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RESEARCH ARTICLE

Response Modification Factors for Reinforced Concrete Structures Equipped with Viscous Damper Devices

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Abstract

The response modification factor is one of the seismic design parameters that determine the nonlinear performance of building structures during strong earthquakes. Most seismic design codes lead to reduced loads. Nevertheless, an extensive review of related literature indicates that the effect of viscous dampers on the response modification factor is no longer considered. In this study, the effect of implementing viscous damper devices in reinforced concrete structures on the response modification factor was investigated. Reinforced concrete structures with different stories were considered to evaluate the values of the response modification factors. A nonlinear statistic analysis was performed with finite element software. The values of the response modification factors were evaluated and formulated on the basis of three factors: strength, ductility, and redundancy. Results revealed that the response modification factors for reinforced concrete structures equipped with viscous damper devices are higher than those for structures without viscous damper devices. The number of damper devices and the height of buildings have significant effects on response modification factors. In view of the analytical results across different cases, we proposed an equation according to the values of damping coefficients to determine the response modification factors for reinforced concrete structures furnished with viscous damper devices.

Keywords

response modification factor, equivalent statistical analysis, ductility factor, over strength factor, seismic response, frames without viscous dampers, frames with viscous dampers

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1 Introduction

The response modification factor is one of the main parameters in seismic construction design. Equivalent static analysis is the technique for evaluating the seismic response of structures. This technique can be implemented by determining the response modification factor. Current structural design codes focus on complete safety and sturdiness even during earthquakes. However, such endeavor is impossible to achieve. Nevertheless, certain structural and nonstructural damages can be studied to economically achieve a high level of life safety in structural design by applying an inelastic energy dissipation system. The designed lateral strength of structures must be kept within the elastic range according to seismic codes. Hence, the designed lateral strength is usually lower than the required lateral strength. Maintaining the inelastic range of a structure means that all the structural and nonstructural members of this structure that are subjected to lateral motion are assured to return to their initial state without permanent deformations and damages. Preserving this state is far from being feasible and rational in many cases. On the contrary, going beyond the elastic frontier in an earthquake event may lead to the yielding and cracking of structural members, which can lead to catastrophic results unless these inelastic actions are limited to a certain degree. Thus, inelastic behavior definitely decreases overall construction costs by reducing member sizes and thus reducing materials and construction time. It also facilitates operability and construction.

According to the International Building Code [1], a response modification coefficient (R), including the effect of inelastic deformations, must be applied to evaluate the design of the seismic forces of structures that have been reduced and to evaluate the deflection amplification factor (Cd) for converting elastic lateral displacements to total lateral displacements. The values of the R factor and Cdset in the IBC [1] are based on observations of the performance of different structural systems in previous strong earthquakes, on technical justification, and on tradition [2]. The R coefficient is proposed to explain ductility, over strength, and energy dissipation through the soil foundation system [2].

Numerous studies have been performed on the selection of response modification factors (R) for the seismic design of structures. For example, Miranda [3] presented a summary of different investigations on the R coefficient, which the author described as a strength reduction factor (R_μ). Miranda [3] further suggested that the factor (R_μ) is mostly a function of displacement ductility (μ), natural period of a structure (T), and soil conditions. The study concluded that the use of strength reduction factors based on ductility, period, and soil conditions, together with the estimation of structural over strength factors and relationships between local and global ductility demands, is required to establish rational seismic design approaches. Lin and Chang [4] subjected 102 earthquake records to linear elastic single degree-of-freedom (SDOF) systems with damping ratios between 2% and 50% and with periods ranging from 0.01 s to 10 s to develop a formula for a period-dependent damping factor.

Ramirez et al. [5] derived damping factor data through 10 earthquake histories for linear elastic SDOF systems with damping ratios ranging from 2% to 100%.The authors considered BSand B1as the damping reduction factors for period T, which is given by 0.2Ts and Ts. On the basis of this study, the National Earthquake Hazards Reduction Program [2] developed a two-parameter model for the design of structures with damping systems. Wu and Hanson [6] obtained a formulation for damping reduction factors from a statistical study of nonlinear response spectra with high damping ratios. Ten earthquake records were used as input ground motions for elasto-plastic SDOF systems with damping ratios between 10% and 50%. Ashour [7]developed a relationship that describes the decrease in the displacement response spectra for elastic systems with changes in viscous damping. Viscous damping ratios of 0%, 2%, 5%, 10%, 20%, 30%, 50%, 75%, 100%, 125%, and 150% were considered in the study. The α coefficients were set to 18 and 65 for the upper and lower bounds of B, respectively.

Freeman [8] reported over strength factors for three steel moment frames. Two of these frames were constructed in seismic zone 4, and one frame was constructed in seismic zone 3. Their over strength factors were determined to be 1.9, 3.6, and 3.3.Osteraas and Krawinkler [9] observed the over strength and ductility of steel frames designed in compliance with the working stress design provisions of the Uniform Building Code. In their study, the over strength factor for the moment frames ranged from 8 in the short period range to 2.1 at 4 s. The over strength factor for the concentric braced frames (CBFs) ranged from 2.8 to 2.2 at 0.1s to 0.9s, respectively. Kappos [10] examined five reinforced concrete (RC) buildings with one to five stories consisting of beams, columns, and structural walls and obtained an over strength factor ranging from 1.5 to 2.7. In the *Response Modification Factors for Earthquake Resistant Design of Short Period Structures*, which was based on inelastic spectra, Riddell et al. [11] computed for four different earthquake records using SDOF systems with an elasto-plastic behavior and with 5% damping.

Mondal et al. [12] estimated the actual R factor value for a realistic RC moment frame building and compared it with the value suggested in the design based on the Indian code. The R value based on the Indian standard code is higher than the actual R value obtained in the study; such difference is potentially dangerous[12]. Mahmoudi and Zaree[13] evaluated the response modification factors for congenital CBFs and buckling-restrained braced frames (BRBFs). Their results revealed that a conventional pushover analysis (CPA) cannot count high mode outcomes and member stiffness changes, whereas an adaptive pushover analysis (APA) can overcome these drawbacks. Mahmoudi and Abdi [14] evaluated the response modification factors for triangular-plate added damping and stiffness frames and discovered that the response modification factor for T-SMRFs has a higher value than that for SMRFs. Mahmoudi et al. [15] investigated the equivalent damping and response modification factors for frames equipped with pall friction dampers. Kappos et al. [16] evaluated the response modification factors for concrete bridges in Europe.

According to the research of Galasso et al. [17], code provisions are not conservative and fail to provide a basis for an improved calibration of future editions of seismic design codes for buildings. Bojórquez et al. [18] studied the influence of cumulative plastic deformation demands on the values of the target ductility and their corresponding strength reduction factors. Mollaioli et al. [19] studied the displacement damping modification factors for pulse-like and ordinary records. Records from 110 near-fault pulse-like ground motions and 224 ordinary ground motions were used to calculate elastic displacements and DMF spectra corresponding to different values of the damping ratio ranging from 2% to 50%.According to the study of Mahmudi and Zaree [20], the response modification factors for BRBFs have high values, and the number of bracing bays and the height of buildings have a significant effect on response modification factors.

Hejazi et al. [21] conducted an earthquake analysis of reinforced concrete frame structures with viscous dampers and found that using a damper device as a seismic energy dissipation system can effectively reduce the structure response of a frame structure during an earthquake. Hejazi et al. [22] also examined the inelastic seismic response of an RC building with a control system. The result of their nonlinear analysis of a structure furnished with viscous dampers indicated that viscous dampers effectively reduce building damage and structural motion during severe earthquakes. Hejazi et al. [23] optimized an earthquake energy dissipation system with a genetic algorithm and discovered that an optimized control system effectively reduces the seismic response of structures, thereby enhancing building safety during earthquake excitation.

Daza [24] investigated the relationship between response modification factors and minimum building strength and illustrated the relationship between the R factor and the essential strength of the building established on the basis of these mechanisms and the pushover analysis of the building. Zeynalian and Ronagh [25] performed experimental investigations to estimate the lateral seismic characteristics of lightweight knee-braced cold-formed steel structures; the R factor of knee-braced walls was found to range from2.8 to 3.61 with an average of 3.18.

Shedid et al. [26] studied the seismic response modification factors for reinforced masonry structural walls. According to Shedid et al. [26], the derived values of seismic force reduction factors (*R*) are close to 5.0 for rectangular walls and 36 for the corresponding flanged and end-confined walls; the former value is reliable based on the ASCE 7 standard, and the latter value is 90% higher than the former.

The equivalent lateral force method is a well-known approach for structural engineers because of its simplicity and reliability when used to calculate the lateral forces induced by earthquakes. The R factor is a seismic design parameter that considers the nonlinear performance of building structures during strong earthquakes. Furthermore, the application of supplementary energy dissipation systems, such as viscous dampers, has attracted increasing interest among engineers, experts, and researchers. The literature indicates that information on the effect of viscous dampers on over strength, ductility, and response modification factors is not available, and no study has evaluated R factors for reinforced concrete structures equipped with viscous damper devices. Moreover, the effect of damping coefficients on R factors when structures are equipped with viscous damper devices has not been reported. Accordingly, the present study intends to derive and discuss the effects of viscous dampers on the over strength, ductility, and response modification factors for structures equipped with viscous dampers at different story levels. The main aim is to perform an equivalent static analysis of reinforced concrete structures equipped with viscous damper devices and to evaluate the related R factors. Numerical studies using the SAP2000 program were performed on reinforced concrete structures with viscous dampers at different story levels. The graph and equation for determining the R factors were derived from the analysis results.

2 Response modification factors (R)

Force reduction factors are necessary to design earthquake load-resisting elements. Response modification factors proposed for the first time in ATC 3-06 [27] were selected according to the observed performance of buildings during previous earthquakes and to the estimation of over strength and damping [28]. Response modification factors such as over strength, ductility, and redundancy were selected according to ATC-19 [28].

R factors act as an important component of the estimation of the seismic forces of structural buildings. Response modification factors are considered on the basis of ductility (μ), over strength (Ω), and redundancy (ρ) because dynamic structural responses activate these factors to reduce elastic forces into inelastic loads beyond the elastic range.

A load versus displacement curve was used to analyze the excessive behavior of any structural building when subjected to a particular one-directional lateral load. If parameters such as ductility (R_μ), over strength (R_S), and redundancy (R_R) can be evaluated during loading procedures, then R factors can be developed and estimated. The response modification factors in this study were estimated as follows:

$$R = R_S . R_\mu . R_R \tag{1}$$

Fig. 1 shows the over strength and ductility factors based on the pushover curve. These two factors were considered as key components of the R formulation. The parameters in this figure are as follows: design base shear (V_d), displacement caused by design base shear (Δ_w), base shear versus roof displacement relationship at yield point (v_y), roof displacement relationship at yield point (Δ_y), max base shear (v_μ), and max displacement (Δ_{max}).

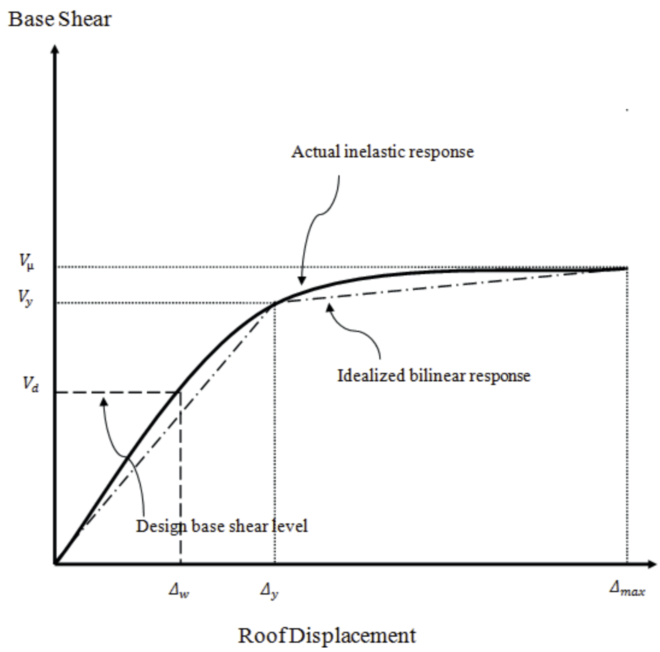


Fig. 1 Idealization of the inelastic response of a structure

Strength factors area measure of base shear force at the design level and at yield point, whereas ductility factors serve as criteria of roof displacement at yield point and at a code-specified limit. Meanwhile, redundancy factors depend on the number of vertical framing in seismic resistance.

Fig. 2presentsthe relationship between the base shear and the roof displacement of a structure with and without a viscous damper device. This relationship was determined by conducting a nonlinear statistical analysis. Fig. 2 particularly demonstrates that the nonlinear behavior of the structure was idealized through a bilinear elasto-plastic relationship. V_{yd} and $V_{\mu d}$ denote the base shear at yield point and the max base shear caused by the damper device, respectively.

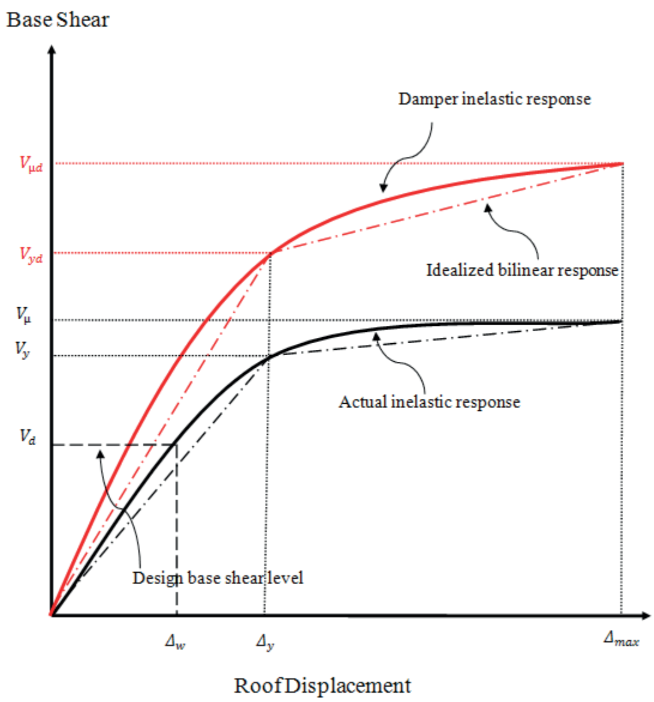


Fig.2 Idealization of the inelastic response of structures with and without damper devices

2.1 Ductility factor

Ductility factors (R_μ) are used to evaluate translation ductility ratios. The relationship between maximum elastic loads (V_{ue}) and maximum inelastic loads (V_u) can define the R_μ factors for the same structural building under inelastic behavior. Newmark and Hall [29] conducted essential studies about response modification factors resulting from ductility. Rμis sensitive to the natural period of structures. Five periods with different ranges exist, and Rμ can be determined according to different values. Fig. 3 illustrates R_μ–μ–T for numerous ductility ratios and periods, and Eqs. (2)–(6)are used to estimate R_μ factors for the different natural periods of structures.

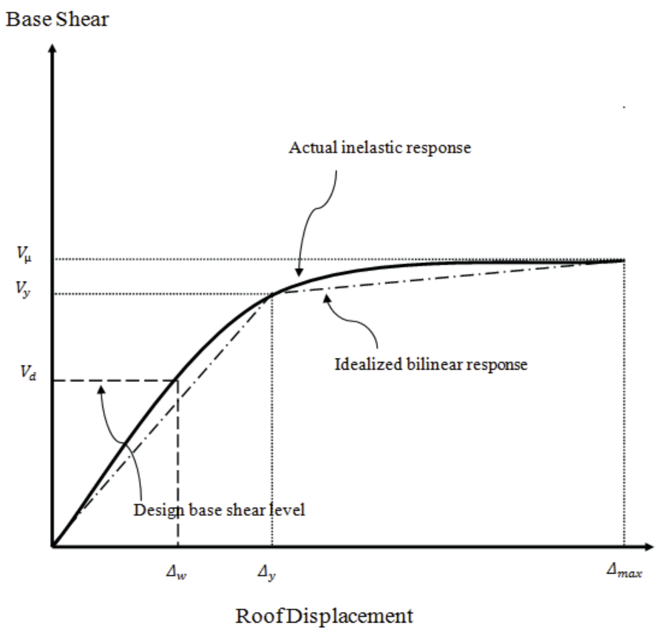


Fig.3 R_μ–μ–T curves (Newmark & Hall)

Periods ≤ 0.03 sec:

$$R_\mu = 1.0 \tag{2}$$

Periods 0.03 <t < 0.12 sec:

$$R_\mu = 1 + \frac{(T-0.03)\cdot\left(\sqrt{(2\mu-1)}-1\right)}{0.09} \tag{3}$$

Periods 0.12 ≤ T ≤ 0.5 sec:

$$R_\mu = \sqrt{(2\mu-1)} \tag{4}$$

Periods 0.5<T <1.0 sec

$$R_\mu = \sqrt{(2\mu-1)} + 2(T-0.5)\cdot\left(\mu-\sqrt{2\mu-1}\right) \tag{5}$$

Periods T ≥ 1.0 sec:

$$R_\mu = \mu \tag{6}$$

2.2 Over strength factor

The real strength of a structure may be higher than its design strength because of overall design simplifications. Modern computer-aided tools allow engineers to model and design structures that closely match those that are actually built. Major simplifications and assumptions are incorporated in the process. These assumptions and design practices are usually in favor of a conservative design to stay on the safe side. The presence of over strength in structures may be examined in a local and global manner. Equation 7 presents the relationship between design base shear (V_d) and max base shear coefficient (V_0).

$$R_S = \frac{V_0}{V_d} \tag{7}$$

2.3 Redundancy factor

Redundancy and over strength are two concepts that should be clearly distinguished. Redundancy is defined as something beyond essential or naturally excessive. The same definition is perhaps applied to over strength. However, this definition is misleading because redundancy in the perspective of structural engineering does not indicate what is unnecessary or excessive. The following is an accurate but indirect definition of redundancy: in a non redundant system, the failure of a member is equivalent to the failure of the entire system. However, failure occurs in a redundant system if more than one member fails. Thus, the dependability of a system is a function of the redundancy of the system, that is, dependability depends on whether the system is redundant. A redundant seismic framing system is composed of multiple vertical lines of framing, which is designed and detailed to transfer seismic-induced inertial forces to the foundation. The multiple lines of framing must be strength-and deformation-compatible to ensure a good response in an earthquake [28].

Redundancy in a system may be of the active or standby type. All members of actively redundant systems participate in load carrying. By contrast, some of the members of systems with standby redundancies are typically inactive and become active only when some of the active components fail. In earthquake design, redundancy in a structural system is of the active type.

2.4 Damping factor

Damping characterizes energy dissipation in a building frame. Such characterization is achieved regardless of whether the energy is dissipated through hysteretic behavior or through viscous damping[28]. Damping is an effect that is either intentionally created or essential to a system. It reduces the oscillation amplitude of an oscillatory system, with a magnitude proportional to that of the velocity of a system but directed to displacement. In structural engineering, the cause of this energy dissipation is related to material internal friction, friction at joints, radiation damping at the supports, or hysteretic system behavior. Modal damping ratios are typically used in computer models to estimate unknown nonlinear energy dissipation within a structure.

3 Pushover analysis

A capacity curve presents the primary data for the evaluation of response modification factors for structures. However, relevant information collected from the plot must first be idealized. In this study, the over strength and ductility factors were evaluated by performing a nonlinear statistical (pushover) analysis. In implementing the effect of the viscous dampers on the response of the structure, we applied the incremental load for pushover within 10 s to provide enough velocity for the viscous dampers to function.

Bilinear idealization provides essential components, namely, significant yield strength and significant yield displacement, as well as predetermined design strength and ultimate displacement. On the basis of these components, the over strength factor can be easily calculated as the ratio of yield strength to design strength. Furthermore, the ductility ratio can be calculated as the ratio of ultimate displacement to yield displacement; it is the key element to calculate the ductility reduction factor.

4 Structural model

The equivalent lateral force analysis is a prominent technique for evaluating the seismic responses of structures. This approach is implemented by determining response modification factors, importance factors, and seismic zone factors. This study proposed response modification factors for reinforced concrete structures equipped with viscous damper devices intended for numerical analyses.

In this study, reinforced concrete structures with different stories that are compliant with UBC [30] and IBC [31] design codes were considered to evaluate the effect of viscous damper devices on response modification factors.

The factors involved in calculating the R factors were evaluated by conducting nonlinear statistical pushover analyses. The R factors were classified on the basis of factors such as over strength and ductility by designing five reinforced concrete structures in 4-, 8-, 12-, 16-, and 20-story buildings for non seismic detailing. In addition to these geometrical variations, structures without dampers at 20%, 40%, 60%, and 80% of the bays equipped with viscous damper devices were considered. Reinforced concrete structures have arrangement plans comprising five bays (6 m each) in both directions, as shown in Fig. 4.

Frame types are illustrated in Fig. 5. Fig. 6 shows the 3D images of the 4-, 8-, 12-, 16-, and 20-story buildings that were explored in this research and considered as new buildings. As the 3D images show, the different floors of the structures were equipped with viscous damper devices according to the percentage of the bay closed by the damper devices. The reinforced concrete structures featured beam-to-column connections that were assumed to be pinned at both ends. The beams measured 400 mm × 500mm, 400 mm × 550 mm, and 500 mm × 700 mm while the columns measured600 mm ×600mm and 800 mm × 1,000mm.

Fig. 7presents the 2D view of each floor of the structures with a span of6 m and a height of 3 m. The load distributions described as dead and live loads of 4 and 5kN/m^2 for each floor and roof were used for gravity. The seismic design base shear was calculated by considering several parameters, such as importance factor I=1.25, seismic zone factor Z = 0.15, soil type II, R = 5.6, seismic coefficient C_v=0.5, and seismic coefficient C_a= 0.3, according to the UBC [30] and IBC [31].Table 1 exhibits the analysis quantities for evaluating the R factors. The beam and column connections were pinned; hence, the seismic load was mainly resisted by the damper device.

Table 1 Sample frame analysis quantities

C_v = Seismic coefficient	0.5
I = Importance factor	1.25
R = Numerical coefficient	5.6
W = Total seismic weight (kN)	W = (DL + 0.25×LL)
C_a = Seismic coefficient	0.3
Z = Seismic zone factor	0.15
N_v = Near-source factor	1

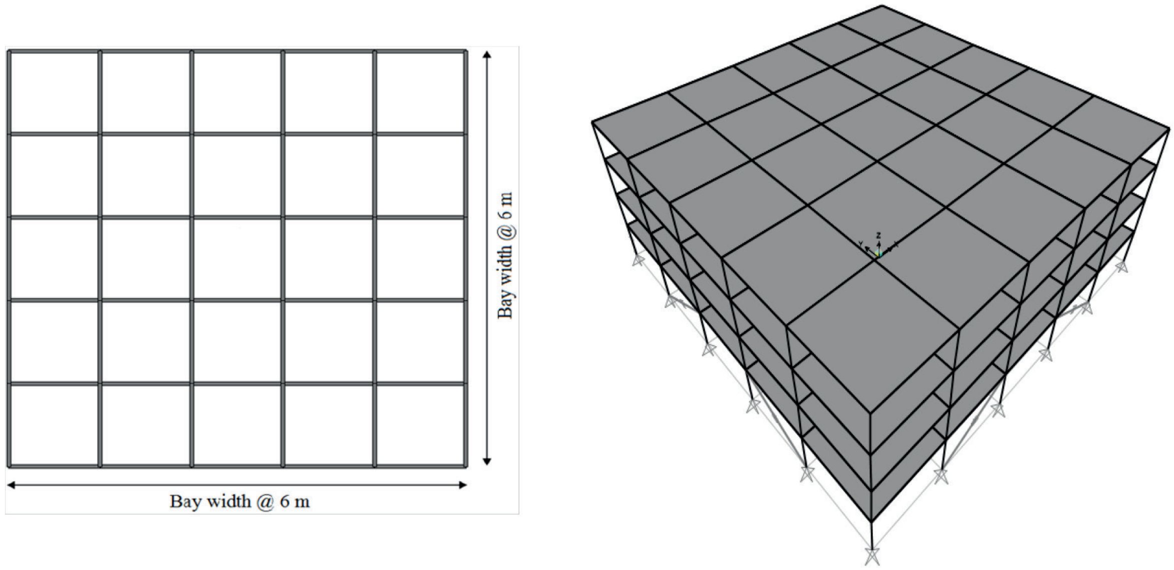
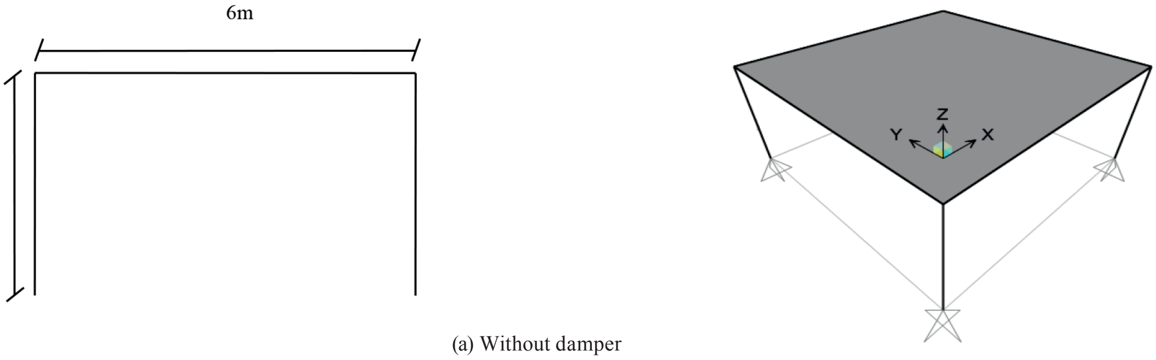
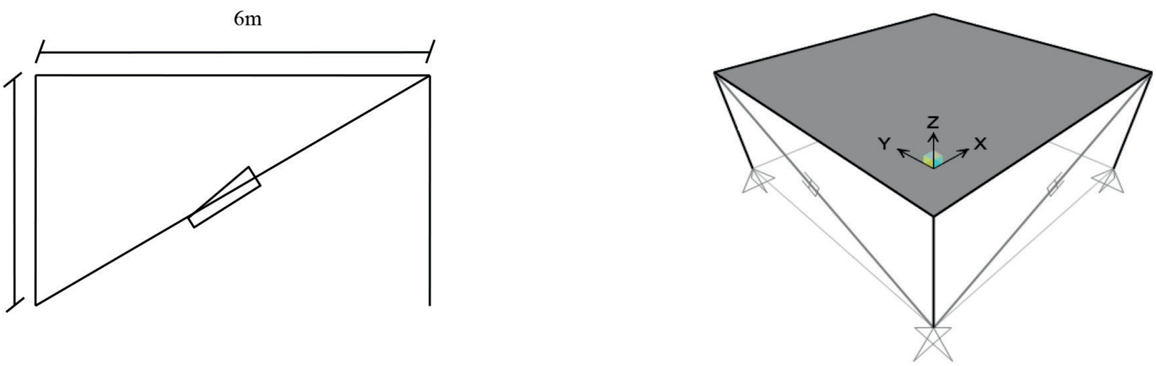


Fig.4 Structural arrangement of buildings in the plan

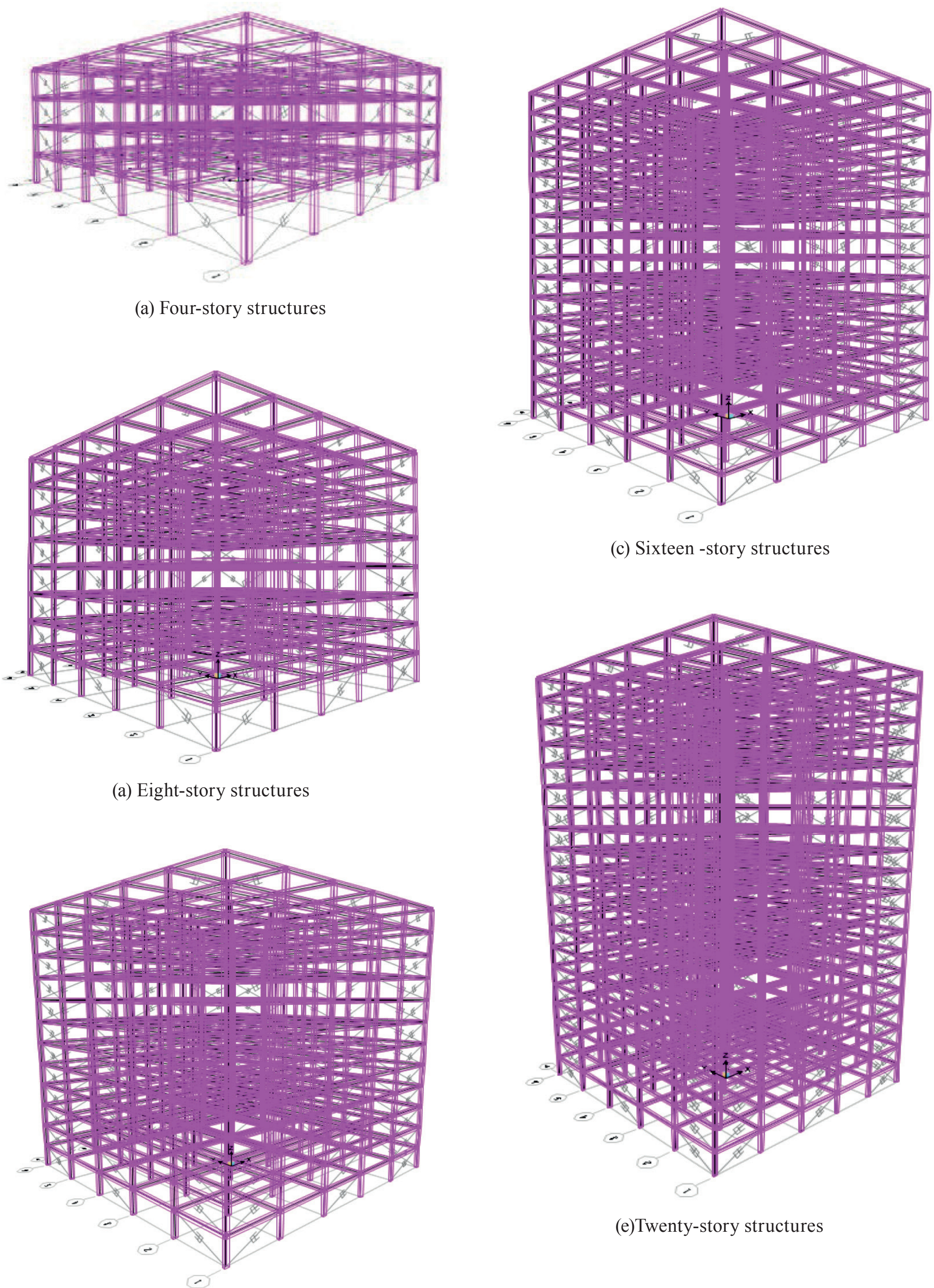


(a) Without damper



(b) With damper

Fig. 5 Frame types



(a) Four-story structures

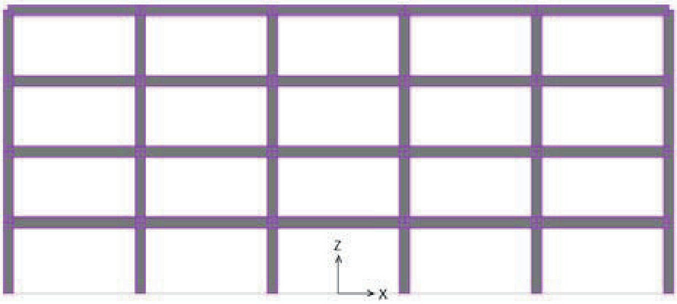
(a) Eight-story structures

(b) Twelve -story structures

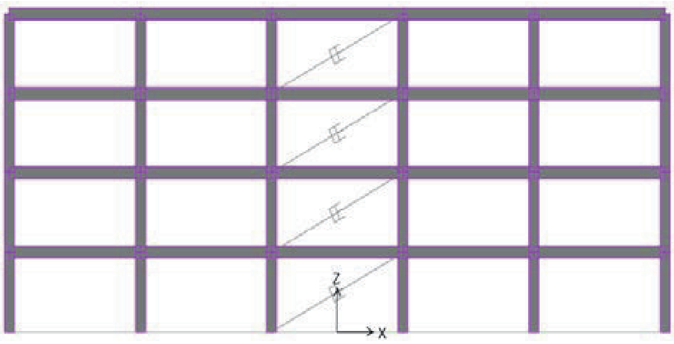
(c) Sixteen -story structures

(e)Twenty-story structures

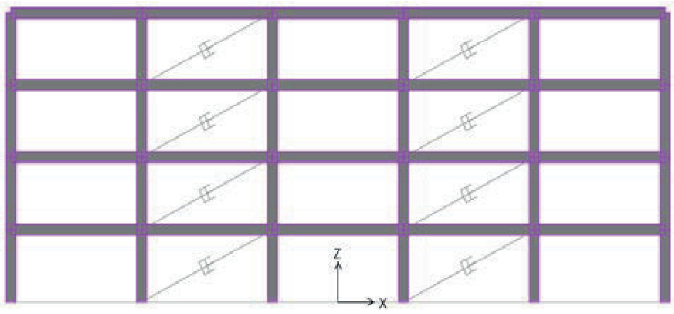
Fig. 6 Design of reinforced concrete structures



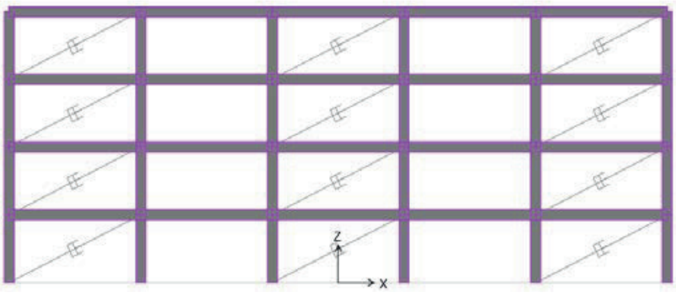
(a) Structures without damper (0%)



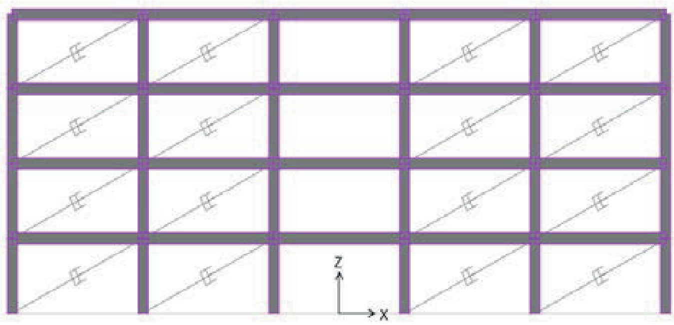
(b) 20% of baysof structuresequipped with damper devices



(c) 40% of bays of structures equipped with damper devices



(d) 60% of bays of structures equipped with damper devices



(e) 80% of bays of structures equipped with damper devices

Fig.7 Structures with different damper assignments

5 Reinforced concrete structures equipped with viscous damper devices

The effect of the number of viscous dampers in each story on the R factors was appraised by considering four different cases, namely, 20%, 40%, 60%,and 80% of the bays equipped with viscous damper devices according to a damping ratio of 5%. The effect of the damper devices on the R factors for the reinforced concrete structures was proposed by selecting available viscous damper devices. Table 2 displays the properties of the fluid viscous dampers [32].

Table 2 Properties of viscous dampers[32]

Force (kN)	C (kN.s/mm)	Mass (kN.mm)
245	0.2568533	0.0408
490	0.5137048	0.08388
734	0.7705581	0.136
980	1.0274114	0.1927
1,470	1.5411163	0.27204
1,958	2.0548211	0.40807
3,003	3.1522833	0.5894
4,004	4.2030444	1.2015
6,450	6.7715721	1.859

6 Results of analysis

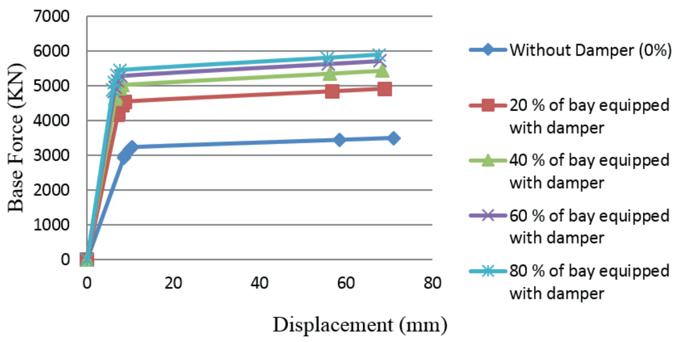
To propose response modification factors for reinforced concrete structures equipped with viscous dampers, we applied an analysis method and illustrated the effect of viscous dampers on response modification factors. An inelastic pushover analysis was conducted for each model. Fig. 7 shows the arrangement of the damper devices in the structures. The pushover curve particularly demonstrates that the implemented viscous dampers were extremely effective in the structures and that the capacity of the structures under applied forces evidently increased with the increase in the number of dampers in each story. Figs. 8 to 10 illustrate the pushover graph for the structures without dampers and the structures with 20%, 40%, 60%, and 80% bays furnished with viscous dampers according to different damping coefficients. Fig. 8 illustrates the structural pushover graphs for the viscous dampers with a damping coefficient of 0.2568533(kN·s/mm).

Table 3 presents the response modification factors for the structures with different arrangements of damper devices. A damping coefficient of 0.2568533 (kN·s/mm) was considered and tabulated with the pushover curves. The results of the calculation revealed that the R factors increased with the installation of damper devices in the different structure levels. Table 3 shows that unlike that in the case without any dampers, the R values could increase by up to 75.3% depending on the different story levels, such as for the 12-story structure. The R factors increased by56.4% on average. This value depends on the percentage of bays equipped with damper devices. The number of dampers and the position of each damper affected the R factors.

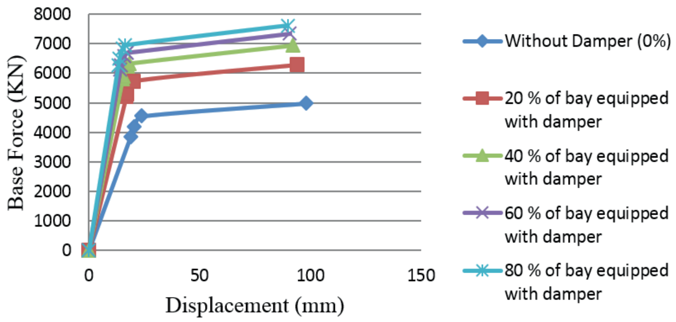
The values of the over strength and ductility factors were increased with the pushover curve for high damping coefficients. Fig. 9 illustrates the structural pushover graphs for the viscous dampers with a damping coefficient of 2.0548211(kN·s/mm) and with different parameters of damper installation. Such parameters affected the base force and roof displacement, which in turn affected the final values of the R factors. In this case, R_S had a high value because of the installed damper devices in the structures. In this research, R_μ was affected by the displacements, and R_R was set to1.Table 4 indicates that the values of the R factors were increased by increasing the damping coefficient. The effect of the damper devices on R ranged from 37.6% to 83%.

The application of the damper devices in the different building levels also significantly influenced the R factors. The dependence of R on the number of bays equipped with dampers and the value of the damping coefficient were considered. Table 5 specifies the R value for each model according to a damping coefficient of 8.4060888 (kN·s/mm). R increased with the addition of the damper devices to the structures. Therefore, the R factors increased by 71.6% on average. This result indicated that the R values increased by 15.2% with the addition of the viscous damper devices under a high damping coefficient.

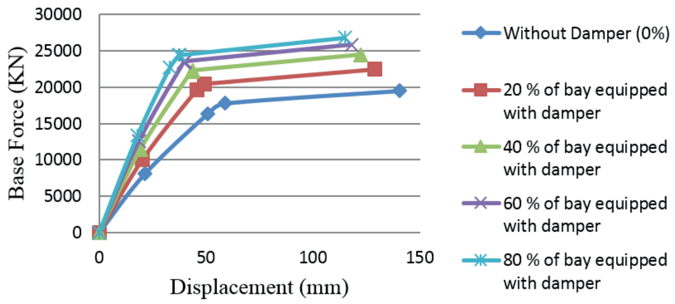
The results indicated that the application of the viscous dampers significantly increased the response modification factors. With this improvement brought by the viscous dampers, the buildings would be effectively protected against severe earthquakes. The increasing trend of the R factors depended on the damper properties and on the percentage of the bays equipped with viscous dampers. The values of the response modification factors obtained in this study are within the range of the response modification factors proposed by FEMA 450 [33]and UBC [30].



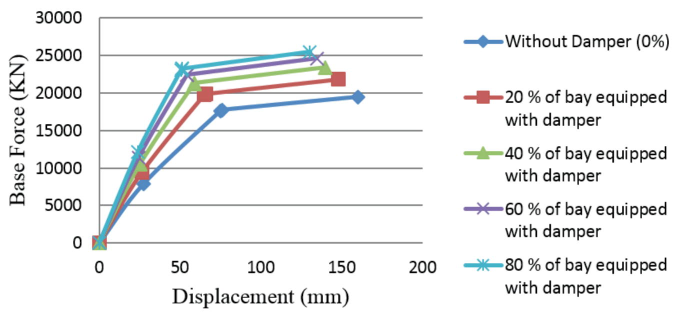
(a) Pushover curve for four-story buildings



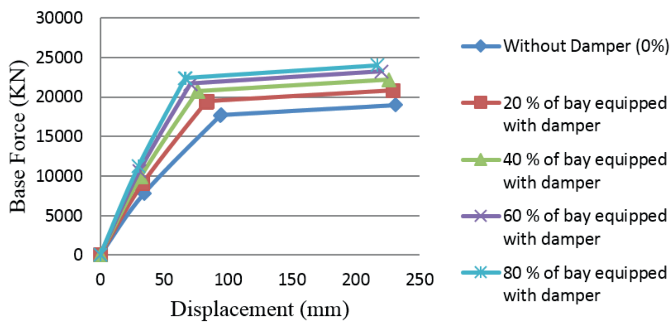
(b) Pushover curve for eight-story buildings



(c) Pushover curve for twelve-story buildings

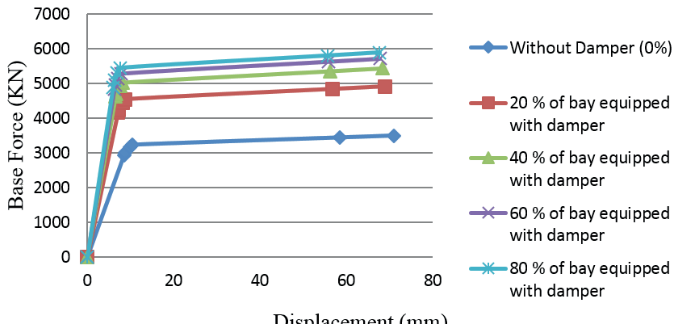


(d) Pushover curve for sixteen-story buildings

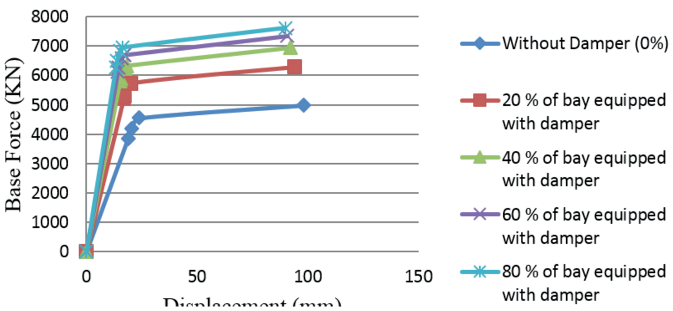


(e) Pushover curve for twenty-story buildings

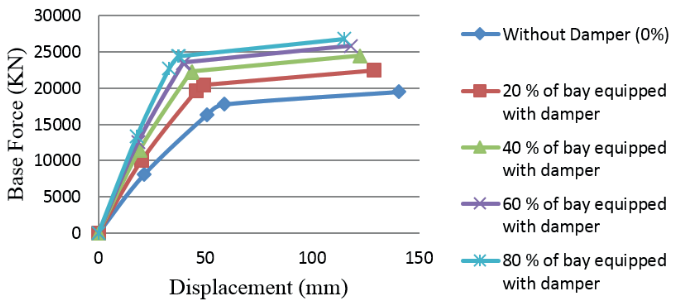
Fig. 8 Pushover curve for viscous damper with C= 0.2568533(kN.s/mm)



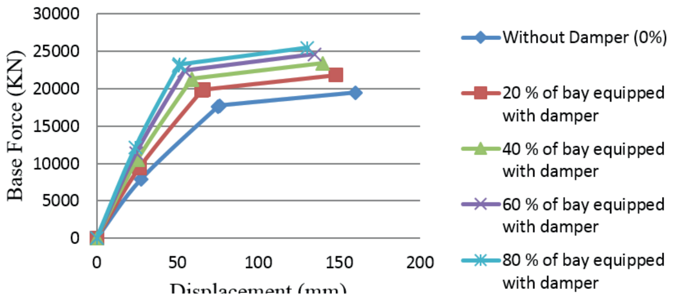
(a) Pushover curve for four-story buildings



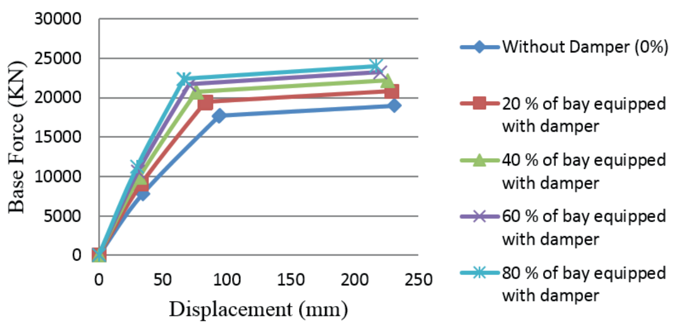
(b) Pushover curve for eight-story buildings



(c) Pushover curve for twelve-story buildings

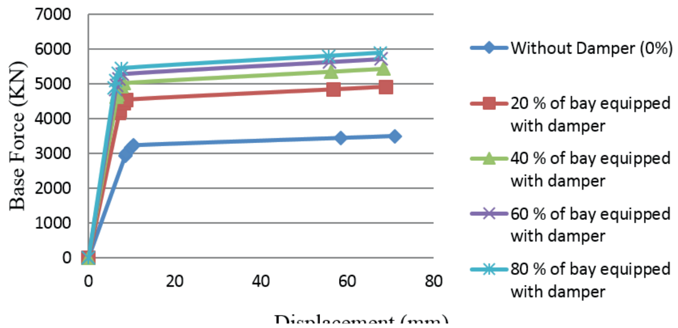


(d) Pushover curve for sixteen-story buildings

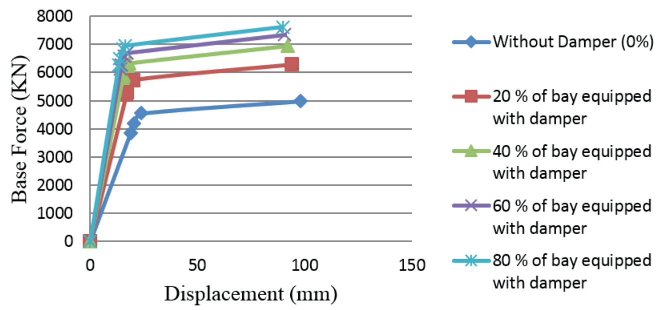


(e) Pushover curve for twenty-story buildings

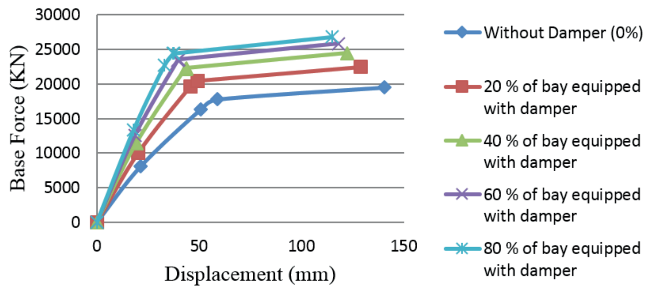
Fig. 9 Pushover curve for viscous damper with C = 2.0548211(kN.s/mm)



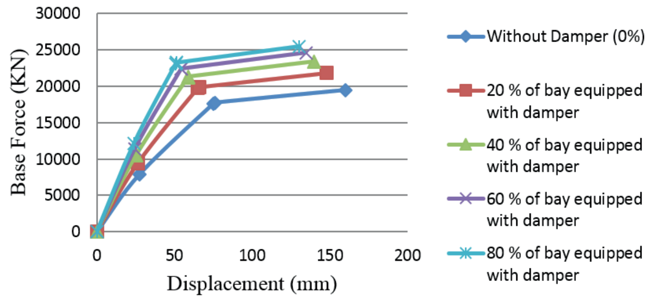
(a) Pushover curve for four-story buildings



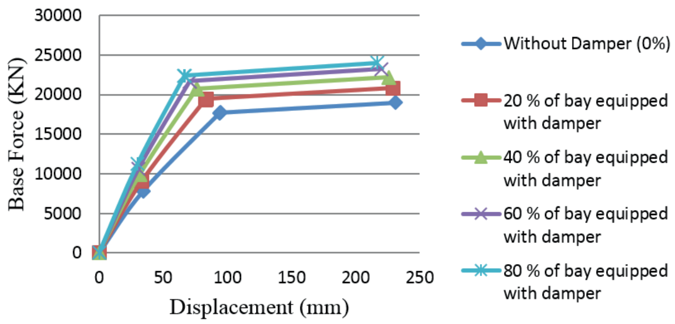
(b) Pushover curve for eight-story buildings



(c) Pushover curve for twelve-story buildings



(d) Pushover curve for sixteen-story buildings



(e) Pushover curve for twenty-story buildings

Fig. 10 Pushover curve for viscous damper with C = 8.4060888(kN.s/mm)

Table 3 Response modification factor for damping coefficient of 0.2568533 (kN.s/mm)

4 story building	V_0(KN)	Δ_y(mm)	Δ_m (mm)	R	% of different each in compare to model 1
Model 1(0%)	3250	9.8	72	1.57	-
Model 2(20%)	4560	9	66	2.20	40
Model 3(40%)	5070	9	66	2.45	56.1
Model 4(60%)	5310	8.5	64	2.56	63.1
Model 5(80%)	5498	8.8	64	2.65	69
Average					57.1
8 story building					
Model 1(0%)	4549	19	98.17	2	-
Model 2(20%)	5770	16	97	2.86	43
Model 3(40%)	6375	14.4	97	3.35	67.5
Model 4(60%)	6775	13	94	3.65	82.5
Model 5(80%)	7030	12	92	3.8	90
Average					70.75
12 story building					
Model 1(0%)	17700	55	138	3.22	-
Model 2(20%)	20563	43.3	129	4.49	39.4
Model 3(40%)	22241	37	123	5.43	68.6
Model 4(60%)	23604	34	118	6.02	86.9
Model 5(80%)	24512	31	114.4	6.64	106.2
Average					75.3
16 story building					
Model 1(0%)	18000	57	162	3.50	-
Model 2(20%)	19972	45	149	4.56	30.3
Model 3(40%)	21493	42	142	5.01	43.1
Model 4(60%)	22560	39	136	5.43	55.1
Model 5(80%)	23500	38	135	5.76	64.6
Average					48.3
20 story building					
Model 1(0%)	17601	70	230	3.69	-
Model 2(20%)	19428	67	229	4.24	14.9
Model 3(40%)	20702	64	226	4.67	26.6
Model 4(60%)	21638	61	220	4.99	35.2
Model 5(80%)	22400	58	216	5.33	44.4
Average					30.3

Table 4 Response modification factor with damping coefficient of 2.0548211(kN.s/mm)

Four-story building	V_0 (kN)	Δ_y (mm)	Δ_m (mm)	R	% of difference between models in comparison with model 1model 1
Model 1(0%)	3,250	9.8	72	1.57	-
Model 2(20%)	5,061	9.1	66	2.44	55.4
Model 3(40%)	5,571	9	66	2.69	71.3
Model 4(60%)	5,812	8.5	64	2.8	78.3
Model 5(80%)	6,001	8.8	64	2.9	85
Average					72.5
Eight-story building					
Model 1(0%)	4,549	19	98.17	2	-
Model 2(20%)	6,270	16	97	3.11	55.5
Model 3(40%)	6,875	14.4	97	3.61	80.5
Model 4(60%)	7,275	13	94	3.92	96
Model 5(80%)	7,530	12	92	4.	100
Average					83
Twelve-story building					
Model 1(0%)	17,700	55	138	3.22	-
Model 2(20%)	21,213	43.3	129	4.63	43.8
Model 3(40%)	22,891	37	123	5.89	82.9
Model 4(60%)	24,254	34	118	6.18	91.9
Model 5(80%)	25,162	31	114.4	6.82	111.8
Average					82.6
Sixteen-story building					
Model 1(0%)	18,000	57	162	3.50	-
Model 2(20%)	20,722	45	149	4.73	35.1
Model 3(40%)	22,245	42	142	5.19	48.3
Model 4(60%)	23,315	39	136	5.61	60.3
Model 5(80%)	24,254	38	135	5.95	70
Average					53.4
Twenty-story building					
Model 1(0%)	17,601	70	230	3.69	-
Model 2(20%)	20,178	67	229	4.50	21.9
Model 3(40%)	21,465	64	226	4.94	33.8
Model 4(60%)	22,392	61	220	5.26	42.5
Model 5(80%)	23,170	58	216	5.61	52
Average					37.6

Table 5 Response modification factor with damping coefficient of 8.4060888 (kN.s/mm)

Four-story building	V_0 (kN)	Δ_y (mm)	Δ_m (mm)	R	% of difference between models in comparison with model 1
Model 1(0%)	3,250	9.8	72	1.57	-
Model 2(20%)	5,411	9.1	66	2.61	66.2
Model 3(40%)	5,870	9	66	2.83	80.3
Model 4(60%)	6,111	8.5	64	2.94	87.3
Model 5(80%)	6,298	8.8	64	3.04	93.6
Average					81.85
Eight-story building					
Model 1(0%)	4,549	19	98.17	2	-
Model 2(20%)	6,621	16	97	3.28	64
Model 3(40%)	7,327	14.4	97	3.85	92.5
Model 4(60%)	7,628	13	94	4.11	105.5
Model 5(80%)	7,881	12	92	4.26	113
Average					93.75
Twelve-story building					
Model 1(0%)	17,700	55	138	3.22	-
Model 2(20%)	21,623	43.3	129	4.72	46.6
Model 3(40%)	23,300	37	123	5.69	76.7
Model 4(60%)	24,665	34	118	6.29	95.3
Model 5(80%)	25,564	31	114.4	6.93	115.2
Average					83.45
Sixteen-story building					
Model 1(0%)	18,000	57	162	3.50	-
Model 2(20%)	21,126	45	149	4.89	39.7
Model 3(40%)	22,645	42	142	5.36	53.1
Model 4(60%)	23,715	39	136	5.79	65.4
Model 5(80%)	24,656	38	135	6.14	75.4
Average					58.4
Twenty-story building					
Model 1(0%)	17,601	70	230	3.69	-
Model 2(20%)	20,628	67	229	4.6	24.7
Model 3(40%)	21,902	64	226	5.02	36
Model 4(60%)	22,840	61	220	5.38	45.8
Model 5(80%)	23,605	58	216	5.70	54.5
Average					40.3

7 R factors for reinforced concrete structures equipped with viscous damper devices

This study attempted to calculate the effect of viscous dampers on over strength, ductility, and response modification factors for reinforced concrete structures on the basis of different damping coefficients. The calculation was carried out by conducting an equivalent statistical analysis. The formulation was proposed according to the response modification factors for the structures equipped with viscous damper devices. In the formulation, several factors such as the number of dampers, the damping coefficient, and the height of the structures were considered. The R factors for the structures

equipped with viscous damper devices were then evaluated by proposing the addition of R_d to the main equation of R. R_d was used to evaluate the effect of the damper devices on the R values on the basis of the following equation:

$$R = R_S \,.\, R_\mu \,.\, R_R + R_d \quad (8)$$

The equation for evaluating R_d on the basis of the percentage of bays equipped with viscous dampers and under different damping coefficients for reinforced concrete structures was derived by adopting the described results of the numerical study. The final formulation of Rd was derived and added to the main equation of R for reinforced concrete structures equipped with damper devices in different levels. In this research, the equation of Rd was based on the structures with 20% to 80% of the bays equipped with damper devices in different levels. Accordingly, the following equations were developed on the basis of the response factors for structures equipped with damper devices:

where

$$C < 1 \text{ (kN.s/mm)}$$
$$R_d = -0.009x^2 + 0.222x - 0.172 + (C/1.24) \times n \quad (9)$$

$$1 \leq C \leq 2 \text{ (kN.s/mm)}$$
$$R_d = -0.009x^2 + 0.214x - 0.068 + (C/3.61) \times n \quad (10)$$

$$2 < C \leq 8.4 \text{ (kN.s/mm)}$$
$$R_d = -0.008x^2 + 0.208x + 0.004 + (C/14) \times n \quad (11)$$

whereC = damping coefficient (kN × s/mm), X = number of stories,and N = % of bays equipped with dampers (Table 6) according to Eqs.(9)–(10).

Table 6 Value of N based on the percentage of bays equipped with dampers

% of bays equipped with dampers	Value of N
20%	0
40%	1
60%	1.5
80%	2.5

The comparison of the R factors (i.e., structures without energy dissipation systems and structures equipped with energy dissipation systems) showed that the applications of viscous dampers efficiently affect R factors. Furthermore, viscous dampers influence structural displacement. The following conclusions were derived from the research results:

I. The implementation of viscous damper devices is effective in reducing the nonlinear response or displacement of structures during earthquakes.
II. The nonlinear responses of structures with respect to the occurrence of plastic hinges and structural movement are reduced when dampers are used.
III. The increase of damping coefficients enhances response modification factors.
IV. Increasing the number of dampers results in high R factor values.
V. The height of structures affects response modification factors.

8 Conclusions

In this study, viscous damper devices were installed in reinforced concrete structures with different levels to reduce seismic design loads. Specifically, this research attempted to evaluate the effect of viscous dampers on over strength, ductility, and response modification factors for structures on the basis of different damping coefficients through an equivalent statistical analysis. The over strength and reduction ductility factors of 75 reinforced concrete structural models with and without viscous damper devices were evaluated. A nonlinear statistical analysis was performed to evaluate the over strength and reduction factors based on the ductility of the structures with various stories. The results indicated that structures equipped with damper devices can carry more loads than structures without damper devices. The evaluation of the average R factor values for different structures indicated that the R values increased from 30% to 94% for the structures equipped with damper devices compared with those with bare frames. This increase depended on the different types of damper and the percentage of the bays equipped with dampers. The number of dampers clearly has a significant effect on R factors. On the basis of the numerical results, we finally developed the equation for evaluating the R factors for structures equipped with viscous dampers according to damping coefficients.

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