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Evaluation of Response Modification Factor of Multiple Story Steel Buildings

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ABSTRACT

Response modification factor (R) is a significant design parameter of steel structures under seismic loads. Thus, determine the factor benefits the design process. This study aims to evaluate the values of response modification factors of multiple story steel buildings with considering various damping ratios. Different types of steel structures, from 4- to 12-story buildings, with various damping ratios were first analyzed using SAP software. The results from SAP, then, have been used to calculate the response modification factors using existing models. Results indicate that the use of damper increases significantly the response modification factors of steel structures, e.g., the factor of structures with dampers are 22 - 110% higher than the structures without dampers. The height of structures and the number of viscous dampers was found to have significant effect on the response modification factor.

Key words: steel building, seismic response, modification factor, damper

1. INTRODUCTION

Natural disasters occur worldwide and, among them, earthquakes are considered the most destructive as they leave severe social and economic impacts. Civil structures could be collapsed when an earthquake occurs if the structures are not adequately designed for the level of the earthquake [1-3]. The collapsed of the structures could not only injure people but also require a high cost of damaged structures demolition [4]. Determining seismic performances of civil structures, hence, becomes an essential requirement. One method to calculate the seismic response of structures is equivalent lateral force analysis. This approach is implemented by determining various factors i.e. the response modification factor (*R*), the importance factor, and the seismic zone factor.

The *R* has been proposed for over strength, whereas ductility and damping factors are critical for structural systems at displacements exceeding the initial yield to obtain the ultimate load displacement of such systems. The thought of the *R* was proposed based on the assumption that well-detailed seismic framing systems could develop lateral strength beyond their design strength and could bear large deformations without collapsing [5]. The response modification factor, together with several major assumptions and experiences, was proposed by the Applied Technology Council (ATC) [6].

The *R* has been investigated by many authors e.g., Andalib *et al.* [7]; Hanson *et al.*[8]; and FEMA [5], mainly concentrated on displacement responses. The propositions of Newmark [9] were applied to FEMA [5], UBC [10], ATC-40 [11], the Structural Engineers Association of California [12] and the International Building Code (IBC) [13] to design structural buildings with seismic isolation and passive energy dissipation systems.

Abdi *et al.*[14, 15]studied the *R* of steel structures with viscous dampers and their effects on soft floor levels and *R*. The results indicated that the *R* of steel structures with dampers were greater than steel structures without dampers. Patil and Jangid [16] investigated the response of a 76-story benchmark building under across-wind loads. Miyamoto *et al.*[17] studied the collapse risk of tall steel moment-frame buildings (10-, 20-, 30-, and 40-story models) with viscous dampers subjected to severe earthquakes. The analysis showed that during extreme seismic events, the design exhibited satisfactory performance. Significant improvements were observed in reducing collapse hazard through an increased damper safety factor.

Abdollahzadeh and Kambakhsh [18] studied the effect of height on the *R* of open chevron eccentrically braced frames. They found that increasing the height of the frame resulted in a relatively fixed *R* of the consequence of over strength. When frame height is increased, the *R* of the consequence of ductility is decreased. Lastly, when the height of the building is increased, the *R* of the frame based on the allowable stress design method R_w is decreased. Rahgozar and Humar [19]evaluated over strength factors ranging from 1.5 to 3.5 for two types of concentrically braced 10-story frames. Kappos [20] studied the seismic performance of reinforced concrete (RC) buildings. The columns, beams, and walls of these buildings were examined, and over strength factors ranging from 1.5 to 2.7 were obtained. Lee *et al.* (2005) investigated the over strength factors and plastic rotation demands of 5-, 10-, and 15-story RC buildings designed in low- and high-seismicity regions through 3D pushover analyses. The results ranged from 2.3 to 8.3.

Zulham *et al.*[21] investigated the over strength factor of RC frames designed based on Euro codes (ECs), such as EC2 and EC8. They concluded that the geometry and ductility of the frames affected the over strength factor. Seismic over strength in the braced frames of modular steel buildings (MSBs) was studied by Youssef and Naggar [22-24]. The results illustrated that height of systems affected the response modification factor.

The equivalent lateral force method is one of the popular approaches used by structural engineers in calculating lateral forces induced by earthquakes due to its simplicity and reliability. In this strategy, the adoption of the *R* is one of the controversial approaches when different structural systems reused. Moreover, supplementary energy dissipation systems, for example viscous damper, have attracted the interest of structural engineer, researchers and experts.

This study determines the modification factors of multiple story steel buildings with consideration of various damping ratio. Different types of steel structures, from 4- to 12-story buildings, with various damping ratios are analyzed using SAP software. The response modification factors, then, are computed using selected existing models. The results could be used for determine the value of R in designing steel structures.

2. NUMERICAL ANALYSIS

This study is conducted to evaluate how the number of dampers affect the response modification factor. Therefore, steel structures were designed with 4, 8, 12, 16, and 20 stories according to IBC [13] design codes. Various numbers of dampers were added to the structure with the following percentage of bays: 0 (without damper), 20% (dampers were added in one bay), 40% (dampers were added in two bays), 60% (dampers were added in three bays), and 80% (dampers are added in four bays).

The material property for steel is ASTM A992 with Fy = 50 ksi. Table 1 presents the details of the steel profiles used for the beams and columns of the various considered structures. The slab is concrete grade 30 with a thickness of 150 mm.

Two steel profiles, namely, types W10×33 and W10×39, were used for the beams. Steel profile type W10×33 was used for the perimeter beams because it could withstand less loads compared with the other beams. Steel profile type W10×39 was used for the rest of the beams because it could withstand heavier loads than the perimeter beams. Column size was reduced by increasing the height of the building due to decreasing cumulative loads.

Distribution of loads was described as a dead load of 4 $kN/m^2$and a live load of $5kN/m^2$ for each floor to consider gravity. The support condition of the frame was also pinned connection.

The steel structures exhibit a planning of five bays of 6 meter in each direction, as presented in Figure 1. The stories and variations are illustrated in Figure 2. Figure 3 shows that 60% of the bay is equipped with a damper in 3D view. The damper properties of the steel structures are selected according to Taylor’s fluid viscous dampers [25], as shown in Table 2.

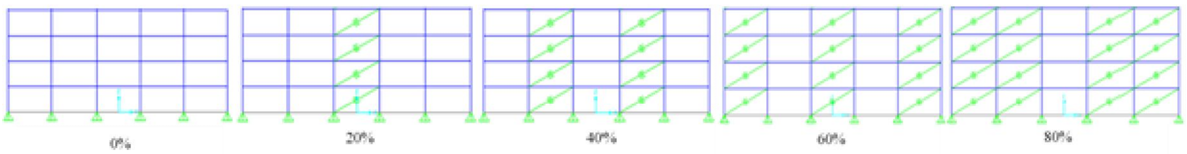
Table 1: Details of the beams and columns.

# stories	Beams	Columns
4	W10 X 33 W10 X 39	level 1 – level 2 : W10 X 77 level 3 – level 4 : W10 X 54
8	W10 X 33 W10 X 39	Level 1 – level 2 : W12 X 120 Level 3 – level 5 : W10 X 100 Level 6 – level 8 : W10 X 68
12	W10 X 33 W10 X 39	Level 1 – level 3 : W12 X 170 Level 4 – level 6 : W12 X 136 Level 7 – level 9 : W10 X 100 Level 10 – level 12 : W10 X 68
16	W10 X 33 W10 X 39	Level 1 – level 4 : W12 X 210 Level 5 – level 7 : W12 X 170 Level 8 – level 10 : W12 X 136 Level 11 – level 13 : W10 X 100 Level 14 – level 16 : W10 X 68
20	W10 X 33 W10 X 39	Level 1 – level 2 : W12 X 279 Level 3 – level 5 : W12 X 252 Level 6 – level 8 : W12 X 210 Level 9 – level 11 : W12 X 170 Level 12 – level 14 : W12 X 136 Level 15 – level 17 : W10 X 100 Level 18 – level 20 : W10 X 68

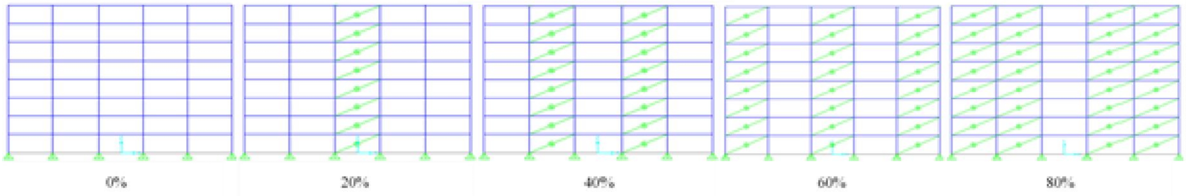
In this study, the values of R1, R2, and R3 were evaluated based on the methods of Miranda and Bertero [26]. R4 and R5 were proposed based on the methods of Nassar [27] and Newmark [9] respectively. The response modification factors are presented as R1 to R5 in Tables 3 to 7, respectively. The value of the response modification factor obtained from this study is within the range (i.e., 1 to 8.5) proposed by the Federal Emergency Management Agency (FEMA) [5] and UBC [10].

Table 2: Properties of fluid viscous dampers.

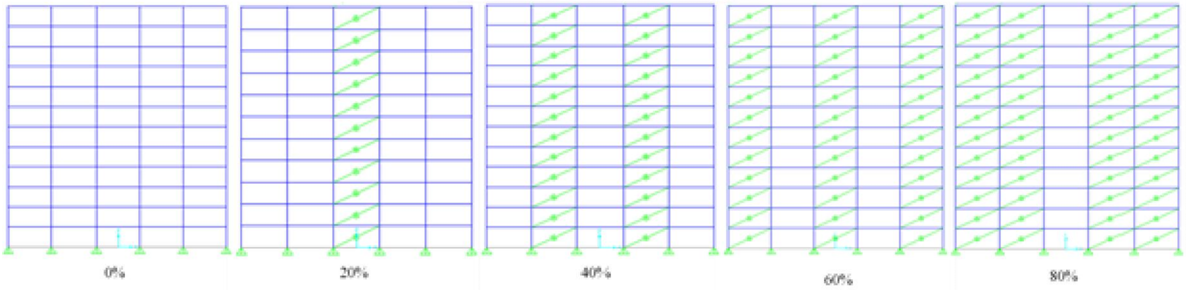
Force (kN)	Damping Coefficient kN/(m/s)	Mass (kg)
245	256.85	41



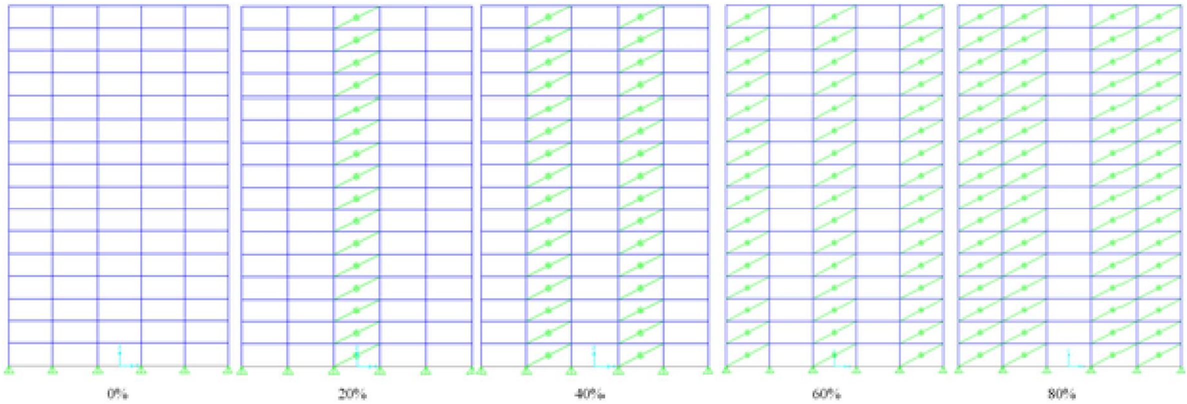
(A) 4 story structures



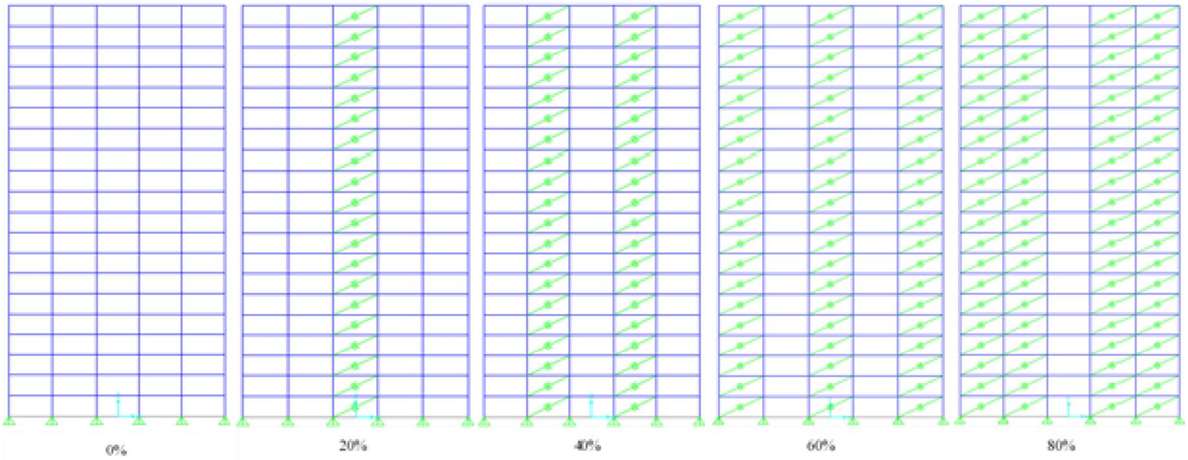
(B) 8 story structures



(C) 12 story structures



(D) 16 story structures



(E) 20 story structures

Figure 2: Stories and percentages of the bay with a damper

3. RESULTS AND DISCUSSION

Figures 4 to 8 show the results of the nonlinear pushover analysis of the steel structures with variations in numbers of stories and dampers. The figures indicate that the base shear force for the structures without a damper is the lowest value at the yield point compared with those for the other structures. The result of the comparison of the structures when 20% of the bay is equipped with dampers shows that all the structures require a higher force to reach their elastic limit compared with the case without a damper. The load–displacement curve shows that, by adding more dampers, the base force will have a higher value at the elastic limit or will cause the structures to resist the same load at less displacement. Then the displacement at the yield point will be less with the addition of more dampers even if the structures resist a high force.

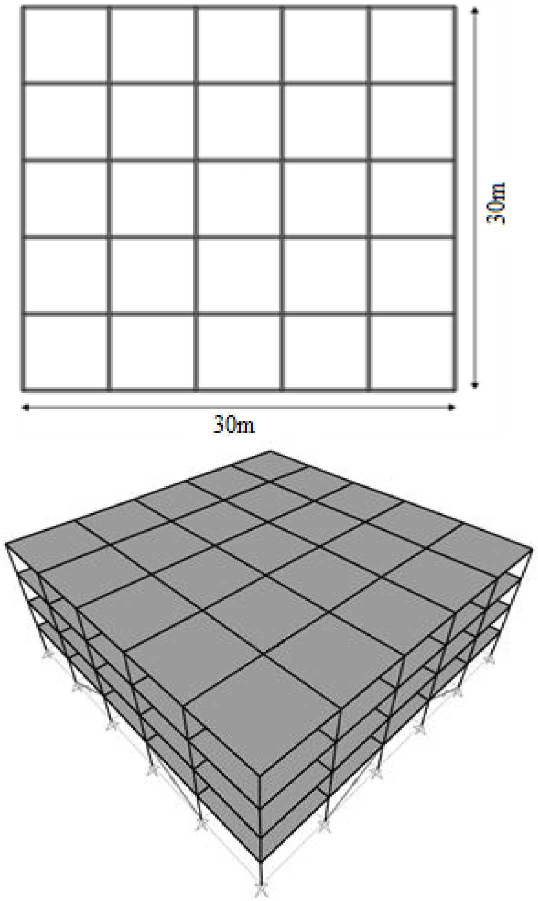


Figure 1: Structural arrangement.

The effects of supplementary dampers on each model vary; though, the responses of all the models have been generally improved. The objective is to obtain high over strength and ductility values, which will result in a high value of the response modification factor (*R*). The analysis results show that the structures with viscous dampers can resist high lateral forces, and thus, a high *R* is achieved compared with that for the structure without a damper. The height of the structures, the number of dampers, and the value of the damping coefficient, affect the response modification factor.

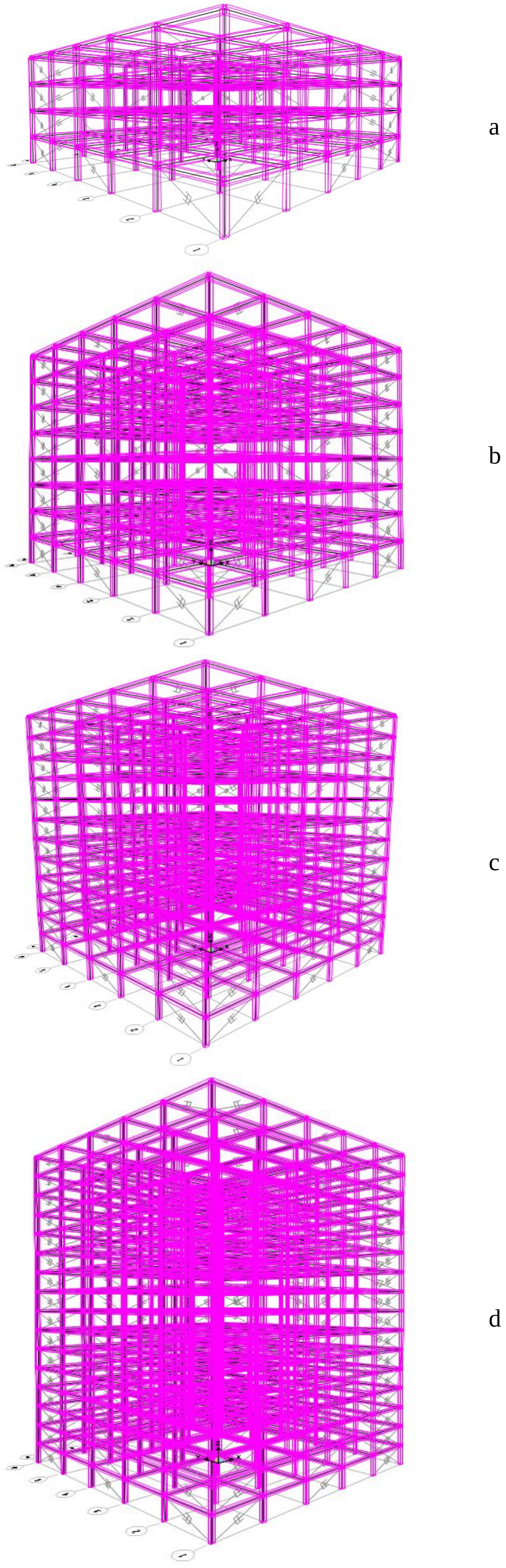


Figure 3: Design of steel structures of (a) four-, (b) eight-, (c) twelve-, (d) sixteen- and (e) twenty-story.

The values of *R* of the considered steel structures are presented in Tables 3 to 7 according to different damping coefficients. The results demonstrate the use of viscous damper increases the value of the *R*. The effect of dampers on the value of the *R* is described as a percentage of increment. This effect will differ among structures depending on the number of dampers, damping coefficient, height of the structure, and pushover of each model.

In Table 3, the value of the *R* increased significantly by adding a viscous damper to the building. This effect can be observed as increments of 70.5%, 95.8%, 102%, and 109.8% for structures with 20%, 40%, 60% and 80% of bays with damping, respectively, compared with the structure without a damper (0%). Therefore, the response modification factor increased accordingly by adding dampers in more bays of a building. However, with regard to the architectural design of a structure, limitations always exist to cover the frames in the structure and implementing 80% damping in the bays of a structure is actually impossible.

In Tables 4 and 5, the results of the 8-story and 12-story buildings indicate that by using a damper device in one of the bays of the frame (20%), the value of the *R* is increased to approximately 48.6% and 34.23% for the 8-story and 12-story frames, respectively, compared with the structure without a damper. These results demonstrate significant effect of viscous dampers to dissipate vibration energy in a building, particularly for the 8-story building.

Similarly, using viscous dampers in 40%, 60%, and 80% of the bays of the frames of the 8-story and 12-story buildings, the increment of the response modification factor is 76.5%, 92%, and 104%, respectively, for the 8-story building and 55%, 68.1%, and 79%, respectively, for the 12-story building. These results show the significant contribution of viscous dampers to diminish the vibration effect in structures.

In Tables 6 and 7, the values of the response modification factor increased for structures with 20%, 40%, 60% and 80% of bays with damping due to the effect of damper application within the ranges of 25.5%, 42%, 53.2%, and 62%, respectively, for the16-story building and 22.3%, 33.12%, 41%, and 48 %, respectively, for the 20-story building. The addition of dampers to a structure leads to a high response modification factor. However, in the aforementioned result, the effect of a viscous damper on the *R* decreased by increasing the number of stories. In this case, the decrement is mostly observed in 15-story to 20-story buildings.

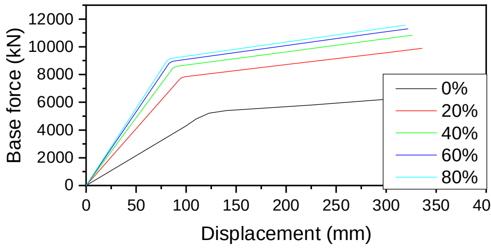


Figure 4: Load–displacement results, four-story steel structures.

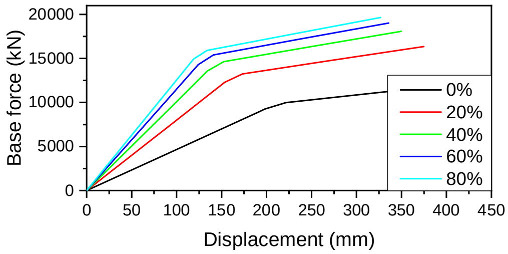


Figure 5: Load–displacement results, eight-story steel structures.

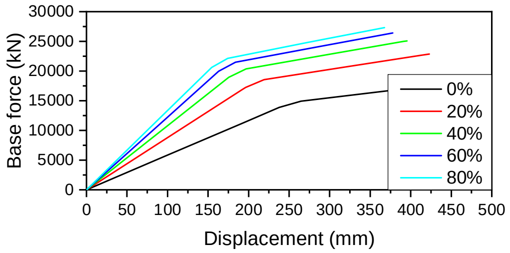


Figure 6: Load–displacement results, twelve-story steel structures.

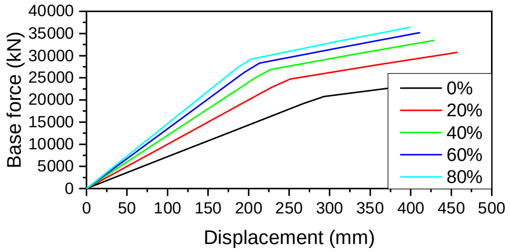


Figure 7: Load–displacement result, sixteen-story steel structures.

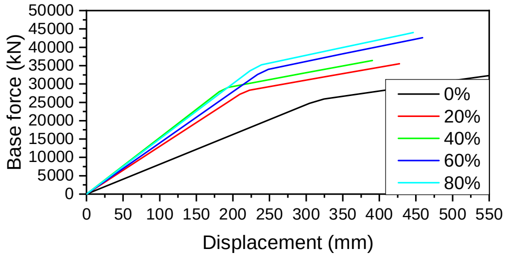


Figure 8: Load–displacement results, twenty-story steel structures.

Table 3: Proposed response modification factor for 4 story building.

4 story building	R1	R2	R3	R4	R5
0%	1.7300	1.9064	1.2057	1.7191	1.2280
20%	2.9560	3.2838	2.0114	2.9176	1.837
40%	3.3950	3.7860	2.2967	3.3476	2.0151
60%	3.5041	3.9028	2.3747	3.4561	2.1108
80%	3.6370	4.0556	2.4606	3.5863	2.1604

Table 4: Proposed response modification factor for 8 story building.

8 story building	R1	R2	R3	R4	R5
0%	2.2099	2.4193	1.6293	2.0652	1.9362
20%	3.2836	3.6239	2.3525	3.0641	2.5755
40%	3.8994	4.3242	2.7487	3.6390	2.8542
60%	4.2431	4.7164	2.9682	3.9610	2.9998
80%	4.5062	5.0179	3.1341	4.2084	3.1001

Table 5: Proposed response modification factor for 12 story building.

12 story building	R1	R2	R3	R4	R5
0%	2.8835	2.9136	2.2727	2.6102	2.5968
20%	3.8705	3.9150	3.0038	3.4986	3.2377
40%	4.4621	4.5165	3.4308	4.0323	3.5601
60%	4.8468	4.9082	3.7062	4.3805	3.7558
80%	5.1543	5.2219	3.9206	4.6599	3.8803

Table 6: Proposed response modification factor for 16 story building.

16 story building	R1	R2	R3	R4	R5
0%	3.4962	3.3541	3.1140	3.1947	3.2953
20%	4.3863	4.2042	3.8965	4.0069	4.0293
40%	4.9546	4.7433	4.3858	4.5257	4.390
60%	5.3545	5.1224	4.7292	4.8917	4.6346
80%	5.6531	5.4047	4.8937	5.1657	4.7961

Table 7: Proposed response modification factor for 20 story building

20 story building	R1	R2	R3	R4	R5
0%	4.0549	3.7773	4.3978	4.6249	4.0112
20%	4.9580	4.6467	5.0186	4.9545	4.3762
40%	5.3977	5.044	5.4705	5.0834	4.4921
60%	5.7020	5.3551	5.7672	5.3445	5.2376
80%	5.9905	5.621	6.0607	5.6179	5.4205

4. CONCLUSION

This study evaluates the response modification factors of steel structures with considering various damping ratios. The results shown the application of dampers to a structure significantly affects the *R*. This study shows an average increase of approximately 36% to 94.5% for different structures depending on the number of bays with viscous dampers. In this study, the difference between the highest level (20-story building) and the lowest level (4-story building) exhibits a reduction range of 48% to 58% for different numbers of used viscous dampers.

Therefore, the findings of this study indicate that using a viscous damper significantly affects the *R* for structures with up to 15 stories. However, the effect of a damper on the *R* is reduced for structures with more than 15 stories.

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