY fuse, after yielding, with increasing the drifts, the secondary stiffening of the system is also increased, which makes it possible for the frame equipped with YBS to withstand more seismic force as compared to BRBF for the same drifts. Therefore, in the fragility curves associated with the fourth performance level, which actually evaluates the performance of the structure under larger drifts than those of other performance levels, the difference between the performances of the two systems has significantly increased in different frames as compared to other performance levels.

By examining Figure 16, it can be seen that the fragility of the four-story frame with the YBS system is lower than that of the BRBF frame. This difference in fragility is higher in the irregular Frame 4-2, so that the maximum difference in Frame 4-2 is 60%, and in Frame 4-4, it is 35%. Thus, as can be seen, the YBS system in four-story frames has been able to improve the performance of the irregular frames very well and lower its fragility as compared to regular four-story frames, while the BRBF frame lacks such a feature. This result was also true for interstory drift engineering demand at structural collapse prevention performance level. This figure also shows that in all eight-story structures except for an irregularly-shaped structure in the middle section, the performance of the BRBF system is weaker than that in the YBS system. As shown in the diagrams of this figure, Frame 8-4 with the YBS system has the weakest performance as compared to other frames with the same system, and by contrast, Frame 8-4 with the BRBF system has the best performance among the eight-story frames with the BRBF system in seismic intensities

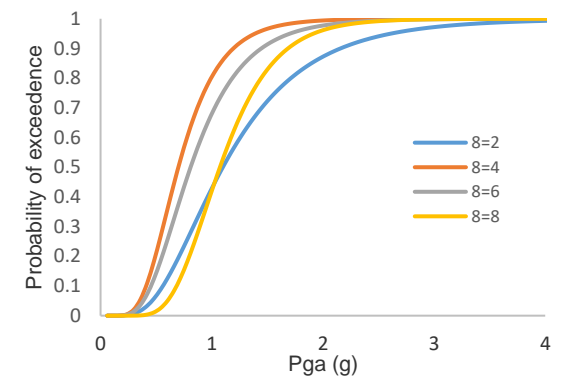
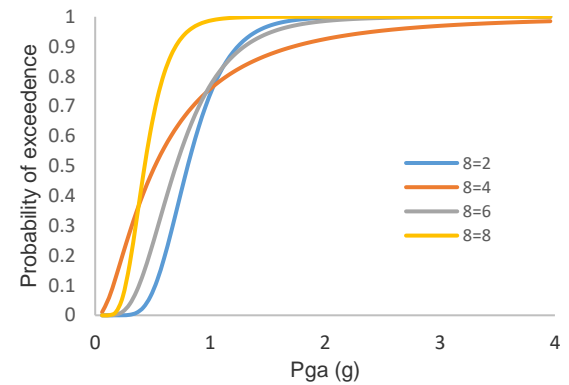
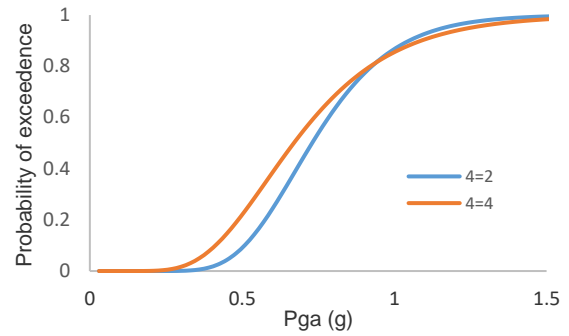
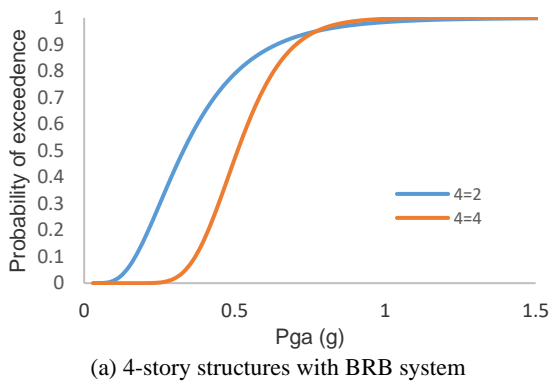


Figure 16. Fragility curves of structures for the fourth performance level for residual interstory drifts under the impact of the mainshock and the aftershocks

higher than 1g. However, in Frame 8-4 (the eight-story frame with irregularity in the middle part), in seismicity of less than 1g, the fragility of the YBS frame is less than that of the BRBF frame. Therefore, even in the eight-story frames with irregularity in the middle section, in which the YBS system has the weakest performance as compared to other irregularity modes in eight-story frames, in seismicity below 1g, the same system also has a better performance than the BRB system in Frame 8-4.

11. CONCLUSION

In this paper, the performance of regular and irregular structures with BRB and YBS braces was investigated. First, a nonlinear dynamic analysis was conducted on the structures, and the residual drift and drift response of the structures were compared with each other. Then, using the incremental dynamic analysis, the seismic performance of the structures was investigated. According to the results of the analyses in this study, the conclusions can be summarized as follows:

1. Nonlinear dynamic analysis results show that in regular frames, performance of both systems is approximately the same. However, in irregular frames, it was observed that the YBS system shows less maximum story drifts, less residual story drifts, and a more uniform drift profile. As far as, in 4-3 frame equipped with YBS showed 185% less story drift, 150% less residual story drifts and 217% lower story drift range. In fact, the YBS system has been very successful in preventing the creation of a soft story. This superiority is also clearly evident in controlling the residual interstory drift, which is due to the secondary hardening in the YBS system
2. By increasing the structural height, the difference in the mainshock IDA curves of the two systems is increased. However, the YBS system still gives significantly lower interstory drifts in all structures compared to the BRB system. In 4-story structures, IDA curves of 4-story YBS and BRB systems show 150% difference in tolerable PGA. However, in 12-story frames they show about 190% difference.
3. Seismic sequence fragility curves show that regular structures have better performance than irregular structures. However, this phenomenon is not true in all cases. In 4-2 structures, the performance of the irregular structure is significantly improved compared to that of the regular structure. In total, YBS structures show less probability of exceeding than BRB structures in all cases. So that, the YBS system has had a much better performance in the event of a mainshock with its aftershocks in both regular and irregular structures.

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Comparison of Seismic Behavior of Buckling-restrained Braces and Yielding Brace System in Irregular and Regular Steel Frames under Mainshock and Mainshock-Aftershock

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تحقیقات گذشته نشان داده است که سازه های مجهز به مهاربند کمناش تاب (BRB) در زلزله به علت سختی پس از تسلیم کم مهاربندها، جابجایی پسماند بالایی را تجربه می کنند که این جابجایی در پس لرزه تشدید یافته و موجب خسارات زیاد به سازه می شود. این مشکل برای سازه های نامنظم با توجه به عدم توزیع مناسب سختی دوچندان است. به تازگی سیستم مهاربند جاری شونده (YBS) معرفی شده است که می تواند به عنوان جایگزینی برای مهاربند BRB برای رفع این مشکل باشد. با این حال عملکرد لرزه ای سیستم YBS در سازه های نامنظم تاکنون مطالعه نشده است. بر این اساس، در این مقاله عملکرد لرزه ای قابهای مجهز به مهاربندهای BRB و YBS در سازه های منظم و نامنظم مورد بررسی قرار گرفته است. تعداد ۲۴ قاب ۴-، ۸-، و ۱۲- طبقه مجهز به این دو سیستم طراحی شده و مورد ارزیابی قرار گرفته اند. ابتدا تحلیل دینامیکی غیرخطی بر روی قابها انجام شده و مقادیر بیشینه جابجایی نسبی و جابجایی نسبی پسماند قابها تحت زلزله اصلی با یکدیگر مقایسه شده است. سپس با استفاده از تحلیل دینامیکی افزایشی و منحنی های شکنندگی عملکرد قابها تحت زلزله اصلی در ۴ سطح عملکرد مورد بررسی قرار گرفته است. آنگاه با استفاده از تحلیل دینامیکی افزایشی و منحنی های شکنندگی عملکرد قابهای چهار طبقه و هشت طبقه تحت زلزله اصلی- پس لرزه در ۳ سطح عملکردی مورد بررسی قرار گرفته است. نتایج نشان می دهد که مهاربند YBS، به خصوص در سازه های کوتاه، جابجایی های نسبی حداکثر و جابه جایی های نسبی پسماند حداکثر به مراتب کمتری از مهاربندهای BRB بدست می دهد که می تواند از وقوع طبقه نرم در سازه بکاهد.

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