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Overstrength Factor and Ductility Factor for Seismic Design of RC Buildings

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Abstract
It is utmost importance to design a structure such that they are economical and also has an adequate strength to resist the loads applied on them. Due to this reason, the design lateral strength in most of the design codes including NBC 105: 2020 is lowered from the required elastic lateral strength by the combination of overstrength factor (Ω_u) and ductility factor (R_μ) resulting in smaller member section. The structural member sizes govern the time period and drift of the structure on which the overstrength factor (Ω_u) and ductility factor (R_μ) is dependent. The total number of 36 configurations of low-rise buildings most common in Nepal is selected and each building is analysed with two different structural member sizes. The NBC 105:2020 is selected for the seismic design of RC buildings and non-linear analysis is performed using provision in FEMA 356:2000. The results indicated that the change in building configuration and structural member sizes affects the overstrength factor (Ω_u) and ductility factor (R_μ).

Keywords
Overstrength Factor, Ductility Factor, Response Reduction Factor

1. Introduction

RC buildings are the ones in which members resisting horizontal and vertical forces are made up of reinforced concrete. According to latest census data of Nepal out of total 54,23,297 buildings, 5,39,004 of them are RC structure which accounts for around 9.94%. This value is increasing rapidly as now people are aware of the benefit of RC structure in resisting earthquake over load-bearing masonry structure.

It is very important to design a structure such that they are economical and also has an adequate strength to resist the loads applied on them. Most of the design codes makes use of the design philosophy that total safety and no damage, even in an earthquake with a reasonable probability of occurrence, cannot be attained[1]. Allowing some nonstructural as well as structural damage can still have a high level of safety making the structure economical. Utilization of inelastic behavior of the structure helps in reducing the lateral force to be resisted by the structure hence reducing the member sizes and finally reducing the cost of construction[2]. So, the design lateral strength in most of the design codes including NBC 105: 2020[3] is lowered from the required elastic lateral strength by the combination of overstrength factor (Ω_u) and ductility factor (R_μ).

2. Overstrength and Ductility Factor

Response reduction factor is a ratio of maximum lateral force (V_e) which structure would reach, if it were to remain entirely linear elastic under the particular ground motion to the design lateral force (V_d) which it has been designed to resist.

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

University of California in Berekely, in the mid-1980s, carried out experimental research and concluded a response reduction factor (R) as the product of three cofactors that included reserve strength, ductility, and added viscous damping. So, mathematically (R) can be expressed as:

$$R = \Omega * R_\mu * R_x \tag{2}$$

As most of the structure don't have an added damping device, so it is neglected unless it has one. Later, Applied Technology Council[4] re-defined R and expressed it as the product of 3 main factors i.e.,

$$R = \Omega * R_{\mu} * R_{r} \quad (3)$$

Where, Redundancy factor (R_r) accounts for the reliability of seismic framing systems which should be composed of multiple vertical lines of seismic framing in each principal direction of a building.

Overstrength factor (Ω) is the ratio of V_y and V_d. It is an additional reserve strength beyond design strength[5]. V_y is the significant yield strength which is the point in the capacity curve where the change in slope occurs can be located by idealizing the capacity curve to bilinear curve and V_d is the design lateral strength.

$$\Omega = \frac{V_y}{V_d} \quad (4)$$

The ductility of the structure determines its ability to withstand large lateral displacement imposed by severe earthquake, as during which the structures cross their elastic limit and reach the inelastic region. The ductility factor (R_μ) can be defined as the ratio of maximum lateral force (V_e) which structure would reach, if it were to remain entirely linear elastic (μ = 1) under the particular ground motion to the idealized yield strength (V_y) of the structure.

$$R_{\mu} = \frac{V_e}{V_y} \quad (5)$$

The displacement ductility ratio (μ) is the ratio of maximum absolute displacement (d_u) to the idealized yield displacement (d_y) and measures the amount of inelastic deformation.

$$\mu = \frac{d_u}{d_y} \quad (6)$$

The ductility factor (R_μ) gets affected mainly by displacement ductility ratio (μ), period of vibration (T) and local soil condition (SC). So, ductility factor (R_μ) can be expressed as:

$$R_{\mu} = f(\mu, T, SC) \quad (7)$$

Also, some of the other condition of ductility factor (R_μ) are as follows:

$$\lim_{T \to 0} f(\mu, T, SC) = 1 \quad (8)$$

$$\lim_{T \to \infty} f(\mu, T, SC) = \mu \quad (9)$$

$$R_{\mu} = f(\mu, T, SC) = 1; \mu \leq 1 \quad (10)$$

In 1993, Eduardo Miranda[6] considered a recorded earthquake ground motion in which on 38 were on rock soil, 62 were on alluvium soil, and 24 were on soft soil. After carrying out the regression analysis the equation for ductility factor (R_μ) was computed assuming 5% critical damping.

$$R_{\mu} = \frac{\mu - 1}{\phi} \geq 1 \quad (11)$$

Where,

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

3. Building Description and Modelling

The 3D mathematical model is created in ETABS2020 v19.0.0 where both the columns and beams are modelled as the frame elements and slabs as shell elements that are interconnected at nodes.

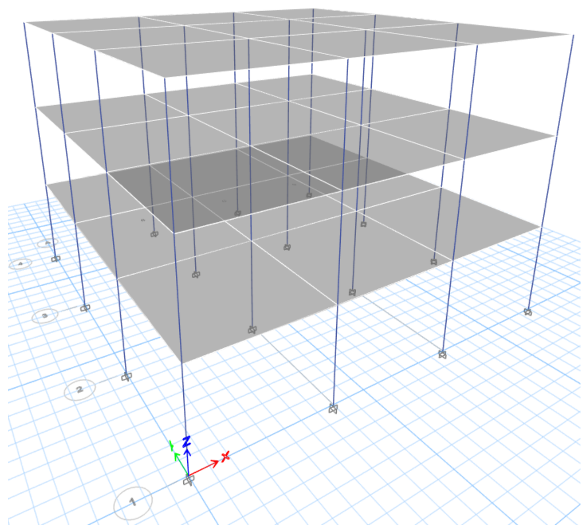

Figure 1: Finite Element Modelling of 3 Storey 3 Bay 4m Bay Length (3S3B4BLM2) Model

3.1 Structural Modelling Parameters

The varying parameters considered in this study are number of storeys, numbers of bays, bay length and member sizes. There are 4 numbers of storeys i.e., 2, 3, 4, and 5. Also, these models have 3 variations of bays i.e., 2, 3, and 4 in which each bays have 3 different bay lengths i.e., 3m, 3.5m, and 4m[7]. Again, these 36 different configurations of building models, are each modelled with 2 different structural member sizes making a total of 72 models.

Table 1: Material Propoerties

	Reinforcement	Concrete
Grade	HYSD 500	M25
Unit Weight	76.97 kN/m^3	25 kN/m^3
Modulus of Elasticity	200 Gpa	25 Gpa
Poisson's Ratio	0.3	0.2

Table 2: Structure Detail

Storey Height	2.9 m
Slab Thickness	125 mm
Soil Type	Medium Soil
Seismic Zoning Factor	0.4
Importance Factor	1
Damping in Structure	5%

Table 3: Loads on Struture

Floor Finish	1 kN/m^2
Roof Live Load	1.5 kN/m^2
General Floor Live Load	2 kN/m^2
Outer Wall Load	7.5 kN/m
Partition Wall Load	4 kN/m
Lateral Load	NBC 105: 2020

3.2 Structural Members

A 36 unique configuration of buildings are first modelled with smallest (base) size of beam and column possible to satisfy the necessary design and serviceability check following NBC 105:2020 in which sizes of column and beam differ according to number of storeys only i.e., within a particular storey for different number of bay and bay length, the sizes of beam and column doesnot differ. However, all the frame elements (column, beam) in a particular building model are of the same size.

To study the effect of building configuration in Section 5.1.1 and 5.2.1 , the sizes are adopted as per Table 4.

Table 4: Base Size of Beam and Column for a Storey

For Storey	Beam Dimension (D X B)	Column Dimension (D X B)	Code Assigned (Mn)
2	14" X 9"	12" X 12"	M1
3	14" X 9"	13" X 13"	M2
4	14" X 10"	14" X 14"	M3
5	16" X 10"	15" X 15"	M4

Later to study the effect of member size on overstrength factor (Ω_u) and ductility factor (R_μ), a larger but same cross-sectional sizes' column and beam are provided irrespective of the number of storeys for all these 36 models. The larger size thus adopted has a depth and width of 16" X 12" for beam and 16" X 16" for column respectively. This member size of column and beam is assigned with code M5.

4. Pushover Analysis

The non-linear static pushover analysis[8] is carried out to obtain the capacity curve for the three-dimensional models. The material non-linearities are considered by assigning frame hinge properties near to the column beam joints which represents post yield behavior. The default hinges are assigned for both the frame elements in which force - displacement behavior is described by properties that are provided based on ASCE 41 - 13[9]. The beams are assigned with uncoupled moment M3 hinges and the columns are assigned with P-M2-M3 hinges. The procedure done during the pushover analysis is:

- The three-dimensional building is modelled and all the necessary loads are applied.
- Hinges are assigned at the point where the member is expected to fail near the joint.
- At first, a force-controlled method is initiated for gravity loads which is the sum of all the dead loads and 30% of live loads.
- Lastly, the displacement-controlled method is carried out until the target displacement is achieved or the structure reaches its maximum base shear.
- The force-displacement curve is obtained which is then idealized to obtain yield displacement (d_y), ultimate displacement (d_u), yield base shear (V_y).

FEMA 356:2000[10] provides a procedure for bilinearization based on equal energy concept. The process is an iterative method. The two main points considered for bilinearization of pushover curve is as follows:

- The area under the two curves must be equal i.e., area under the pushover curve before idealization and area under the idealized bilinear curve must be equal.
- The first line segment of the bilinear curve must intersect the original pushover curve at 60% of significant yield strength.

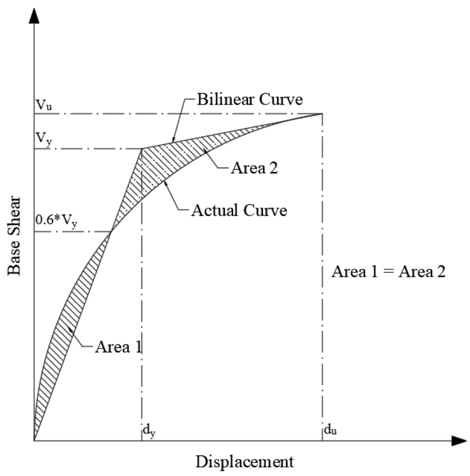

Figure 2: Bilinear Idealization of Pushover Curve

5. Results and Discussion

This section presents the results obtained from the non-linear pushover analysis of the building models. The results are evaluated and compared to find the influence of different parameters on overstrength factor (Ω_u) and ductility factor (R_μ).

5.1 Effect on Overstrength Factor

Overstrength factor is examined for every combination of building configuration and different structural member sizes.

5.1.1 Due to Building Configuration

The overstrength factor decreases while increasing the number of storey. While increasing the number of storey, both the design base shear and the yield strength increase but the yield strength increases at a lower rate than the design base shear which eventually decreases the overstrength factor. While increasing the number of bay does not affect the overstrength factor, as both the design base shear and the yield strength increases at almost the same rate. So, the overstrength factor varies only slightly. Also, its effect further decreases with an increase in the number of storey.

In the case of bay length, increasing it decreases the overstrength factor. This can be explained as increasing the bay length only increases the seismic weight / design base shear but does not increase the lateral stiffness.

The overstrength factor varied from the highest 2.873 for the smallest model having 2 storey, 2 bays and 3m bay span to the lowest 1.886 for the largest model having 5 storey, 4 bays and 4m bay span.

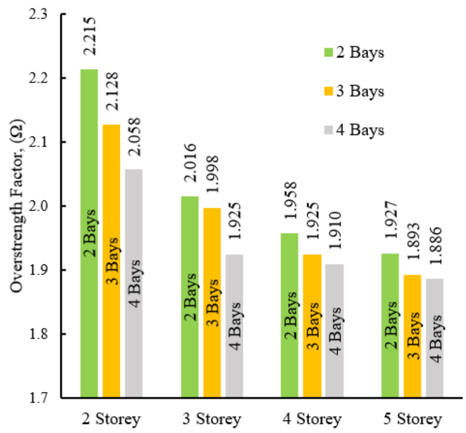

Figure 3: Overstrength factor for number of bay for various number of storey

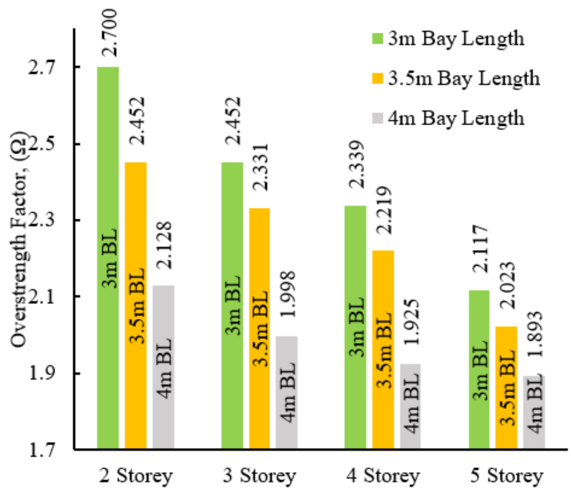

Figure 4: Overstrength factor for bay length for various number of storey

The Figure 5 represents the overstrength factor for model having same length of 12m. There are two 12m model for all storied building from 2 storey to 5 storey in which one has 4 bays with 3m bay length and other has 3 bays with 4m bay length. As dependency on bay length is more, the model which has smaller bay length by having more bays i.e., model with 4 bays and 3m bay length has higher value of overstrength factor.

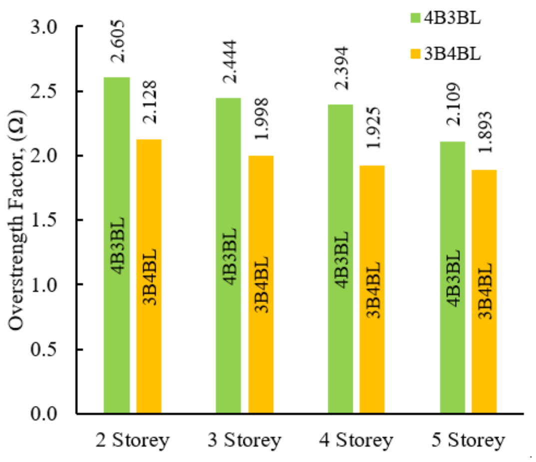

Figure 5: Overstrength Factor for Model having Same Length (12m)

5.1.2 Due to Structural Member Size

The models are analysed with varying column and beam sizes and its effect on the overstrength factor is observed. The overstrength factor rapidly increased by 1.14 to 2.28 times when difference between the structural member size also increased. This can be attributed to the concept that increasing the member sizes increases its lateral stiffness which then gives higher yield strength. The Section 3.2 shows the member sizes used with its code assigned.

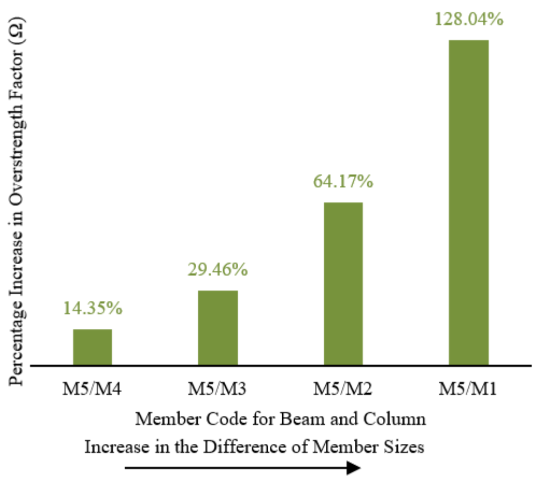

Figure 6: Effect on Overstrength Factor by Varying Member Sizes

Where M5/M4 represents a model with member sizes M4 which is then replaced by member sizes M5 and it is similar for all the other designation mentioned in the Figure 6 and 10.

5.2 Effect on Ductility Factor

Ductility factor (R_μ) is calculated based on the formulation mentioned in Section 2. Building configuration and structure member size are varied to study its effect on ductility factor.

5.2.1 Due to Building Configurations

The value for ductility factor is higher for 2 storey building but reduces with the increase in number of storey from 2 to 5. Even though the time period increases as the number of storey increases but the value of displacement ductility ratio (μ) decreases significantly which then reduces the ductility factor. The effect of number of bay on the ductility factor is very less showing slight decrease with increase in number of bay. This can be explained as increasing the number of bay makes the building stiff. But contrary to overstrength factor, the effect of number of bay further demises as the storey decreases.

Similar to the overstrength factor, increasing the bay length decreases the ductility factor. This can be justified cause increasing the bay length decreases the displacement ductility ratio (μ), decreasing the ductility factor.

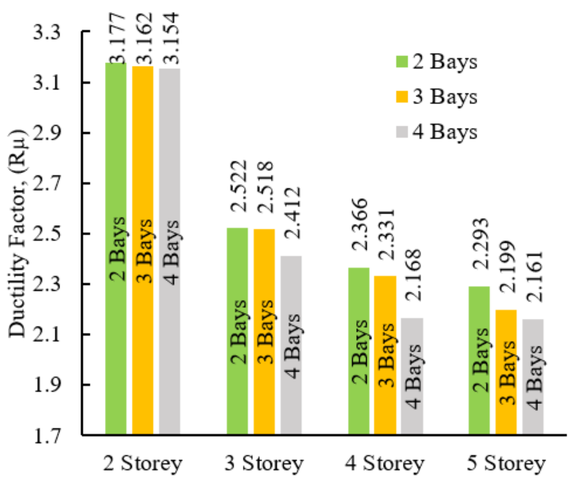

Figure 7: Ductility factor for number of bay for various number of storey

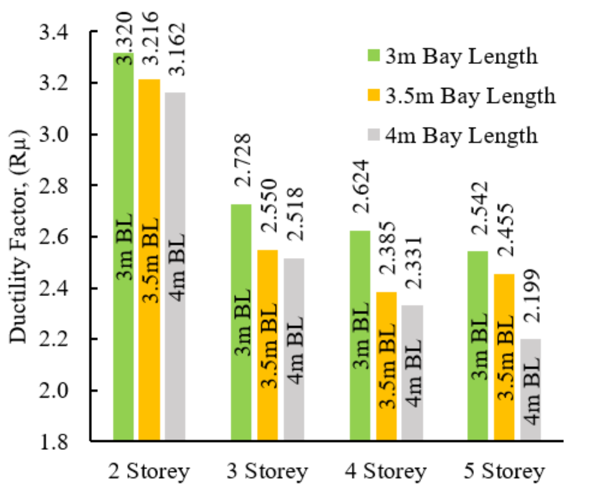

Figure 8: Ductility factor for bay length for various number of storey

The Figure 9 represents the ductility factor for model having same length of 12m. There are two 12m model for all storied building from 2 storey to 5 storey in which one has 4 bays with 3m bay length and other has 3 bays with 4m bay length. As dependency on bay length is more, the model which has smaller bay length by having more bays i.e., model with 4 bays and 3m bay length has higher value of ductility factor.

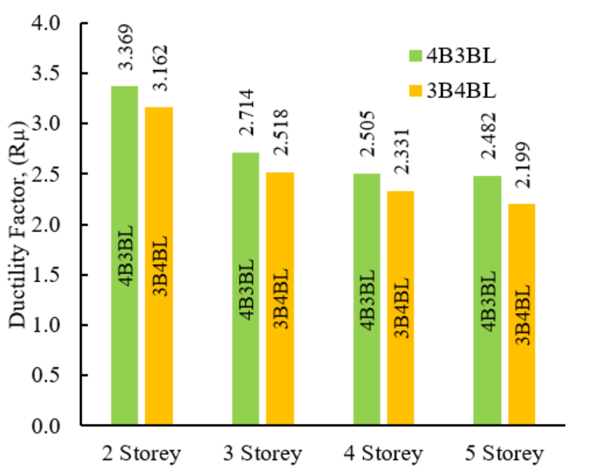

Figure 9: Ductility Factor for Model having Same Length (12m)

5.2.2 Due to Structural Member Size

The ductility factor decreased by the lowest 0.9 to the highest 0.79 times when difference between the structural member size assigned to them increased. This can be attributed to the concept that increasing the member sizes increases its lateral stiffness which makes the structure stiffer resulting in less plastic deformation. The Section 3.2 shows the member sizes used with its code assigned.

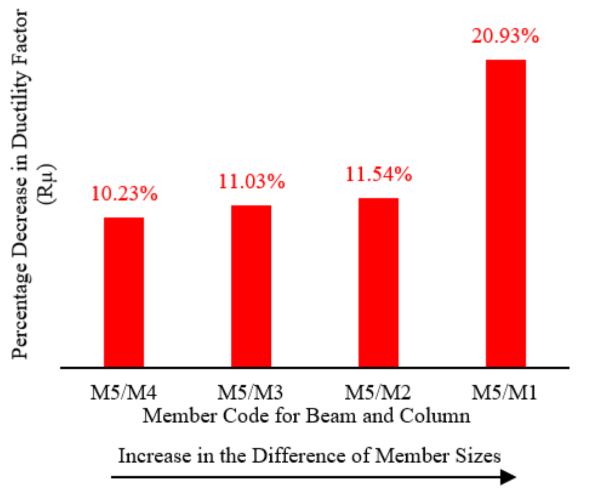

Figure 10: Effect on Ductility Factor by Difference in Member Sizes

6. Conclusions

The following conclusions has been made from the analytical study carried out by varying the building configurations and structural member sizes.

- Both the overstrength factor (Ω_u) and ductility factor (R_μ) is dependent upon parameters such as building configuration and member sizes. Using a single value for them will introduce the unwanted uncertainty in the building.
- The dependency on bay length is more than the number of bays for both the overstrength factor and ductility factor. For the overstrength factor the effect of bay length and number of bays reduced as the number of storey increased but it is opposite in the case of ductility factor.
- or a given fixed span, if it is divided in a way that has a higher number of bays by reducing the bay length, then the value for the overstrength factor (Ω_u) and ductility factor (R_μ) increased.
- The overstrength factor increased and ductility factor decreased while providing higher sizes of column and beam than required.

These conclusions are limited to the scope of the work carried out in this research. More wider parameters need to be included to reduce the limitations of this research in order to accurately predict the overstrength factor and ductility factor.

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