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Effect of Size of Building on Response Reduction Factor of Low Rise Residential Regular Buildings

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Abstract
Most of the seismic design codes used worldwide apply reduction factor (R) in linear static design to scale down the elastic response of structure. Structures are designed to have higher strengths and ductility than those required which affects structural overstrength, ductility and ultimately R.
The value of reduction factor for similar buildings of different size is evaluated and the effect of building size on components of R factor is determined in this paper. Several moment resisting frame layouts (regular in plan and elevation) with different number of bay, bay length and story number are designed and analyzed for response reduction factor. Linear static design and non-linear static analysis is done in SAP2000 for each structure to evaluate ductility, overstrength factor and eventually reduction factor. It is observed that reduction factor and its components doesn't vary significantly with variation in number of bay and its dependency on span is not same for all storys.

Keywords
response reduction factor – ductility factor – overstrength factor

1. Introduction

Current structural design philosophies used in building codes emphasizes that absolute safety and no damage cannot be achieved even in an earthquake with satisfactory probability of occurrence. Since no structure can be utterly immune to the damage from earthquake, construction of structures with ability to withstand strong ground motion without collapse, but potentially with some significant structural damage should be of concern to limit the repercussion of ground shaking. This results in lower design lateral strength as compared to lateral strength required to maintain the structure in elastic range. This is done by using Response Reduction Factor (R) which simply is a scale factor to obtain design lateral force from the lateral force if the structure remain elastic. This factor reflects the capability of structure to dissipate energy through inelastic behavior and accounts for over-strength, energy absorption and dissipation as well as structural capacity to redistribute forces. It can be represented as the ratio of the maximum lateral force, V_e, which would develop in a structure (responding entirely linear elastic under the specified ground motion) to the lateral force, V_d, which it has been designed to withstand.

$$R = \frac{V_e}{V_d} \tag{1}$$

Response reduction factor reflects the capacity of structure to dissipate energy through inelastic behavior and is a combined effect of overstrength, ductility and redundancy represented as[4]

$$R = \Omega * R_R * R\mu \tag{2}$$

where,
Ω is overstrength factor
R_R is redundancy reduction factor
R_μ is ductility reduction factor

The additional strength beyond design strength is called overstrength. Structures are routinely designed and built to have higher strengths than those required for service load conditions. The overstrength factor (Ω) may be defined as the ratio of yield to the design lateral strength.

$$\Omega = \frac{V_y}{V_d} \tag{3}$$

Where V_y is the base shear coefficient corresponding to the actual yielding of the structure and V_d is the code-prescribed unfactored design base shear coefficient. There are many factors that might increase or limit the overstrength of structure. Participation of nonstructural elements, load combinations, minimum size and spacing of reinforcement, importance of building, material overstrength, increased resistance due to confinement etc. are some factors that increase overstrength. Although not intended, some factors can actually reduce the structural strengths. Some of such factors are nonstructural elements like sort column, deterioration, poor structural system like soft storey, consideration of redistribution in design, lack of confinement etc[5].

Ductility is the measure of ability of structure/structural elements to deform prior to failure, once it has attained its yield strength in elasto-plastic system. In severe and most of moderate earthquakes, the structures pass the elastic limit and reach the inelastic state. Under such conditions, ductility becomes very important. The ductility reduction factor, R_μ is a factor which reduces the elastic force demand to the level of idealized yield strength of the structure and is represented as

$$R_\mu = \frac{V_e}{V_y} \tag{4}$$

Where V_e is the max base shear coefficient if the structure remains elastic. Ductility reduction factor depends on ductility demand of the structure, μ which is the ratio of maximum roof displacement to yield roof displacement.

$$\mu = \frac{d_u}{d_y} \tag{5}$$

Many studies have been carried out to determine the value of R_μ. The one proposed by Miranda is used in this study.

$$R_\mu = \frac{\mu - 1}{\phi} + 1 \geq 1 \tag{6}$$

Assuming soil to be alluvium,

$$\phi = 1 + \frac{1}{12T - \mu T} - \frac{2}{5T} \exp\left[-2\left(lnT - \frac{1}{5}\right)^2\right] \tag{7}$$

RC structural systems with multiple lines of lateral load resisting frames are generally in the category of redundant structural systems. In a nonredundant system the failure of a member is equivalent to the failure of the entire system however in a redundant system failure will occur if more than one member fails [6]. As per ATC-19, higher design force can be used for less redundant structures by modifying the response reduction factor with redundancy factor given in the table below.

Table 1: Redundancy Factors

line of vertical seismic framing	Redundancy factor
2	0.71
2	0.86
4	1

Since these factors make up response reduction factor, seismic codes in most of the countries incorporate all these factors in R value either explicitly or implicitly. Some of the international codes along with their provision of factor to scale down the elastic force is shown below.

1. Nepal - NBC 105:1994 - Structural performance factor, K - dependency of design on ductility
2. New Zealand - NZS 1170.5:2004 - Structural performance factor, S_p - dependency of design on overstrength, ductility and redundancy factor
3. Europe - BS EN 1998-1:2004 - Behavior factor, q - dependency of design on overstrength, ductility and redundancy factor
4. USA - IBC 2015, ASCE-7,2016 - Response modification coefficient, R - dependency of design on overstrength, ductility and redundancy factor
5. China - GB5011-2010 - Seismic influence coefficient, α - dependency on the factors is not mentioned
6. Pakistan - Building Code of Pakistan-Seismic Provisions 2007 - numerical coefficient representative of the inherent overstrength and global ductility capacity, R - dependency of design on overstrength, ductility and redundancy factor
7. India - IS 1893 (Part 1) : 2016 - Response reduction factor, R - dependency of design on overstrength, ductility and redundancy factor

8. Bangladesh - Bangladesh National Building Code 2015 - Response reduction factor, R - dependency of design on overstrength, ductility and redundancy factor

9. Japan - Building Standard Law of Japan, BSLJ - Design spectral factor, R_t - dependency on the factors is not mentioned

Since R is a function of overstrength factor, ductility factor and redundancy factor, variation in these values affect the reduction factor and ultimately design base shear. Although building codes address these value either implicitly or explicitly, it is difficult to assess the value of these factors for building of different geometric configuration. This paper describes this issue using non-linear static analysis.

2. Description of the structural systems considered

The structural systems considered for this study are typical symmetric in plan and elevation RC frame structures having 3, 4, 5 and 6 storied configurations. Different assumptions are made to reduce the complexity without much variation in result of model and real structure. Following section describes the assumptions made during the modeling of buildings.

- Soil structure interaction is not considered i.e. foundation is assumed to be rigid.
- Effect of non-structural components like staircase is assumed to be negligible.
- Floor slabs are assumed to be rigid in their own plane.
- Secondary effects such as temperature, creep, shrinkage etc. are not considered.

Different models are created changing the parameters of building considering each combination based on the following scope.

- Buildings with equal number of bay in both horizontal directions.
- Low rise regular in plan and elevation residential buildings with plinth area ranging from $49m^2$ to $506.25m^2$.
- Number of storys considered: 3,4,5,6
- Number of bays considered: 2,3,4,5
- Bay length considered: 3.5m, 4m, 4.5m

Each building model is designed as per IS456:2000. Other design criteria is shown in table 2.

Table 2: Design Parameters

Importance factor	1
R factor	5
Soil type	Medium soil
Concrete	Grade=M25 Unit weight=25kN/m^3 Modulus of Elasticity=25000MPa Poisson's ratio=0.2
Reinforcement	Grade=HYSD500 Unit weight=76.9kN/m^3 Modulus of Elasticity=200000MPa Poisson's ratio=0.3
Story height	3m
Beam size	350mm*300mm
Column size	400mm*400mm
Slab thickness	125mm
Live load	3kN/m^2 on all floors 1.5kN/m^2 on the roof
Floor finish	1kN/m^2
Wall load	as UDL on beam
Lateral load	According to IS 1893(PartI):2016

3. Methodology

The fictitious buildings were designed as per IS 456:2000 and static nonlinear analysis in SAP2000 was done for every model to find force-displacement curve. Geometric non-linearity in the form of p-delta effect was considered in the analysis. Material non-linearity of frame element was represented by hinges. Default force deformation criteria based on ASCE 41-13 was used for hinges in beams and columns. Pushover curve, after being transformed into bilinear idealized curve using equal area approximation, was used to calculate yield base shear, yield deformation and ultimate deformation. Design base shear was obtained using linear static method following Indian standard in SAP2000. Overstrength and ductility factor were then calculated using equation 3, 6 and 7. Redundancy factor was taken as per ATC-19 (Table 1). Using these values, reduction factor was calculated for every model taken into consideration using equation 2.

4. Results and Discussions

The results of pushover analysis were evaluated to obtain ductility and overstrength factors which is discussed in this section. As consideration of every data is a bit tedious, result from representative set of buildings are discussed here.

4.1 Variation in number of story

Different models are created and analyzed by varying the number of story keeping its bay length and number of bay as constant. Story number is changed for every combination of bay length and bay number. To study the variation of reduction factor and its components, a typical result of 3.5m 2 bay buildings with story number ranging from 3 to 6 is tabulated in table 3

Table 3: Reduction factor for varying number of story for 2 number of 3.5m bay models

Model	3 storied	4 storied	5 storied	6 storied
T (sec)	0.371042	0.520454	0.673176	0.828545
V_d (kN)	171.90	240.55	249.85	248.07
V_y (kN)	717.94	775.00	733.19	742.54
d_y (mm)	18.624	27.033	31.6	41.13
d_u (mm)	55.73	75.77	78.25	136.22
μ	2.99	2.80	2.48	3.31
ϕ	1.27	1.13	1.03	0.97
Ω	4.18	3.22	2.93	2.99
R_μ	2.56	2.59	2.44	3.37
R_r	0.86	0.86	0.86	0.86
R	9.21	7.18	6.15	8.68

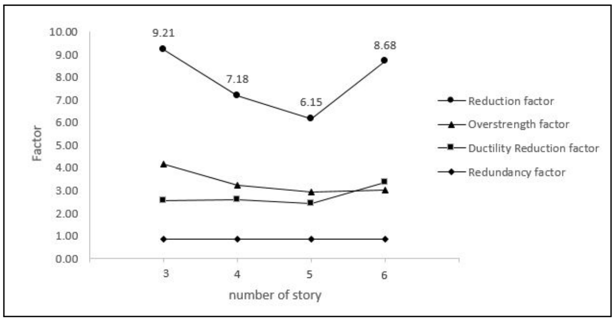

Figure 1: Reduction factor versus number of story for 2 number of 3.5m bay models)

4.1.1 Influence of number of story on overstrength factor

It can be seen from figure 1 that the overstrength factor decreases with increase in number of story. Since same frame section is used for all models, this result is justified. However, overstrength factor of 6 storied building is higher than that for others even by very minute value. From equation 3, we can infer that overstrength factor increases if the yield base shear increases or design base decreases. In this case, increment of overstrength factor might be due to slight decrease in design base shear value of 6 storied configuration as seen from table 3. Design base shear as per IS code is calculated by multiplying design horizontal seismic coefficient, A_h with seismic weight. With increase in number of story, time period of building increases which decreases the value of design acceleration coefficient, $\frac{S_a}{g}$. With this, A_h also get decreased. But since the value of seismic weight of building increases, design base shear don't follow increasing trend with increase in number of story.

4.1.2 Influence of number of story on Ductility Reduction factor

On contrary to overstrength factor, ductility reduction factor doesn't follow certain trend of data variation for different storied building. We can see that both the yield displacement and ultimate displacement increases with increase in number of story as tabulated in table 3. This seems true because increase in time period increases displacement value. However, since the ratio in which these value increase is not same, displacement ductility varies in a non definitive manner. Ductility reduction factor is a function of period of vibration and level of inelastic deformation (displacement ductility), these two factors independently cannot predict its value. With increase in number of story, time period increases whereas displacement ductility may or may not follow this trend. Hence, the behavior of ductility reduction factor also can not be predicted.

4.1.3 Influence of number of story on Reduction factor

It can be inferred from figure 1 that since ductility reduction factor do not follow a definite pattern with increase in number of story, overall reduction factor also shows no such correlation.

4.2 Variation in number of bay

To determine the effect of number of bay on reduction factor and its components, models of varying number of bay are analyzed by keeping bay size and number of story as constant. Analysis is done for every combination of bay size and bay number.

Table 4: Reduction factor for varying number of bay for 5 storied 4m bay models

Model	2 bay	3 bay	4 bay	5 bay
T (sec)	0.748836	0.759471	0.765411	0.769213
V_d (kN)	264.71	521.79	863.80	1290.80
V_y (kN)	760.13	1472.47	2417.41	3571.20
d_y (mm)	35.90	34.87	34.25	33.91
d_u (mm)	97.50	76.80	69.19	66.52
μ	2.72	2.20	2.02	1.96
ϕ	0.99	0.98	0.98	0.98
Ω	2.87	2.82	2.80	2.77
R_μ	2.73	2.22	2.04	1.99
R_r	0.86	1.00	1.00	1.00
R	6.73	6.27	5.72	5.49

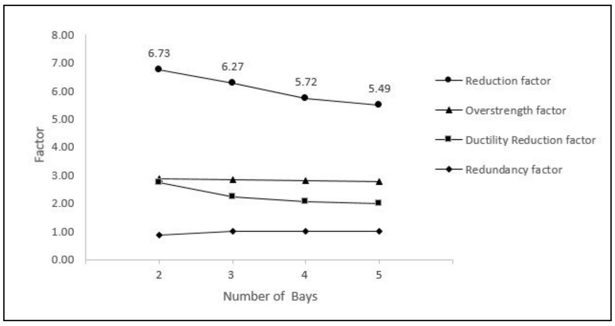

Figure 2: Reduction factor versus number of story for 5 storied 4m bay models)

4.2.1 Influence of number of bay on Overstrength factor

From the overstrength plot of figure 2, we can say that line joining two values have low gradient. This means that overstrength factor do not get affected by much with change in number of bay. Furthermore, on increasing number of bay, both the design base shear and yield base shear increases as seen in table 4. This increment follows a proportion such that Ω do not change by much.

4.2.2 Influence of number of bay on Ductility Reduction factor

Table 4 shows that displacement ductility decreases by slight amount with increase in number of bay. Furthermore, the value of factor for 2 bay is slightly higher than that for 3, 4 and 5 bay models where the value do not differ by much. However, they decrease with increase in number of bay. This might be attributed to the notion that, while increasing the bay, effective stiffness of the system increases decreasing overall ductility of the system.

4.2.3 Influence of number of bay on Reduction factor

Although, overstrength and ductility reduction factor shows very slight variation with number of bay, being their product, reduction factor decreases by significant amount with change in number of bay as seen from figure 2. However, for some models where the sub factors decreases by very slight amount, overall reduction factor seem to decrease when number of bay increases to 3 as demonstrated by figure 3. This is because the reduction factor incorporate redundancy factor as well whose value for 2 and 3 bay frame is taken to be 0.86 and 1 respectively.

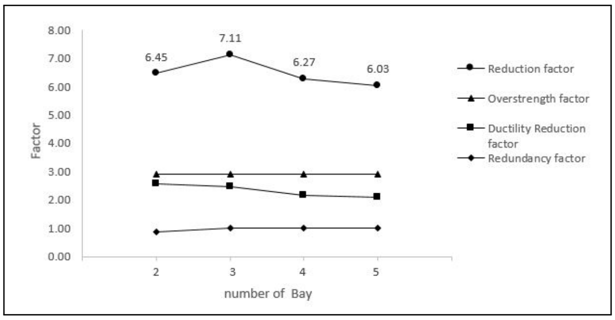

Figure 3: Reduction factor versus number of story for 5 storied 4.5m bay models)

5. Variation in bay size

To find and compare the value of reduction factor and its components among buildings whose span is different, models are created by fixing number of story and bay and varying the bay size. As the factors do not follow similar trend for every combination of number of story and number of bay, two representative plots are shown here.

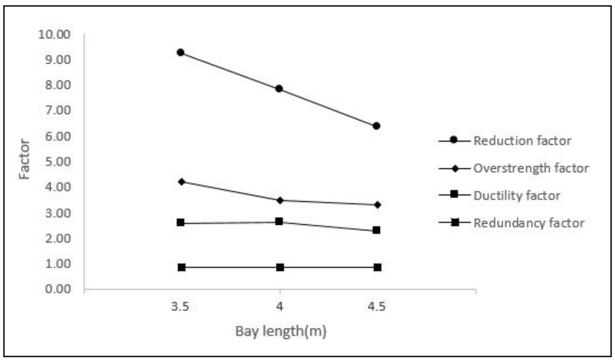

Figure 4: Reduction factor versus number of bay for 3 storied 2 bay models)

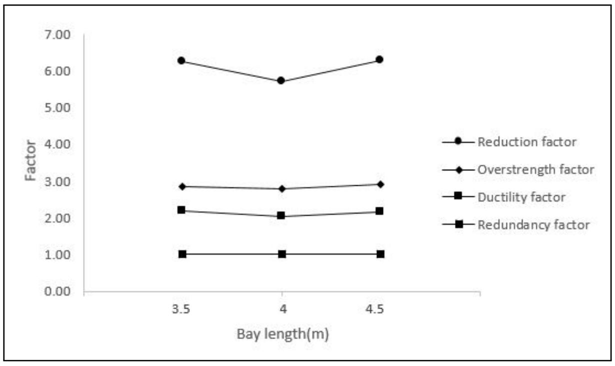

Figure 5: Reduction factor versus number of bay for 5 storied 4 bay models)

5.0.1 Influence of bay size on Overstrength factor

The value of overstrength factor follows a decreasing trend with increase in bay length for all number of bays for 3 and 4 storied buildings as illustrated by figure 4. However, overstrength factor do not follow this trend for 5 and 6 storied buildings. Yield base shear is found to increase by large amount with respect to design base shear which causes their ratio i.e. overstrength factor to increase when bay length is increased from 4m to 4.5m as described by figure 5.

5.0.2 Influence of bay size on Ductility Reduction factor

On increasing bay length, ductility reduction factor do not show a specific pattern for all number of bay under consideration. Also, the factor is found to vary in accordance to displacement ductility irrespective of ϕ value which increases with increase in time period or bay size.

5.0.3 Influence of bay size on Reduction factor

The reduction factor shows decreasing trend with increase in bay length keeping other parameters as constant for 3 and 4 storied buildings similar to overstrength factor. For 5 and 6 storied buildings, reduction factor follows no such pattern with increase in bay size. From figure 5, we can see that neither reduction factor nor its components show strong correlation with bay size for 5 and 6 storied buildings.

Based on this study, the value of overstrength factor, ductility reduction factor and overall reduction factor for considered models fall in the range of 2.68-4.18, 1.83-3.37 and 5.14-9.21 respectively.

In addition to this, while designing two buildings following same code, even if the value of reduction factor is very near or even equal, it cannot be said that these buildings will perform in similar manner under seismic load. They might behave differently since overstrength and ductility reduction factor may be different. As an illustration, let's compare reduction factor of models 5S4BC1B3 and 6S5BC1B3.

Table 5: Sub-factors of models with same Reduction factor

	5S4BC1B3	6S5BC1B3
Overstrength factor	2.90	3.18
Ductility Reduction factor	2.16	1.97
Redundancy factor	1	1
Reduction factor	6.27	6.26

Since the ductility reduction factor of two models are different, they will behave differently under lateral load even if the value of reduction factor is same. Figure 6 gives the comparison of pushover curve for these buildings.

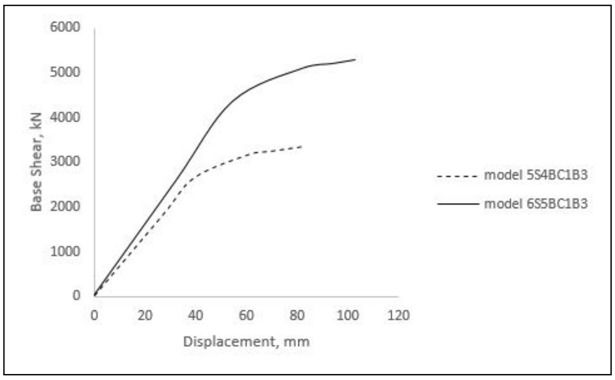

Figure 6: Pushover curve for models 5S4BC1B3 & 6S5BC1B3)

6. Conclusion

The main motive of this study is determine the effect of building size on ductility and overstrength of regular in plan and elevation buildings. Here are some conclusions drawn from the analytical investigation of datas obtained.

- Single value of overstrength, ductility and reduction factor for similar buildings of different size cannot be justified.
- With increase in number of story, overstrength factor decreases from 3 to 4 story while it remains very close on further increasing the building height. Ductility factor and reduction factor do not show any specific trend with variation in number of story.

- The factors do not show significant variation with number of bay in both horizontal direction. However, maximum value is obtained for lower number of bay.

- Dependency of the factors on the span is not same for buildings of all story. Overstrength factor decreases with increase in size of bay for 3 and 4 storied building while Ductility reduction factor do not follow specific trend with variation in span. Like overstrength factor, R value also decreases with increase in span for 3 and 4 storied building while no clear dependency is seen for 5 and 6 storied building.

The conclusions are valid for the regular building models considered and other data assumed in this study. Further investigation considering a wider set of geometrical parameters and higher number of model is required for better performance evaluation.

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