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Research Article

# Evaluation of Seismic Design Parameters for Reinforced Concrete Frames Retrofitted using Eccentric Steel Bracings

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**Keywords**

Pushover Analysis, Response Modification factor, Eccentric Steel Bracings, Seismic Design Parameters.

**Abstract**

In this study, overstrength, ductility, and response modification factor of eccentric steel bracing in reinforced concrete frames were evaluated based on nonlinear static analysis. Therefore, structures consisting of 3, 6, 9, and 12 stories and different bracing locations were assessed. The effect of link beam length on the retrofitted stock RC structures have been considered. In this way, using the Seismostruct software, static adaptive pushover analyses have been performed to obtain the capacity curves, and accordingly, normalized capacity curves have been determined. For this purpose, 36 frames have been modelled. Eventually, based on calculations, the R factor, the deflection amplification factor ($C_d$), and other seismic behavior parameters have been determined for this type of strengthening technique.

## 1. Introduction

Steel bracings are usually applied to RC structure to resist seismic loads like wind or earthquake; however, braces may have interaction with architectural appearance. The steel braces are often set in vertically gap spans. Adding this technique permits achieving a notable increase in stiffness with a small extra weight. Therefore, this method is effective and enormous for the existing structure, where the inefficient lateral stiffness is the main issue. Bracings are afforded to improve rigidity and stability of the structure under seismic loads, and additionally to decrease the lateral displacement and story drifts, considerably.

Numerous studies have been conducted on analytical and empirical forms of braced RC structural systems. Riddell et al. [1] investigated the seismic factors of low-rise structures. It was shown the reduction factor is lower than the values of medium and high-rise structures. Miranda and Bertero [2] described the coefficient of R, and also clarified its relevance to earthquake-resistant design. It was explained the strength reduction factors of one-degree freedom systems should be modified in the design of multi-degree freedom systems. Mazzolani [3] investigated the seismic resistance of retrofitted reinforced concrete structures by steel bracing systems. Moreover, it was pointed out the stability and wideness of the excellent ductility of these structures. Nevertheless, architectural issues and the problems of creating suitable connections between steel braces and concrete frames are the shortcomings of this technique. By experimenting with the K bracing frames, Tagawa et al. [4] concluded that the composite capacity of the reinforced concrete frame and steel bracing could be assumed with the sum of the strengths of each part. Maheri and Sahebi [5] found a direct connection between the steel braces and concrete without the need for a steel frame. They proposed a direct internal bracing method to refine existing structures as well as a shear reinforced element in the design of a new structure. Besides, they also found out that the frame shear capacity can be raised by adding braces up to three times. Numerical work was carried out by Ghobarah and Abou-Elfath [6] for the low-rise and non-ductile reinforced concrete, which showed the optimal seismic performance of these RC structures where eccentric steel bracing has been used. Kim and Choi [7] studied about overstrength and response modification factor (R factor) of special and ordinary concentric braced frames by pushover analysis and nonlinear incremental analyses, the results of both methods were generally matched well. Kim and Park [8] studied dual systems and represented that the R factor

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decreased as the numbers of stories increased. Maheri and Akbari [9] considered the behavior influence for X-braced and knee braced steel structures through nonlinear pushover analyses. They concluded types of bracing might have local effects on the R factor. However, for RC eccentric braced dual-frame systems, these seismic parameters are still unidentified. Recently, Khademi and Rezaei [10] studied about stresses in the EBF and CBF bracing type and has shown more energy dissipating of EBF bracing types. Due to the importance of design, especially in new structural systems, it is still essential to find seismic design factors. So, many researchers recently employed pushover analysis and other procedures to assess the R factor of different structural systems [11-14].

Based on FEMA P695 methodology, Sadeghpour and Ozay [15] evaluated the reinforced concrete structures designed according to the previous Iranian seismic codes. They showed that the low and mid-rise RC structures designed based on the second edition of 2800 [16] are vulnerable in moderately intense earthquakes. So, this research has been done to evaluate the design parameters of RC structures which retrofitted by eccentric Steel bracing systems. Subsequently, the seismic parameters such as response modification factor, ductility factor, overstrength, and other parameters have defined. In this way, various frames, and categories consisting of different heights, braced spans, and link beam lengths are considered to cover proper coverage of the requested items.

## 2. Seismic Behavior Characteristic of Structures

For the first time, in 1978, the response modification factor concept was offered by the Applied Technology Council in the ATC report. It was carefully presented about the response of structures and the evaluation of overstrength and ductility [17]. The ATC report relies on the argument that systems that have suitable resistant structural designed have perfect ductile behavior and can be deformed significantly without general failure. Accordingly, with the development of design guidelines, in the event of an earthquake occurrence, a structure may be maintained more stable without severe damage or collapse. The proportion of the required elastic strength demand to the actual inelastic strength of a structure is expressed as a reduction factor or response modification factor.

### *2.1. Seismic Behavior Factor Methodology*

R factor has a significant role in preserving the structure in elastic state within an earthquake event. Consequently, in the estimation of lateral force, the R factor is the main part. Overstrength and ductility are fundamental parameters to achieve the response modification factor because a dynamic structural reaction stimulates these factors to decrease the elastic load into inelastic beyond the elastic phase. According to the pushover curve, ductility and overstrength factor can be calculated. Moreover, it is permitted to use the idealized bilinear schematic with the base shear–displacement curves [18-19]. Fig 1 displays the effective parameters in the R factor achievement. The parameters are defined as; design base shear force ($V_s$), displacement resulting from the design base shear force ($\Delta_w$), base shear force versus roof displacement relationship at yield point ($V_y$), roof displacement relationship at yield point ($\Delta_y$), and maximum displacement ($\Delta_{max}$). Measuring the ratio of base shear force at the design and yielding phases is called strength factor. In contrast, the ductility factor is a ratio of top displacement at yielding and at code-specified limits [18]. Subsequently, the relation of overstrength ($\Omega$), ductility ($R_\mu$), the allowable stress factor (Y), and R factor can be defined as follows:

$$R = \frac{V_e}{V_w} = \frac{V_e}{V_y} \times \frac{V_y}{V_s} \times \frac{V_s}{V_w} = R_\mu \times \Omega \times Y \tag{1}$$

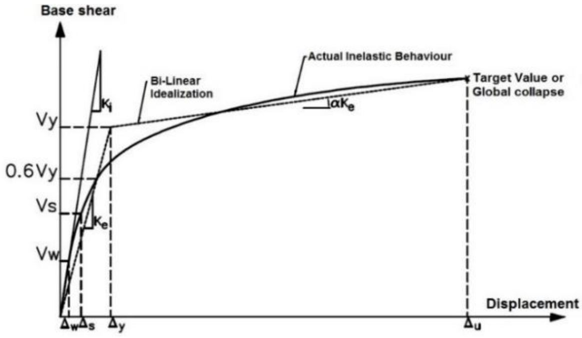


**Figure 1.** Typical Pushover Response Curve [9]

### *2.2. Description of the Seismic Factors*

The nonlinear structural behavior is related to the hysteric energy of a structure, and this phenomenon is attributed to ductility reduction factor. The ductility reduction factor includes the inherent characteristic of structure such as ductility, damping, the fundamental period of the structure, and seismic features of ground motion. The $R_\mu$ is introduced by the proportion of maximum structural drift ($\Delta_u$) and the drift matching to the ideal yield point ($\Delta_y$) [20]. $R_\mu$ is presented as follows:

$$R_\mu = [c(\mu - 1) + 1]^{1/c} \tag{2}$$

$$c(T, \alpha) = \frac{T^a}{1+T^a} + \frac{b}{T} \tag{3}$$

where μ is the ductility ratio, and α is the post-yield stiffness given as the percentage of the initial stiffness of the system. a and b are the parameters given as functions of α that can be taken from Table 1, and T is the fundamental period of the structure.

**Table 1.** Values of a and b Parameters for the Evaluation of Ductility Reduction Factor

| α (%) | a | b |
|---|---|---|
| 0 | 1 | 0.42 |
| 2 | 1 | 0.37 |
| 10 | 0.8 | 0.29 |

In a single degree of freedom system (SDOF), the ductility factor can be attained from the ratio of maximum lateral displacement to the yielding lateral displacement of structures. Moreover, the ductility factor is the description of the capacity that a structure can stand in a nonlinear state. Nevertheless, the ductility factor of multi-degree structures has no perfect description yet. In some regulations, it is anticipated that yielding is simultaneous and not exact [19].

Previous researches have confirmed that the behavior of structures during a severe earthquake is highly related to the structural overstrength factor to prevent structures from collapse [21]. Due to the simplification in the structural design, the actual strength of the structure during the earthquake might be higher than expected. In design methods, a conservative design is generally considered, and these simplification and assumptions make the presence of overstrength factor in general and partial reviews [18]. The ratio between the design base shear force ($V_s$) and maximum base shear coefficient ($V_y$) is described by overstrength. The results have specified that structures may significantly overcome higher forces than those designed to do so. This reason has been explained, despite a large storage capacity, which was not initially taken in the structural design. Consequently, overstrength parameter can be considered as leading to more economical buildings [21].

The allowable stress or allowable strength is the maximum stress (tensile, compressive, or bending) allowed to be applied to a structural material. The permissible stresses are generally defined in terms of building codes. In the allowable stress design (ASD) method, the comparable design base shear is decreased from the code-defined level by stress factor or Y factor. To design according to the ASD method, the design force is reduced from $V_s$ to $V_w$.

The structural damages are usually caused by a seismic stimulus from extreme deformations or displacement of the structure. Accordingly, awareness of the precise judgments and estimation of displacements and structural seismic behavior are the critical goals in seismic design of a structure.

### 3. 3. Structural models and Design Assumptions

In this research, frames of 3, 6, 9, and 12 stories with the spans length of 5 m and four different bracing locations were designed according to the Iranian code of practice for seismic resistant design of buildings second edition (standard No.2800) [16]. Figure 2 shows the typical models used for 12 stories frame. The height of every story and the length of every span are 3 and 5 meters, respectively. The equivalent static method was used for structural analysis. The dead and live loads of 7 and 2 kN/m$^2$ were used for gravity loads. The initial values of the behavior factor in the design of all these models were assumed seven, and the seismic zone factor of A was considered 0.3 for all models (high-risk zone). In pushover analysis, the lateral loads were used similarly to reverse triangular distribution. The latest research shows that the rectangular load distribution provides more accurate estimates of maximum drift and factor R than uniform distributions. The RC models were designed based on intermediate ductility by controlling drift limitation that is defined in the Iranian seismic code. The members of frames were designed in each set separately. The steel material used in the sections of the bracing members is the ST37 type with yielding strength of 2400 kg/cm$^2$ and ultimate strength of 3700 kg/cm$^2$. The compressive strength of concrete material is 240 kg/cm$^2$.

### 4. Analysis of Models

Adaptive pushover analysis has been expanded considerably in recent years and found out to be a powerful analytical tool for analyzing and designing performance assessment goals. Since this method is relatively simple, involves some calculations and an absolute simplicity. As a result, small difference values should be in the assessment of the seismic parameters. The proceeds of the pushover analysis estimate the efficiency and ability of a structural system with the evaluation of strength and displacements in design demand by using a static inelastic analysis method and comparing it with the present capacity [22]. Figures 3 to 7 show normalized pushover curves for all models. Subsequently, for linear analysis and design, Etabs Nonlinear v9.7.0 was applied. All nonlinear analyses were performed using the Seismostruct V7.0.6 [23] software. In all analyses, P-Δ effects were considered by including geometric non-linearity. All members have been modelled with inelastic plastic-hinge force-based frame elements (infrmFBPH) of SeismoStruct. Four elements for each member have been used as subdivision, whose length is equal to 33%, 17%, 17%, and

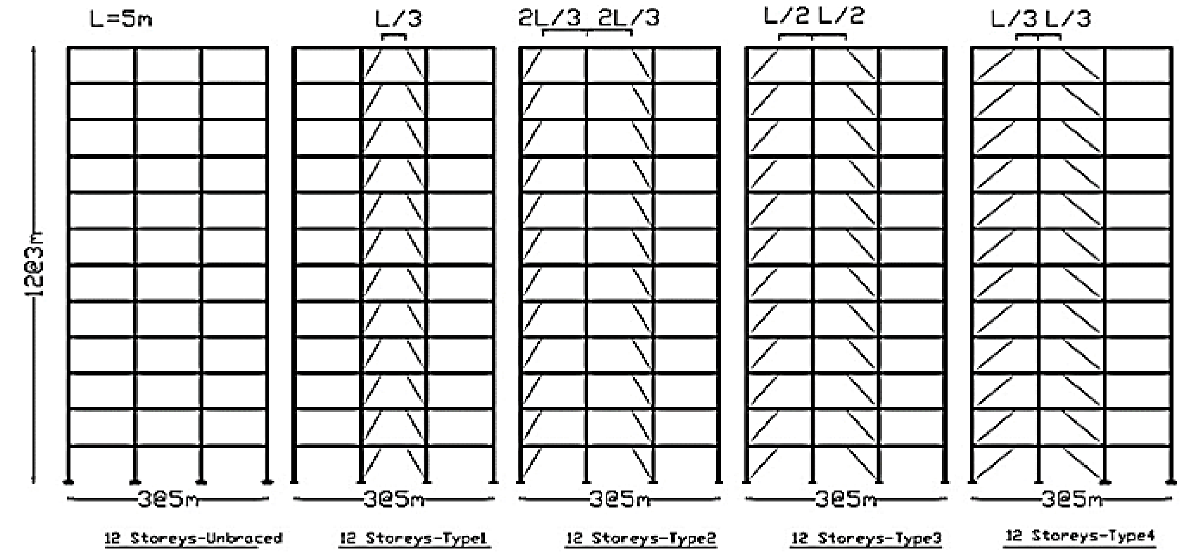


**Figure 2.** Illustration of the Models for 12 Stories

33%. It is a fiber element with spread plasticity. The cross-section of members has been subdivided into 150 fibers approximately.

An elastic-perfectly plastic bilinear curve has adopted for the constitutive stress-strain curve of steel and concrete property according to nonlinear concrete model. At links, the plastic range M-V is defined analytically by terms:

$$V_y = V_p \quad and \quad M_y = \quad if \quad \frac{V_p}{V_p} \leq 2 \tag{4}$$

$$V_p = \frac{2M_P}{e} \quad and \quad M_y = M_p \quad if \quad \frac{eV_p}{M_p} \geq 2 \tag{5}$$

where $V_p$ is the plastic shear force, $M_p$ the plastic bending moment, $V_y$ the yield shear force, and $M_y$ the yield bending moment of links. The links are classified as short and long length links [24]. Accordingly, the ultimate plastic rotation angle ($\varphi_u$) is evaluated in the short and long link as follows:

$$\varphi_u = 0.08Rad \quad if \quad e \leq 1.6\frac{M_p}{V_p} \tag{6}$$

$$\varphi_u = 0.02Rad \quad if \quad e \leq 3.0\frac{M_p}{V_p} \tag{7}$$

Intermediate length links are attained by linear interpolation [25].

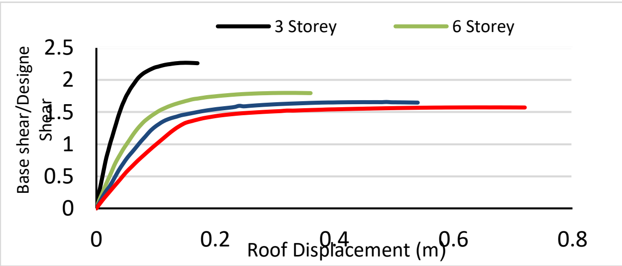


**Figure 3.** Normalized Pushover Response Curves for Unbraced RC Frames

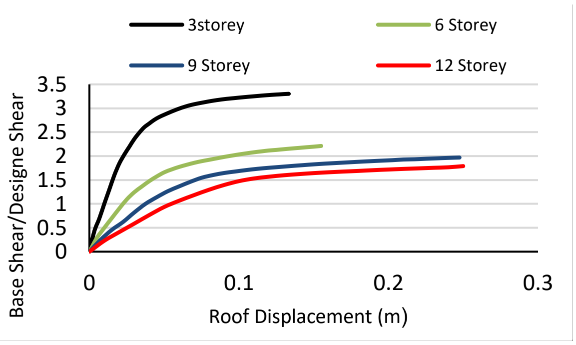


**Figure 4.** Normalized Pushover Response Curves for Type-1

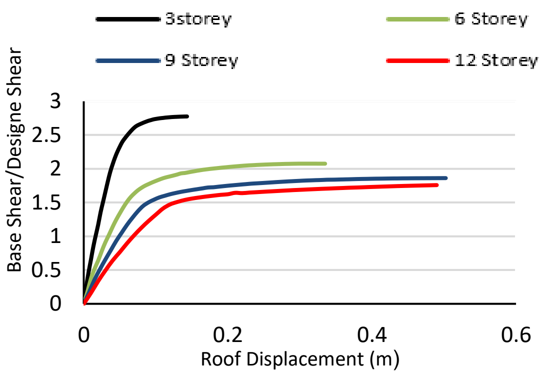


**Figure 5.** Normalized Pushover Response Curves for Type-2

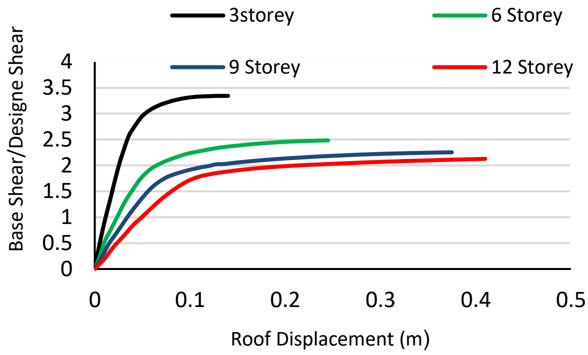


**Figure 6.** Normalized Pushover Response Curves for Type-3

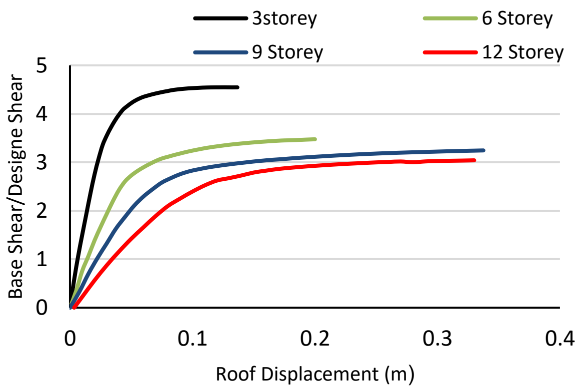


**Figure 7.** Normalized Pushover Response Curves for Type-4

## 4. Results and Discussion

The target displacement and the lateral force distribution in the pushover analysis are according to the presumption that the response is limited by the fundamental mode and the mode shape is constant. These conventions are estimated after yielding occurs in the structure. The behavior factor parameters, overstrength (Ω), Rμ, stress factor (Y), the response modification factor (R), and initial stiffness ($K_i$) are calculated and are listed in Table 2 to Table 5.

**Table 2.** Seismic Behavior Factors of 3-story Frames

| Factor | Unbraced | Type1 | Type2 | Type3 | Type4 |
|---|---|---|---|---|---|
| $K_i$ | 1281462 | 2866604 | 1597763 | 2155930 | 3745511 |
| Ω | 0.92 | 0.98 | 0.96 | 0.99 | 0.94 |
| $\Delta_u$-$\Delta_y$ | 0.12 | 0.10 | 0.13 | 0.14 | 0.11 |
| μ | 3.36 | 4.49 | 4.00 | 4.60 | 4.67 |
| Y | 2.06 | 2.80 | 2.59 | 3.15 | 4.16 |
| $R_\mu$ | 3.58 | 4.51 | 4.19 | 4.59 | 4.09 |
| $C_d$ | 3.09 | 4.40 | 3.84 | 4.55 | 4.39 |
| R | 6.76 | 12.31 | 10.47 | 14.28 | 16.08 |

**Table 3.** Seismic Behavior Factors of 6-story Frames

| Factor | Unbraced | Type1 | Type2 | Type3 | Type4 |
|---|---|---|---|---|---|
| $K_i$ | 1265886 | 2735763 | 1639140 | 2188913 | 3253905 |
| Ω | 0.90 | 0.82 | 0.90 | 0.89 | 0.93 |
| $\Delta_u$-$\Delta_y$ | 0.28 | 0.12 | 0.27 | 0.19 | 0.15 |
| μ | 4.48 | 4.14 | 5.12 | 4.74 | 4.24 |
| Y | 1.62 | 1.69 | 1.87 | 2.14 | 3.05 |
| $R_\mu$ | 5.03 | 4.42 | 5.72 | 5.06 | 4.18 |
| $C_d$ | 4.03 | 3.39 | 4.61 | 4.22 | 3.94 |
| R | 7.33 | 6.14 | 9.66 | 9.68 | 11.86 |

**Table 4.** Seismic Behavior Factors of 9-story Frames

| Factor | Unbraced | Type1 | Type2 | Type3 | Type4 |
|---|---|---|---|---|---|
| $K_i$ | 1156655 | 2187666 | 1531763 | 2050196 | 2815145 |
| Ω | 0.95 | 0.84 | 0.93 | 0.91 | 0.94 |
| $\Delta_u$-$\Delta_y$ | 0.43 | 0.19 | 0.41 | 0.30 | 0.27 |
| μ | 5.11 | 4.04 | 5.57 | 5.26 | 4.66 |
| Y | 1.53 | 1.62 | 1.72 | 1.98 | 2.90 |
| $R_\mu$ | 5.87 | 4.44 | 6.44 | 5.89 | 4.90 |
| $C_d$ | 4.85 | 3.39 | 5.18 | 4.79 | 4.38 |
| R | 8.54 | 6.01 | 10.22 | 10.65 | 13.40 |

**Table 5.** Seismic Behavior Factors of 12-story Frames

| Factor | Unbraced | Type1 | Type2 | Type3 | Type4 |
|---|---|---|---|---|---|
| $K_i$ | 957900 | 1761038 | 1232168 | 1463067 | 1716571.32 |
| Ω | 0.94 | 0.74 | 0.89 | 0.93 | 0.99 |
| $\Delta_u$-$\Delta_y$ | 0.57 | 0.19 | 0.39 | 0.31 | 0.20 |
| μ | 4.85 | 4.36 | 4.81 | 4.02 | 2.53 |
| Y | 1.49 | 1.31 | 1.55 | 1.91 | 2.92 |
| $R_\mu$ | 5.52 | 4.90 | 5.48 | 4.45 | 2.63 |
| $C_d$ | 4.56 | 3.23 | 4.28 | 3.74 | 2.50 |
| R | 7.74 | 4.78 | 7.55 | 7.88 | 7.62 |

Figures 12 and 13 display the variations in R factor owing to changes in the story number in different models. In the eccentrically braced RC frames, the R factor drops whenever the numbers of stories increase in dual systems. While, this amount is almost unchanged in simple reinforced concrete frames. R factor growths by increasing participation of base shear in braces. According to this study, the influence of various components on the R factor shows that the stress factor is more effective parameter. The overstrength factor (Ω) is approximately constant on a story level and independent of configuration or link length. Subsequently, the averages of overstrength of 3, 6, 9, and 12 stories are 0.96, 0.90, 0.91, and 0.90, respectively. The overstrength factor appears to be reasonably and slightly affected by the number of stories. The stress factor (Y) is nearly to rise with the number of story increased. As for the ductility reduction factor, with the growth in brace load share, Rμ declines, regardless of the number of stories.

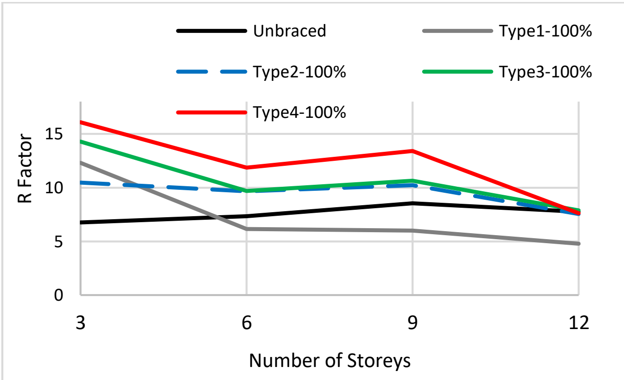


**Figure 8.** The Effect of Number of Stories on the R Factor

Figure 9 shows the changes in ductility, by considering the influence of bracings on ductility. In higher frames of the type2 model have further ductility, the ductility of the type1 model is almost constant. In the unbraced model of type2 and type3 with up to 9 stories, the ductility is increased and then decreased. The ductility demand of 3, 6, 9, and 12 stories were obtained as 3.4 to 4.7, 3.9 to 5.1, 3.8 to 5.7, and 2.2 to 4.9, respectively.

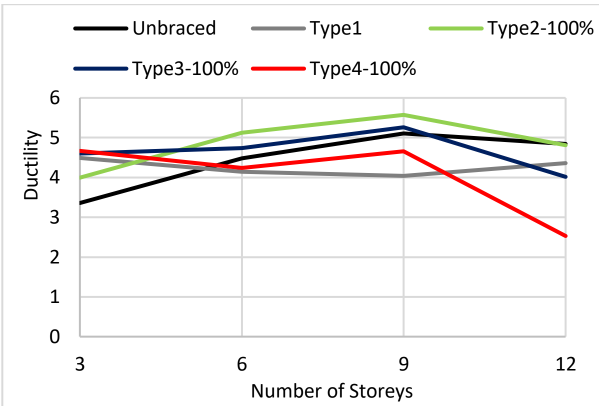


**Figure 9.** The Effect of Number of Stories on the Ductility

## 6. Conclusions

The overstrength, ductility, and response modification factors of the EBF bracing systems in RC frames with several stories were assessed using nonlinear static pushover. The result of the study can be summarized as follows:

1. The stress factor and reduction factor have a more significant influence on determining the R factor in 3 and 6-story models, whereas in 9 and 12-story models, the reduction factors therein effect most.

2. The coefficient of R factor with increasing height in all braced systems has a decreasing trend. However, in unbraced systems, the R factor is almost constant.

3. The ductility and ductility factors growth as the number of stories increases up to 9 stories, and then they decrease.

4. While the link beam length decreases, the overstrength, stress factors and ductility increase and reduction factor and R factors increase**.**

5. The most significant R factor achieved in all stories by the configuration of type4. It shows by considering a shorter link beam, may achieve a bigger R factor.

## Conflict of Interest Statement

The authors declare no conflict of interest.

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