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Evaluation of Seismic Response of Multi-Story Structures: A Comparative Study of Buckling Restrained Braces and Viscous Dampers

Mansour Bagheri,[a,*] Seyed Abbas Hosseini [b]

[a] *Department of Civil Engineering, Birjand University of Technology, Birjand, Iran*

[b] *Faculty of Technology and Mining, Yasouj University,Yasouj, Iran*

ABSTRACT

In buckling restrained bracing systems, earthquake-induced elongation problems are solved, and BRB-equipped structures have a much more effective performance in energy absorption in addition to high lateral stiffness. Systems equipped with viscous dampers (VD) also have great potential to absorb seismic energy. To assess the vulnerability of structures equipped with buckling restrained bracing (BRB) and VD systems, three structures (6-, 10- and 15-story) were chosen as representatives of mid-rise, high-rise and super high-rise buildings and modeled in four states of moment-resisting frame (MRF): the frame equipped with VD, the frame equipped with BRB, and the frame equipped with BRB and viscous damper simultaneously (BRB+VD) using OpenSees-2.4.6 software under incremental dynamic analysis (IDA). Seven seismic records were applied, and the maximum inter-story drift response and fragility curves were determined. The results indicated that although the simultaneous application of BRB+VD causes a significant decline in the response of all structures, each of these two systems is able to provide structural safety at various levels in mid-rise structures. It is required to apply both systems simultaneously to provide safety for slight and moderate levels of damage in high-rise buildings, while super high-rise buildings are vulnerable to whole levels of damage, and their structural safety involves the simultaneous use of both systems.

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1. Introduction

High lateral forces are applied to the structure during an earthquake. Since the philosophy of most design methods is based on the prevention of structural collapse and energy absorption and dissipation, the building must exit the elastic region, and inelastic cyclic displacements should occur when the structure is exposed to seismic forces. Hence, this may lead to irreparable damage to the structure due to plastic hinges formed in specific points. Researchers have examined the effect of modern technologies on structural safety and strength against seismic forces in recent years. The systems are based on energy absorption and changing the frequency of the structure, which eventually withstand the seismic energy and cause less damage to structural elements. Fluid viscous dampers

* Corresponding author. Tel.: +98915543091; e-mail: mnsrbagheri@gmail.com.

(FVDs) are among the systems that consist of a cylinder, a stainless-steel piston, and a perforated bronze cap which has a high capacity to absorb energy and plays a crucial role in the seismic energy dissipation of structures.

On the other hand, there are other resistant systems to retrofit structures against seismic loads that most of which are based on the distribution of seismic force among structural elements such as braced frames. To eliminate the drawbacks of bracing systems, i.e., buckling behavior and yielding, the braces should reach the yield point without bucking under compression and tension. A system equipped with this type of bracing is known as buckling restrained braced frame (BRBF). Bucking restrained bracing system is a new technology which can absorb far more energy than conventional bracing systems due to the prevention of buckling. BRBFs include a variety of components such as a steel brace to withstand axial forces, a gusset plate linked to the connection and brace, a casing to resist buckling, and grout to fill the gap between the steel core and casing. A small gap is also provided to allow the steel core moving freely in the grout infill and decrease friction effects. The steel core is usually designed like a bone with decreased cross-section to concentrate yielding in the region.

Hatzigeorgiou et al. [1] studied the behavior of structures equipped with VDs under near-field earthquakes and evaluated the effect of structural parameters, attached damper parameters, and type of fault on maximum seismic velocity and damping force. Results revealed the profound and significant impact of effective damping ratio of VD on the inelastic seismic response of structures. Introducing the super-elastic VDs, Silwal et al. [2] studied the seismic collapse resistance of steel frames equipped with such dampers. The super-elastic dampers are hybrid passive control devices (HPCDs) combined with viscoelastic materials and alloy cables, possessing higher energy dissipation capacity compared to other VDs. The main results of the research showed a better performance of damping system in comparison with conventional MRF and BRB. Hsu and Halim [3] studied a curved steel damper embedded in the beam-to-column connection. The results of research demonstrated that as curvature angle increases in the damper, the strength of frames rises, and damper considerably enhances the strength, stiffness, and energy dissipation. Banazadeh et al. [4] investigated the performance of structures designing two linear and nonlinear dampers with the same damping ratio for 6, 8 and 12-story frames. Applying incremental dynamic analysis (IDA); the results showed the improved performance of structures equipped with the damper compared to moment resisting frame structures for the same damping ratios. Kazemi et al. [5] investigated the effect of linear FVDs on the seismic vulnerability of buildings. Survey results showed that the installation of linear VD reduces the maximum impact force and duration of impacts exerted to adjacent structures, postpones the collapse of the structures. Abdi et al. [6] investigated the response modification factors for reinforced concrete (RC) structures equipped with VDs. The results suggested that response modification factors for RC structures equipped with VDs are more than those without VDs, and the number of dampers and building height have significant influences on response modification factors. Guo et al. [7] tried to control structural vibration under powerful earthquake excitation. To achieve this goal, they implemented a nine-story benchmark steel building and three different and typical types of dampers. VD, and BRB were mounted to this prototype to examine its response to 10 earthquake records. The fragility curves showed that the largest collapse margin ratio was with the viscoelastic damper, and the greatest drift control was provided by the VD. The floor acceleration responses in the mid-rise building can be reduced effectively by both of the BRB and VDs.

Ataei and Anaraki [8] evaluated seismic response of structures developing a design procedure based on corrected response spectrums. The effectiveness of the proposed method was explored through nonlinear time series analysis of 3, 5 and 7-story steel frames. Consequently, the obtained results were verified with the collapse fragility curves of the generic structures according to the ASCE 7-10 and displacement-based design methodology. survay results show that models designed according to the proposed procedure indicated great performance using degrading dampers. Rofooei and Mohammadzadeh [9] studied the optimal distribution of fluid VDs to control the seismic response of moment-resisting concrete structures by using a previously defined center of damping constant. Findings revealed that the stiffness eccentricity, which is the major parameter in determining the location of the optimal center of damping constant, tended to be smaller than the optimal damping constant eccentricity in the linear range of structural behavior.

Jae-Do Kang and Hiroshi Tagawa [10] designed experimental and numerical research on a seesaw energy dissipation system using FVDs. The results indicated that the system had enough damping capacity to reduce seismic response of frames. He and Lu [11] used three numerical models of a super-tall building to investigate the inter-story drift control effect under different hybrid control schemes using buckling restrained braces and VDs. The results revealed that in fragility analysis, peak ground velocity (PGV) according to its high efficiency is suitable for IDA in high-rise buildings. Kariniotakis and Karavasilis [12] established different steel moment-resisting frames designed according to Eurocode 8 equipped by VDs. Collapse fragility curves were generated performing IDA for 44 ground motions. The design criteria were compared according to Eurocode 8. Yahyazadeh and Yakhchalian [13] investigated the effects of linear and nonlinear FVDs on the maximum residual inter-story drift ratio response of steel special MRF.

Nomura et al. [14] examined how effective viscous dampers are for retrofitting steel moment frames. Through simulations of different seismic scenarios, they discovered that the dampers considerably decreased peak accelerations and inter-story drifts during earthquakes. The findings underscored that viscous dampers not only enhance the structural resilience of buildings but also present a cost-effective alternative to conventional retrofitting methods. Chen et al. [15], introduced a performance-based methodology for retrofitting steel moment frames using viscous dampers. They created a detailed design framework that takes into account various seismic design criteria and also examined an existing steel frame building that was retrofitted with viscous dampers. The findings revealed that this retrofit not only increased the building's energy dissipation capacity but also significantly enhanced its overall performance, resulting in a marked reduction in seismic vulnerability. Kim et al. [16] investigated the integrated design considerations involved in retrofitting steel moment frames using viscous dampers. The authors introduced an innovative design methodology that merges performance-based design principles with numerical simulation techniques to determine the optimal placement and sizing of the dampers. Results indicated that strategically positioning the dampers notably improves energy dissipation and enhances the overall seismic resilience of the structures.

Wakabayashi [17] introduced BRBs for seismic hazard for steel structures. Choi and Kim [18] studied the energy dissipation capacity and seismic response of steel structures equipped with BRBs. They concluded that as the stiffness of BRBs increases, the equivalent damping ratio of single-degree-of-freedom (SDOF) structures rises, and the maximum displacement of buildings declines in general. Sahoo and Chao [19] investigated the performance of the plastic design method for buckling restrained braced frames. The results revealed that the frames designed through the performance-based design (PBD) method could successfully limit the maximum displacements to the predetermined target displacement. Chang and Chiu [20] investigated a 6-story office building equipped with BRBs. Seismic performance of building and capacity and requirements of BRBs through test results and response analysis were studied. Findings showed that BRBs could provide high confidence levels, which guarantee the proper satisfaction of immediate occupancy and life safety performance levels in the building. Guo et al. [21] studied BRBs with two individual cores and evaluated its load-bearing capacity and hysteresis response. The results indicated a good compatibly between test results and finite element analyses and showed that even proposed equations could be used to design the braces; this reveals that buckling does not happen in the independent cores of BRBs before global buckling of bracing system. Bing et al. [22] assessed a new type of BRBs with replaceable angular steel fuses. They tested seven braces to examine the seismic behavior of these BRBs. Given the tests, it was concluded that the hysteretic behavior of these braces resembles conventional BRBs, and the proposed braces can show a stable hysteretic behavior to relatively high levels of strain in the fuses.

Park et al. [23] examined the seismic performance of steel buckling-restrained braces (BRBs) by integrating experimental testing with numerical simulations. The authors performed full-scale tests to evaluate the behavior of the braces under different seismic loading scenarios. The results indicated that BRBs effectively dissipated energy and retained their strength even during intense earthquake events. Morales et al. [24] explored the dynamic behavior of steel structures fitted with buckling-restrained braces (BRBs) when subjected to seismic excitation. They employed sophisticated numerical modeling methods to evaluate the impact of BRBs on the overall performance of these structures during earthquakes. Their findings demonstrated that buildings with BRBs experienced considerably lower inter-story drifts and enhanced energy dissipation compared to those using conventional bracing systems.

Given the increasing development of new technologies for structural improvement using buckling restrained bracing system and promotion of their safety level and seismic resistance using a variety of dampers, particularly VDs, this study attempts to find out how their individual or simultaneous application affects the performance of structures of different stories, ranging from low-rise to high-rise. The vulnerability of structures is evaluated at slight, moderate, extensive and complete levels of damage in order to introduce a suitable system amongst steel moment resisting frame (MRF), moment resisting frame with viscous damper (VD), moment resisting frame with BRB (BRB) and moment resisting frame with BRB and viscous damper (MRF+VD).

2. Investigated models

To evaluate the behavior of structures equipped with BRB or VD, three 6-, 10- and 15-story structures with 4 spans 4m in length, 3m in height are selected as representatives of mid-rise, high-rise and super high-rise building, respectively. These three structures are initially designed as MRF under the requirements of seismic considerations, AISC 360 and AISC 341 codes, respectively [25,26], as shown in the plan in Fig.1 Then, the outer frame of each structure is chosen and modeled by OpenSees software [27]. Fig.2 demonstrates the arrangement of VDs and BRBs within the frames; the sections used for these structures are listed in Table 1. According to the table, W sections are used for beams, and TUB sections are used for columns, both made of steel with the yield strength of 2400 kg/cm2 and elastic modulus of 2.1 × 16 kg/cm2. The buckling restrained braced span should satisfy specific seismic criteria due to the forces applied by the BRB, where the sections must be stronger than other structural members.

2.1. Verification of modeling

In order to ensure the reliability of BRB modeling, a frame illustrated in Fig. 3 was modeled and exposed to cyclic analysis. The BRB is modeled by OpenSees using Corotational truss element and Steel02 material. Fig. 4 shows the results of analysis of modeled bracing system compared with the results of an experimental specimen utilized by Burkholder [28]. To model the VD by OpenSees software, the Viscous Damper material defined by Lignos is used and assigned to a two Node Link element.

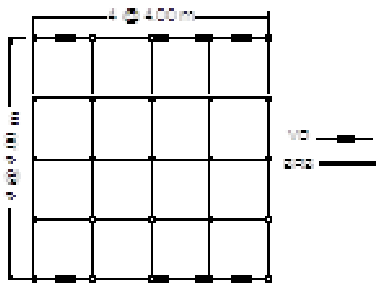

Fig. 1. Plan of investigated models

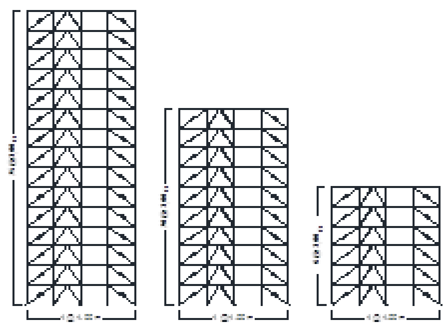

Fig. 2. Arrangement of BRBs and VD in models

Table 1
Frame sections

Element Type		Beam			Column	
Story No.	6 story	10 story	15 story	6 story	10 story	15 story
1	W 12×35	W 12×35	W 14×38	TUB 280×20	TUB 320×28	TUB 320×28
2	W 12×35	W 12×35	W 14×38	TUB 280×20	TUB 320×28	TUB 320×28
3	W 12×19	W 12×26	W 14×38	TUB 220×16	TUB 280×20	TUB 320×28
4	W 12×19	W 12×26	W 12×35	TUB 220×16	TUB 280×20	TUB 320×28
5	W 12×14	W 12×26	W 12×35	TUB 180×16	TUB 260×20	TUB 280×20
6	W 12×14	W 12×26	W 12×35	TUB 180×16	TUB 260×20	TUB 280×20
7	-	W 12×26	W 12×26	-	TUB 220×16	TUB 280×20
8	-	W 12×14	W 12×26	-	TUB 220×16	TUB 280×20
9	-	W 12×14	W 12×26	-	TUB 180×16	TUB 260×20
10	-	W 12×14	W 12×19	-	TUB 180×16	TUB 260×20
11	-	-	W 12×19	-	-	TUB 260×20
12	-	-	W 12×19	-	-	TUB 260×20
13	-	-	W 12×14	-	-	TUB 220×16
14	-	-	W 12×14	-	-	TUB 220×16
15	-	-	W 12×14	-	-	TUB 220×16

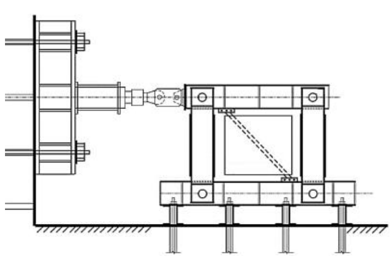

Fig. 3. Prototype of BRB modelling [29]

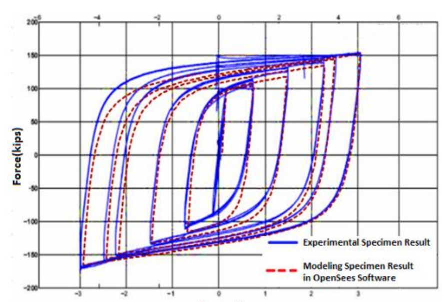

Fig. 4. Verification of BRB modelling

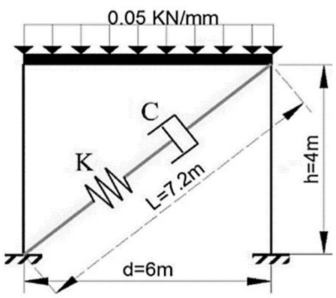

Fig. 5. Prototype of VD modelling [4]

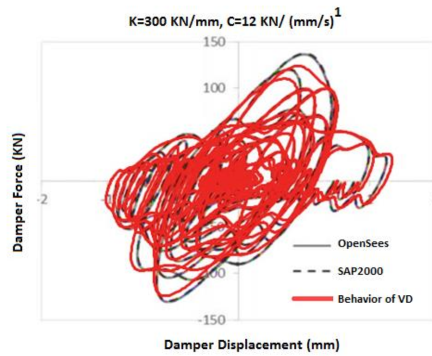

Fig. 6. Verification of VD modelling

Table 2
Specifications of BRBs

Model	6 story	10 story	15 story
Base shear coefficient	0.0933	0.0723	0.0590
Base shear (ton)	91	120	145
Brace axial force (ton)	41.2	53.3	65.3
Brace core area (cm^2)	19.08 ~ 20	24.67 ~ 25	30 ~ 30.23

Table 3
Specifications of VDs

Model	Type	Damping ratio (%)	Magnification factor	Damping Coefficient (ton.sec/m)	Damper Stiffness (ton/m)
6 story	Diagonal	25	f_v=0.6	305.97	4320.88
10 story	Diagonal	25		666.12	5388.43
15 story	Diagonal	25	f_h= 0.8	1310.25	6749.47

To validate the modeling of the behavior of viscous damper, the response presented in a study by Banazadeh [4] is employed, where a 1-story single-span frame is modeled using SAP and OpenSees according to Fig. 5. The frame is made of sections including TUB 200×20 for columns and W 5×16 for beams and subjected to a distributed load of 0.05 KN/mm and the time history analysis is conducted using the Kobe earthquake record at a scale factor of 0.5. In this study, the VD is similarly modeled in a 1-story single-span frame and its response to time history analysis under the Kobe earthquake record at a scale factor of 0.5 is compared with that of study by Banazadeh [4] according to Fig. 6; the acceptable compatibility between the results implies the proper performance of modeled VD in this study.

2.2. BRB and VD modelling

Given the symmetry of braces on both sides of structure for each frame, half of total base shear force calculated for the structure is taken into account in this study and the axial force of the brace and area of BRB steel core are then obtained. Tables 2 and 3 represent the specifications of BRBs and VDs, respectively.

3. Incremental Dynamic Analysis and results

Incremental dynamic analysis (IDA) using 7 earthquake records normalized in acceleration of gravity on 10 scales ranging from 0.1g to 1.0g is performed. The specifications of applied records are given in Table 4. The results of the analysis of each structure are then plotted as IDA curves, i.e. MRF, frame equipped with VD, frame equipped with BRB and frame equipped with BRB+VD. The fragility curves and maximum inter-story drift response of each structure as a failure index at 1PGA are compared with each other in order to estimate the vulnerability of structures during various earthquakes at different performance levels using statistical and probabilistic functions. Fig.7 illustrates the IDA curve of 15-story structure with moment resisting frame system. Table 5 represents the period of 6-, 10- and 15-story models of three states.

Fig. 8 shows that the maximum drift response occurs in middle stories at about 0.4-0.6 of total height in high-rise MRF. The chart of the Tabas earthquake also indicates the instability of mid-rise structure under the record; except for this earthquake, the inter-story drift of structure gradually decreases at the bottom and top floors for other earthquakes.

Given the fragility curve of 10-story MRF in Fig. 9, the exceedance probability (EP) of a slight level of damage between 0.1PGA and 0.4PGA increases dramatically and reaches about 50% at 0.4PGA; then, the slope of the curve lowers and finally reaches about 69% at 1PGA. At the moderate level of damage, the EP uniformly rises for different accelerations and finally reaches about 65% at 1PGA. At extensive level of damage, the EP approximately equals zero up to 0.3PGA and then gently increases to 0.7PGA; the slope continues to grow significantly and then reaches about 50%. A complete level of damage, the EP equals zero up to 0.7PGA and then gradually reaches 13%; so that sudden changes in the slope of curves at 0.7PGA can represent the formation of plastic hinges in the structure and its vulnerability at these accelerations.

Table 4
Applied seismic records [30]

NO	Earthquake	Site	Year	PGA(g)
1	Bam	Bam	2003	0.81
2	Erzincan	Erzincan	1992	0.5
3	Izmir	Izmir	1997	0.42
4	Kobe	Takarazuka	1995	0.67
5	Loma printa	Los Gatos	1989	0.41
6	Northridge	24087 Arleta –Nordhoff Fire	1994	0.34
7	Tabas	Tabas	1999	0.84

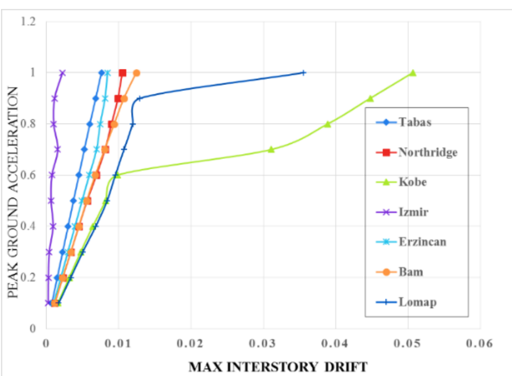

Fig. 7. IDA curve for 15-story structure equipped with VD

Table 5
Period of models (sec)

Model	MRF	VD	BRB	BRB+VD
6 story	0.45	0.45	0.22	0.22
10 story	0.77	0.77	0.32	0.32
15 story	1.22	1.22	0.44	0.44

According to Fig. 10, when seismic dampers are attached to the structures, e.g. mid-rise structures, the maximum responses occur on lower stories at about 0.2-0.4 of building height in comparison with the MRF. According to the fragility curve of the 10-story structure equipped with VD in Fig. 11, the EP of structure at slight level of damage equals zero up to 0.3PGA and then rises uniformly until reaches 38% at 1PGA, indicating a 30% decrease in comparison with the MRF. At the moderate level of damage, the EP equals zero up to 0.5PGA and then constantly reaches 18% at 1PGA, which shows a 50% decrease in comparison with MRF. For the extensive and complete levels of damage, the EP is about zero throughout the analysis, where the structure possesses adequate safety level, which respectively 50% and 15% decreases show a good seismic performance in these structures compared to the MRF.

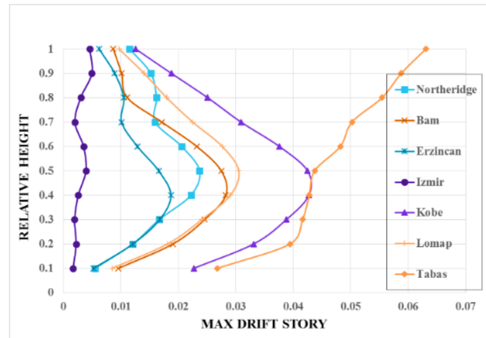

Fig. 8. Inter-story drift responses of 10-story MRF

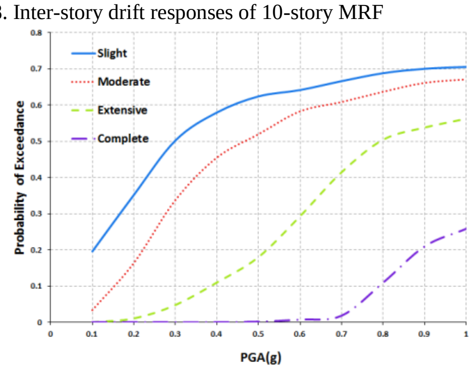

Fig. 9. Fragility curve of 10-story MRF

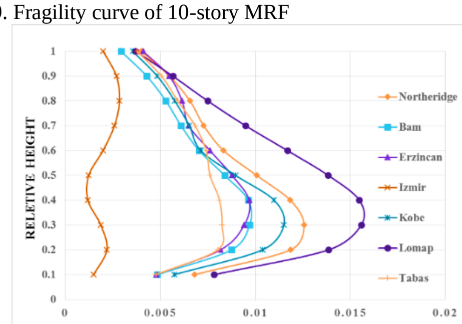

Fig. 10. Inter-story drift responses of a 10-story structure equipped with VD

Fig. 12 shows that in high-rise structures equipped with BRBs, the maximum drift response occurs on the floors at 0.2-0.4 of total building height but the responses on upper floors decrease more intensively compared to

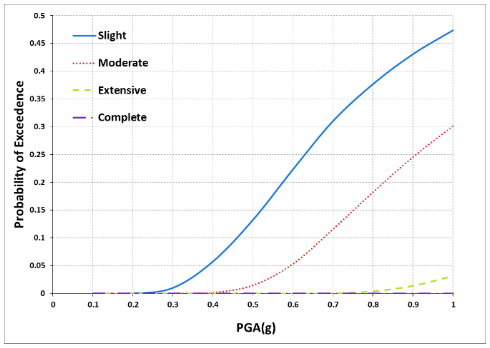

Fig. 11. Fragility curve of a 10-story structure equipped with VD

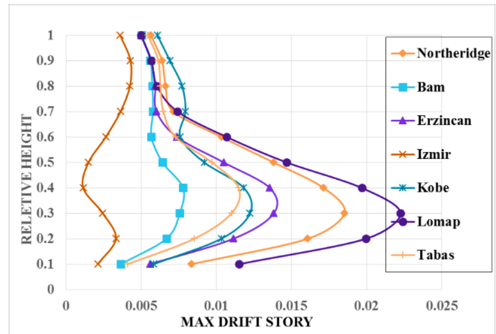

Fig. 12. Inter-story drift responses of a 10-story structure equipped with BRB

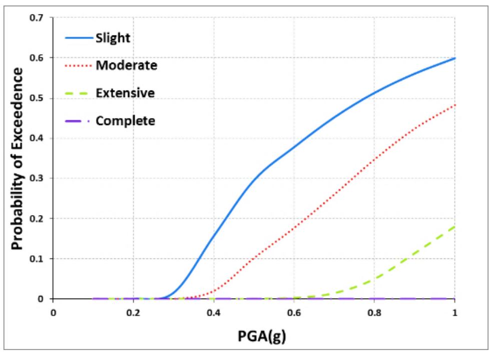

Fig. 13. Fragility curve of a 10-story structure equipped with BRB

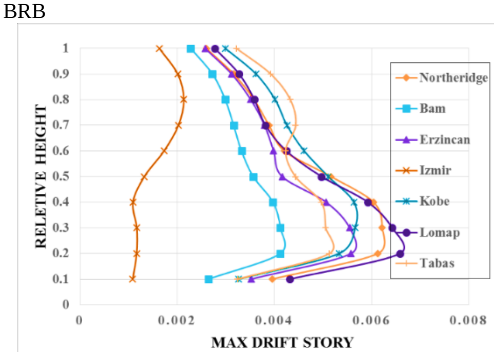

Fig. 14. Inter-story drift responses of a 10-story structure equipped with BRB+VD

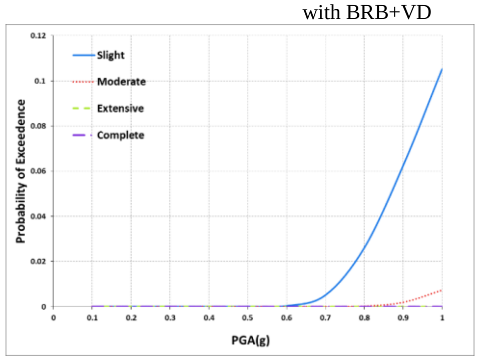

Fig. 15. Fragility curve of a 10-story structure equipped with BRB+VD

mid-rise structures; hence the probability of formation of plastic hinges and their number would be relatively higher than that for mid-rise frames. Given the fragility curve in Fig. 13, it is observed that the EP of 10-story structure equipped with BRB at the slight level of damage equals zero up to 0.3PGA and eventually surges to 53% on a constant steep slope at 1PGA, indicating a 40% decrease at 0.3PGA and a 15% decrease at 1PGA compared to the MRF. At the moderate level of damage, the EP equals zero up to 0.3PGA and then steadily reaches about 53% at 1PGA, showing a 12% decrease compared to the MRF. At extensive level of damage, the EP equals zero up to 0.7PGA and finally reaches about 18%, indicating a 30% decrease compared to the MRF. A complete level of damage, the EP of structure equals zero at all accelerations, which indicates a 13% decrease compared to the MRF.

As shown in Fig. 14, in high-rise structures equipped with BRB+VD, bottom floors are more vulnerable than other floors and the maximum drift response occurs at about 0.2 of building height; this indicates that the maximum response in these structures is still transferred to bottom floors compared to other high-rise structures. In Fig. 15, the fragility curve of a 10-story structure equipped with BRB+VD demonstrates a very low EP for slight level of damage at accelerations above 0.7PGA; so that the EP equals zero up to that acceleration and then reaches 3% at 1PGA on a constant slope. For other performance levels, the EP equals zero up to 1PGA. In Table 6, the changes in drift responses and the decrease in EP for the structure equipped with BRB+VD is compared to those for structures equipped with MRF, VD, and BRB.

According to Table 6, it can be concluded that the simultaneous use of BRB+VD in mid-rise structures causes a 98%, 93% and 53% decrease in inter-story drift response compared to MRF, VD and BRB, respectively, which indicates the good performance of these two systems in the reduction of structural response. It is also seen that although the simultaneous application of BRB+VD leads to a 65%, 55% and 22% decrease compared to the MRF at slight, moderate and extensive levels of damage, respectively, the changes in PE of model equals almost to zero compared to mid-rise BRB or VD structures at different levels; this implies that mid-rise structures equipped with BRB or VD can lonely meet safety requirements at different performance levels and the simultaneous use of both systems seems very conservative and unnecessary in spite of considerable decrease in maximum drift response.

For high-rise structures, the simultaneous use of BRB+VD leads to an 89%, 58%, and 70% decrease compared to MRF, VD and BRB respectively, which indicates the good performance of both systems to reduce the maximum response of structure; but the decrease in maximum structural responses is less than those for mid-rise models. Moreover, the simultaneous use of BRB+VD in high-rise structures reduces the PE by 69%, 38% and 53% at slight level of damage and by 65%, 18% and 40% at moderate level of damage compared to the MRF, VD and BRB, respectively. So, it can be concluded that these structures need to meet safety requirements at 1PGA. At extensive and complete levels of damage, the PE declines by 50% and 13% in BRB+VD compared MRF, respectively; but the decrease in PE equals almost to zero compared to VD or BRB. Results implies that the structure can adequately meet safety requirements at these levels by the installation of BRB or VD alone and the simultaneous use of both systems leads to no changes in PE at these levels. Hence it can be concluded that if it is required to provide safety at slight and moderate levels of damage, the unique performance of both systems can be employed simultaneously; but if safety at extensive and complete levels of damage is required, the BRB or VD can lonely meet the requirements and their simultaneous use is not cost-efficient.

Given the values for super high-rise structures equipped with BRB+VD, it is also observed that the maximum drift response of these structures is reduced by 86%, 86% and 78% compared to the MRF, VD and BRB, respectively. Hence these structures show a good performance by limiting the maximum structural response to allowable values of the code. The structural response decreases by 53%, 51% and 48% at slight level of damage, 68%, 66% and 42% at moderate level of damage, 57%, 57% and 40% at extensive level of damage and 25%, 25% and 4% at complete level of damage compared to the MRF, VD and BRB, respectively. Thus, these structures are vulnerable at all performance levels and just the frame equipped with BRB has relative safety at complete level of damage. Therefore, the simultaneous use of BRB+VD is crucial in super high-rise structures to meet safety requirements at 1PGA.

4. Discussion and interpretation of results

In mid-rise structures equipped with MRF and BRB, the floors at 0.4-0.6 of building height have the maximum inter-story drift during earthquakes and are the most vulnerable points. These structures equipped with MRF system experience higher damage probability in earthquakes above 0.5PGA for slight and moderate levels of damage. So these structures experience PE of 65% and 55% at 1PGA for the performance levels, respectively. This indicates their vulnerability at these performance levels, while PE is zero up to 0.6PGA for extensive level of damage and reaches 20% at 1PGA. The PE equals zero throughout the analysis for complete level of damage; hence the structure generally possesses adequate safety at these performance levels. In the system equipped with VD, the floors at 0.3-0.4 of total building height show the maximum drift responses. These structures have PE of zero throughout the analysis for slight, moderate, extensive and complete levels of damage, indicating 50%, 47%, and 20% reductions compared to the MRF structure for slight, moderate and extensive levels of damage respectively. Therefore, the model has adequate safety at 1PGA for all performance levels. In mid-rise structures equipped with VD, the variation of inter-story drift is linear, which implies that plastic hinges are not formed and the structure does not exceed the elastic region; the maximum drift response is reduced by 74% compared to MRF.

The PE of mid-rise structures equipped with BRB is zero for whole slight, moderate, extensive and complete levels of damage, which shows that BRBs can properly meet safety requirements of these structures at 1PGA. Similar to structures equipped with VD, the variation of maximum drift response in mid-rise structures equipped with BRB is linear, which indicates the elastic conditions and formation of no plastic hinges. In structures equipped with BRB+VD, the maximum drift responses occur at about 0.3 of total building height. Which demonstrates that the model has adequate safety at the performance levels and the variation of maximum drift response is linear.

In high-rise structures equipped with MRF system, the floors at 0.4-0.6 of total building height experience the maximum drift response, which occurs on the floors at 0.2-0.4 of total building height in the structures equipped with

Table 6
BRB+VD Compared to other models

Model	6 Story (mid-rise structure) Loss of PE of damage state: slight	moderate	extensive	complete	Max. response	Response reduction (%)	10 Story (high-rise structure) Loss of PE of damage state: slight	moderate	extensive	complete	Max. response	Response reduction (%)	15 Story (super high-rise structure) Loss of PE of damage state: slight	moderate	extensive	complete	Max. response	Response reduction (%)
MRF	65	55	22	0	0.034	98	69	65	50	13	0.063	89	53	68	57	25	0.051	86
VD	9	1	0	0	0.008	93	38	18	0	0	0.016	58	51	66	57	25	0.05	86
BRB	0	0	0	0	0.001	53	53	40	8	0	0.022	70	48	42	40	4	0.032	78

VD or BRB and at 0.2 of total building height in the structures equipped with BRB+VD, considered as the most vulnerable floors. Compared to initial accelerations, the PE of MRF system undertakes a significant increase at different performance levels, i.e. 69%, 65%, 50% and 13% at 1PGA for slight, moderate, extensive and complete levels of damage, respectively that shows the vulnerability of structure at these levels. In these models, the variation of drift response also increases at accelerations above 0.7PGA, which refers to the formation of plastic hinges. In the models equipped with VD, the PE at 1PGA is 38% and 18% for slight and moderate levels of damage, respectively, and almost zero for both extensive and complete levels of damage with 30%, 50%, 50%, and 15% decrease for slight, moderate, extensive and complete levels of damage, respectively. Which reveals the adequate safety of these structures up to 1PGA. In these structures, the variation of drift response is almost linear, indicating that the structure is in the elastic region during the analysis.

In high-rise structures equipped with BRB, the PE at 1PGA is 53%, 40%, 8% and 0% for slight, moderate, extensive and complete levels of damage and the variation of maximum drift is non-linear at accelerations above 0.4PGA, that demonstrates the relative formation of plastic hinges. For the structures equipped with BRB+VD, reductions of 53%, 40%, and 8% are also observed at slight, moderate and extensive levels of damage compared to the corresponding structure equipped with BRB. In high-rise structures equipped with BRB+VD, the maximum drift response shows a 58% decrease in comparison with the structure equipped with BRB.

The maximum drift response occurs on floors at 0.4-0.6 of building height in super high-rise structures equipped with MRF or VD and on floors at 0.2-0.4 of building height in structures equipped with BRB or BRB+VD, representing the vulnerability of these floors in super high-rise structures. In the structures equipped with MRF, the PE is so great even at low earthquake accelerations for slight and moderate levels of damage, i.e. 73% and 70% at 1PGA, respectively. It increases considerably at accelerations above 0.7PGA for extensive and complete levels of damage, i.e. 58% and 25% at 1PGA, respectively, which represents significant vulnerability of these structures. For the MRF system, the variation of maximum drift response often has a considerable slope at accelerations above 0.4PGA and the non-linear trend indicates the formation of plastic hinges, which mostly exceeds allowable values and reaches twice as much as them in some cases.

In addition, VDs does not have a reliable performance in super high-rise structures and practically lose their efficiency in some seismic records. In these structures, the PE decreases suitably at low accelerations, i.e. 40%, 38% and 35% at 0.6PGA for slight, moderate and extensive levels of damage, respectively. However, they are not efficient at higher accelerations and show negligible variations at 1PGA compared to the MRF structure. In super high-rise structures equipped with VD, the variation of maximum drift response is linear up to 0.6PGA that represents the elastic state, but it abruptly rises at higher accelerations in some earthquakes; hence it does not seem so reasonable to apply dampers in super high-rise structures.

The PEs of super high-rise structures equipped with BRB exhibit the high vulnerability of model for various performance levels, particularly at accelerations above 0.5PGA. The variation of maximum drift response starts to increase significantly at accelerations above 0.4PGA and exceeds allowable values at higher accelerations, which indicates the inefficiency of BRBs to meet safety requirements of the structure. In super high-rise structures equipped with BRB+VD, the PE equals to zero at entire performance levels, indicating appropriate safety at all performance levels. Despite significant decreases in these structures, the variation of maximum drift response at accelerations above 0.4PGA follows an irregular trend compared to other structures, which is due to the distribution of seismic forces applied to structural members, BRB+VD, considering the low values of structural response. Super high-rise structures equipped with BRB+VD show a very good performance due to the 78% decrease in the maximum structural response compared to structures equipped with BRB and the limitation of maximum structural response to allowable values of the code. The super high-rise structure equipped with BRB+VD shows 48%, 42%, 40%, and 4% decreases for slight, moderate, extensive and complete levels of damage, respectively, compared to the structure equipped with BRB.

5. Conclusions

In this study, three 6-, 10- and 15-story structures are considered to investigate the effect of VDs on the response of structures equipped with BRBs. Four systems, e.g. MRF, frame equipped with VD, frame equipped with BRB and frame equipped with BRB+VD, are then modeled using OpenSees. The IDA is conducted for the structures at different accelerations and frequencies under 7 seismic records and the results are finally examined in form of IDA, fragility and inter-story drift curves.

Investigating the IDA results and fragility curves of the structures, it is concluded that the simultaneous use of BRB+VD provides no reduction of PE for mid-rise structures at slight, moderate, extensive and complete levels of damage in comparison to the systems equipped with BRB or VD. Therefore, these structures can meet safety requirements at different performance levels merely by BRBs or VDs and the simultaneous application of both systems seems highly conservative in spite of significant decrease in maximum drift response.

Moreover, high-rise structures equipped with BRBs or VDs can meet safety requirements at extensive and complete levels of damage, but both BRBs and VDs should be utilized to provide safety at slight and moderate levels of damage. One of the key findings of the research is that super high-rise structures equipped with MRF, BRB or VD are vulnerable at the entire slight, moderate, extensive and complete levels of damage; hence it is required to employ structures equipped with BRB+VD to meet safety requirements at accelerations up to 1PGA. This means that structural engineers can significantly enhance the safety of high-rise and super high-rise buildings by ensuring both BRB and VD systems work together. Overall, this study highlights the importance of earthquake resistance structural systems ensuring the safety of the occupants during seismic events.

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