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# Evaluation of the Response Reduction Factor of Confined Brick Masonry Structures

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**Abstract**

Confined masonry is a form of masonry construction involving masonry walls to be confined using horizontal and vertical tie elements to increase their strength and stiffness. Nepal is a country rich in cultural heritage, and masonry has played a significant role in the country's architectural history. Thus, the confined masonry construction technique can be developed as a structurally and aesthetically sound construction practice. As most buildings designed in Nepal are based on equivalent static method, the response reduction factor is a necessary parameter for determining design loads and needs to be used wisely. This study is focused on finding out response reduction factor for confined masonry structures by finding out overstrength factor and ductility factor and observing the variation of these factors by varying building configurations by changing the values of wall density indexes and the number of stories. It has been found that wall density index and the number of stories have a great influence on the overstrength factor and ultimately the response reduction factor of confined masonry structures.

**Keywords**

Confined masonry, Response reduction factor, Ductility factor, Overstrength factor, Response reduction factor, Nonlinear static analysis

## 1. Introduction

Nepal was recently hard hit by the Gorkha Earthquake on April 25, 2015. Even after the earthquake, the RC-framed construction method hasn't completely replaced the masonry construction system because of the accessibility of local resources like bricks, stones, lime, mud, etc. Confined masonry construction system is a great alternative to a mere unreinforced brick masonry construction system and can also perform better than RC-framed construction system because masonry walls in confined masonry also bear horizontal and vertical loads, unlike the infill walls used in RC-framed construction system.

Today, a majority of seismic codes take into account a structure's nonlinear response by applying the proper response reduction factor for different structural systems. The value of the response reduction factor will depend on the type of structure being considered, the intensity and duration of the lateral loads being considered, and other factors that may affect the inelastic behavior of the structure. Given that limited masonry buildings with sufficient wall densities have incurred less damage in previous earthquakes, it has been noticed that the wall density index is important in providing rigidity in the event of an earthquake. Thus, wall density index is a significant parameter in governing the response reduction factor of confined masonry structures. This study is focused on finding out the values of response reduction factor of confined masonry structures and observing its variation by varying wall density and the number of stories.

## 2. Response Characteristics

### 2.1 Response Reduction Factor

Response reduction factor is a parameter used to take into account the actual behavior of a structure during an earthquake and lower the calculated seismic forces on it to a more realistic level. It is used in seismic design to take into consideration a structure's capacity to disperse seismic energy and withstand inelastic deformations without losing stability.

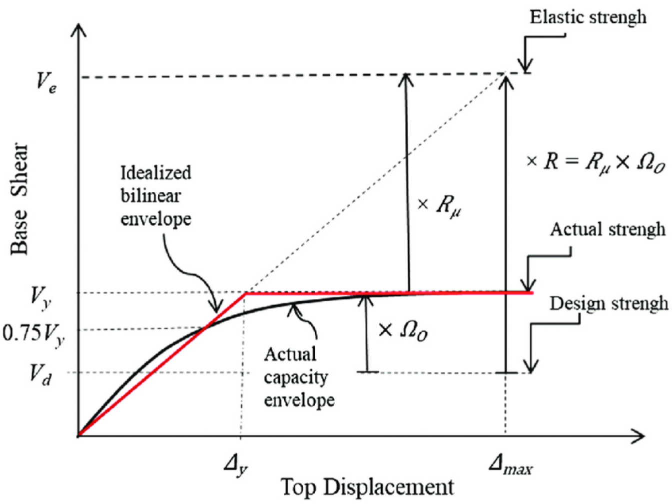


**Figure 1:** Bilinear idealization and R factor calculation [1]

Response reduction factor can be defined as the ratio of maximum lateral force $V_e$ that a structure would experience when assumed to be linear elastic completely for a given ground motion to the design lateral force $V_d$ that the structure is intended to withstand. Mathematically, R is given by

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

Response reduction factor is composed of overstrength, redundancy, and ductility, which is also shown in figure 1. Overstrength factor is used to take into consideration the reserve strength of a structure beyond its elastic limit, which may occur under extreme loading conditions. The redundancy factor is used to account for the ability of a structure to redistribute loads. The ductility factor is used to account for the ability of a structure to deform plastically.

According to ATC-19 [2], response reduction factor can be mathematically given by

$$R = \Omega \times R_\mu \times R_r \tag{2}$$

where $\Omega$ denotes overstrength factor, $R_\mu$ denotes ductility factor, and $R_r$ denotes redundancy factor.

### 2.2 Overstrength Factor

The overstrength factor is used to take into consideration the possibility that a structure's actual strength can be higher than the strength that is required to resist specific design lateral loads.

Overstrength factor ($\Omega$) can be defined as

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

Where $V_y$ denotes base shear at first significant yield, and $V_d$ denotes design base shear.

### 2.3 Ductility Factor

Ductility factor is a measure of a structure's ability to undergo significant deformations beyond the elastic point before collapsing. It is the ratio of maximum lateral force ($V_e$) that a structure would experience when assumed to be linear elastic completely for a given ground motion to the structure's idealized yield strength ($V_y$). Mathematically,

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

Ductility factor refers to the measure of a structure's nonlinear response and is primarily controlled by the parameter displacement ductility($\mu$). The ductility displacement can be expressed as

$$\mu = \frac{\Delta u}{\Delta y} \tag{5}$$

where $\Delta u$ denotes ultimate displacement, and $\Delta y$ denotes yield displacement.

As per Newmark and Hall[3, 4], ductility factor can be calculated as

$$R_\mu = \sqrt{2\mu - 1} \tag{6}$$

### 2.4 Redundancy Factor

The redundancy factor is a parameter used to account for the presence of redundancy in a building's structural system. Redundancy refers to the existence of multiple load paths or structural elements that can share and distribute the applied loads. Redundancy factor is taken one for this study as per past researches. ATC-19 recommends the value of one for redundancy factor for three and more bays. Also, according to ASCE 7[5], redundancy factor can be assigned as one for structures whose design seismic forces may be applied individually in each of the two orthogonal directions and the effects orthogonal interaction effects can be disregarded.

## 3. Wall Density Index

One important safety indication parameter for low-rise confined masonry structures is wall density index. According to reports from past earthquakes, sufficient wall density index led confined masonry structures to withstand major earthquakes without collapsing[6].

Wall density index (WDI) can be expressed as

$$WDI = \frac{A_w}{A_p} \tag{7}$$

where

$A_p$ denotes floor plan area

$A_w$ denotes the sum of the cross-sectional areas (product of wall length and wall thickness) of all walls in the direction that is being considered,

## 4. Methodology

Literature regarding confined masonry structures, response reduction factor, overstrength factor, ductility factor, and codal provisions regarding response reduction factor for confined masonry structures were reviewed to attain knowledge regarding theoretical background and need of research. Suitable building plans were selected. Structural modeling of those buildings were carried out using finite element software. Variations in building models were created by varying wall densities and number of stories. Then nonlinear static pushover analyses were carried out. With the help of pushover curves, overstrength factors and ductility factors were evaluated. Then response reduction factors were calculated for various building configurations. After that, a comparative study of response reduction factors among various building configurations were carried out, and relevant conclusions were derived.

## 5. Structural Description and Material Properties

Two primary building plans, namely B and C, were considered, one with equal building length and building breadth, and another with different building length and building breadth. For evaluating the variation in the response reduction factor, variation in building configurations were carried out by changing the wall density. Variations were observed for two, three, and four stories.

The floor height is taken 9'4". Tie beams and tie columns are of sizes 230mm × 230mm were used with four rebars of 12mm. Slab of thickness 125mm is taken. All internal and external walls used are 230mm thick.

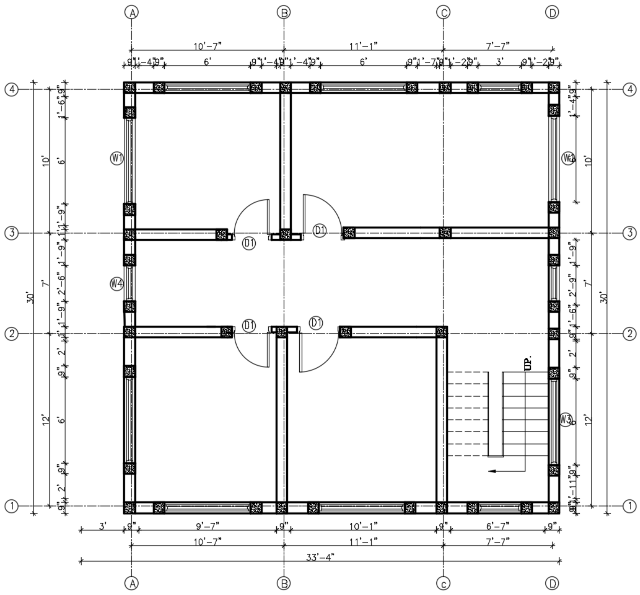


**Figure 2:** Building plan for model B1

Figure 2 is the plan for building model B1. The plans for building models B2 to B6 are primarily based on model B1, where changes were brought by changing the wall densities. The wider windows are 6', and their widths are reduced to increase wall densities in the subsequent models.

For building model B2, windows inside 1-2 and 3-4 of grid line A and grid line D are changed from 6' to 4'. Rest of the dimensions are kept the same as for model B1.

For building model B3, a wall with a 3ft door opening was added between 3-4 in grid line C. Rest of the dimensions are kept the same as for model B2.

For building model B4, building model B1 was analyzed in the X-direction.

For building model B5, windows inside A-B and B-C of grid line 1 and grid line 4 are changed from 6' to 5'. Rest of the dimensions are kept the same as for model B1.

For building model B6, windows inside A-B and B-C of grid line 1 and grid line 4 are changed from 5' to 4'. Rest of the dimensions are kept the same as for model B5.

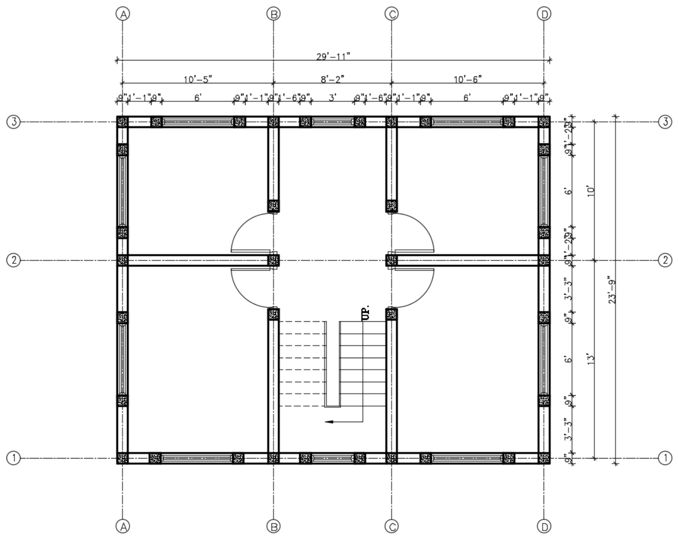


**Figure 3:** Building plan for model C1

Figure 3 is the plan for building model B1. The plans for building models C2 to C6 are primarily based on model C1, where changes were brought by changing the wall densities. The wider windows are 6', and their widths are reduced to increase wall densities in the subsequent models.

For building model C2, windows inside A-B and C-D of grid line 1 and grid line 3 are changed from 6' to 5'. Rest of the dimensions are kept the same as for model C1.

For building model C3, windows inside A-B and C-D of grid line 1 and grid line 3 are changed from 6' to 4'. Rest of the dimensions are kept the same as for model C1.

For building model C4, windows inside A-B and C-D of grid line 1 and grid line 3 are changed from 6' to 3'. Rest of the dimensions are kept the same as for model C1.

For building model C5, windows inside 1-2 and 2-3 of grid line A and grid line D are changed from 6' to 5'. Rest of the dimensions are kept the same as for model C1.

For building model C6, windows inside 1-2 and 2-3 of grid line A and grid line D are changed from 6' to 4'. Rest of the dimensions are kept the same as for model C1.

**Table 1:** Wall density indices

| X-direction | | Y-direction | |
|---|---|---|---|
| Model | WDI (%) | Model | WDI (%) |
| B1 | 6.42 | B4 | 7.91 |
| B2 | 7.37 | B5 | 8.38 |
| B3 | 8.2 | B6 | 8.86 |
| C1 | 5.21 | C5 | 6.32 |
| C2 | 5.63 | C6 | 6.74 |
| C3 | 6.05 | | |
| C4 | 6.47 | | |

Concrete of grade M20 was used. Fe500 rebars were used. Stress strain data for masonry was generated as per Kaushik et al., 2007[7]. Minimum class of brick for load-bearing masonry is class B, and minimum mortar grade of cement sand mortar is 1:6. The Poisson's ratio for masonry was taken 0.25. The strengths of mortar and brick were used to develop a stress-strain curve for masonry as mentioned in [7] and is shown in figure 4.

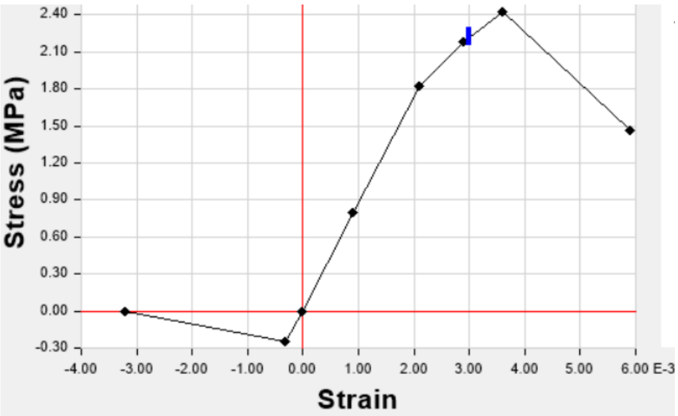


**Figure 4:** stress-strain curve for masonry generated as per [7]

## 6. Structural Analysis and Modeling

For modeling, finite element software ETABS v20.0 was used. Macromodeling technnique was used to model confined masonry buildings in which tie beams and columns are modeled as line elements and walls are modeled as shell elements[8, 9]. For walls, a mesh size of 200mm was adopted. In confined masonry construction, concrete beams and columns are cast after walls are already built, so both concrete members and walls act jointly. Therefore, in ETABS, beams and columns are modeled as line elements and they are discretized such that the size of mesh of beams and columns are equal to the size of mesh of walls, and transfer of load occurs from beams and columns to walls too. Effect of the staircase is not considered. Earthquake load is calculated as per seismic coefficient method based on NBC 105:2020[10]. Moment release were done at the connections of beams and columns, taking in mind the fact that unlike RCC-framed buildings, which are capable of withstanding moments and are stable without walls, confined masonry buildings are not stable without wall panels as walls bear the major portion of both gravity and lateral loads[11].

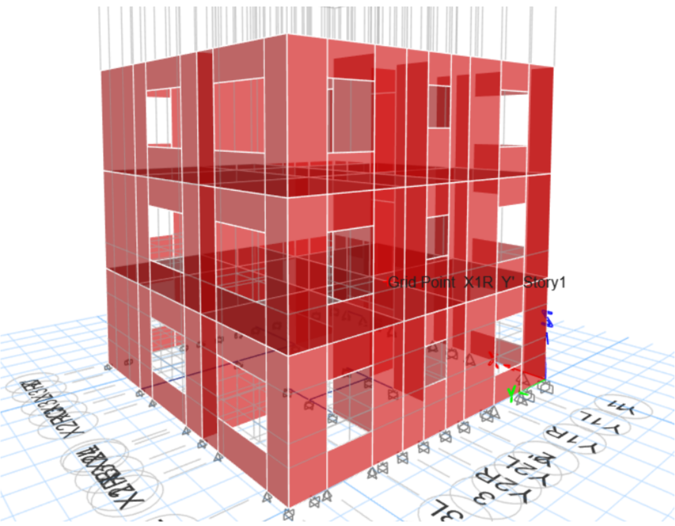

**Figure 5:** Etabs model for building B1 - 3 story

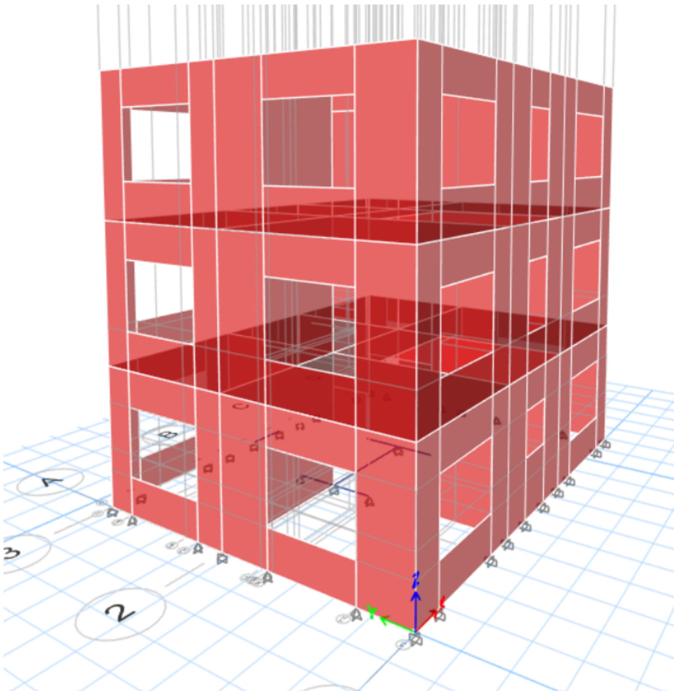

**Figure 6:** Etabs model for building C1 - 3 story

Response reduction factors for each model were computed from overstrength and ductility factors, which were determined by pushover analysis.

## 7. Results and Discussions

Eigen value analysis was done for 36 building models, and the values of fundamental time periods and seismic weights have been mentioned in Tables 2 and 3.

**Table 2:** Fundamental periods and seismic weights of buildings B1 to B6

| Building | Period (s) | Seismic weight (kN) |
|---|---|---|
| B1-2story | 0.16 | 1857.976 |
| B2-2story | 0.17 | 1866.247 |
| B3-2story | 0.17 | 1923.88 |
| B1-3story | 0.24 | 2995.13 |
| B2-3story | 0.24 | 3016.008 |
| B3-3story | 0.24 | 3104.001 |
| B1-4story | 0.32 | 4132.284 |
| B2-4story | 0.32 | 4161.484 |
| B3-4story | 0.32 | 4284.122 |
| B4-2story | 0.16 | 1857.976 |
| B5-2story | 0.16 | 1864.254 |
| B6-2story | 0.16 | 1870.532 |
| B4-3story | 0.24 | 2995.13 |
| B5-3story | 0.24 | 3005.569 |
| B6-3story | 0.24 | 3016.008 |
| B4-4story | 0.32 | 4132.284 |
| B5-4story | 0.32 | 4146.884 |
| B6-4story | 0.32 | 4161.484 |

To compute response reduction factor, pushover curves obtained from ETABS were processed to determine yield base shear, yield displacement, and ultimate displacement by converting them into bilinearly idealized curves as described in FEMA 356:2000[12] to calculate ductility and overstrength factor to determine response reduction factor.

From table 4 to table 5 and figure 7 to figure 10, the variation in the overstrength factor can be observed with the variation in wall density and the number of stories. As we go on increasing wall density index, the value of overstrength factor also increases. This can be attributed to the increased stiffness provided by the increased dimensions of walls, as walls play a major role in providing stiffness in confined masonry structures. Also, it can be observed that as we go on increasing the number of stories, the value of overstrength factor decreases. This can be attributed to the increase in design base shear as the seismic weight of building increases.

**Table 3:** Fundamental periods and seismic weights of buildings C1 to C6

| Building | Period (s) | Seismic weight (kN) |
|---|---|---|
| C1-2story | 0.22 | 1533.152 |
| C2-2story | 0.22 | 1539.43 |
| C3-2story | 0.22 | 1545.709 |
| C4-2story | 0.22 | 1551.987 |
| C1-3story | 0.24 | 2463.791 |
| C2-3story | 0.24 | 2485.105 |
| C3-3story | 0.24 | 2495.544 |
| C4-3story | 0.24 | 2505.983 |
| C1-4story | 0.32 | 3394.43 |
| C2-4story | 0.32 | 3430.78 |
| C3-4story | 0.32 | 3445.38 |
| C4-4story | 0.32 | 3459.98 |
| C5-2story | 0.22 | 1541.276 |
| C6-2story | 0.22 | 1547.555 |
| C5-3story | 0.24 | 2488.797 |
| C6-3story | 0.24 | 2499.237 |
| C5-4story | 0.32 | 3436.318 |
| C6-4story | 0.32 | 3450.918 |

**Table 4:** Overstrength factor for buildings B1 to B6

| Building | WDI(%) | Overstrength factor |
|---|---|---|
| B1-2story | 6.42 | 3.13 |
| B2-2story | 7.37 | 3.15 |
| B3-2story | 8.20 | 3.39 |
| B1-3story | 6.42 | 1.74 |
| B2-3story | 7.37 | 1.90 |
| B3-3story | 8.20 | 2.10 |
| B1-4story | 6.42 | 1.23 |
| B2-4story | 7.37 | 1.37 |
| B3-4story | 8.20 | 1.49 |
| B4-2story | 7.91 | 2.99 |
| B5-2story | 8.38 | 3.35 |
| B6-2story | 8.86 | 3.62 |
| B4-3story | 7.91 | 1.60 |
| B5-3story | 8.38 | 1.90 |
| B6-3story | 8.86 | 2.05 |
| B4-4story | 7.91 | 1.14 |
| B5-4story | 8.38 | 1.32 |
| B6-4story | 8.86 | 1.41 |

**Table 5:** Overstrength factor for buildings C1 to C6

| Building | WDI(%) | Overstrength factor |
|---|---|---|
| C1-2story | 5.21 | 2.78 |
| C2-2story | 5.63 | 3.14 |
| C3-2story | 6.05 | 3.35 |
| C4-2story | 6.47 | 3.46 |
| C1-3story | 5.21 | 1.58 |
| C2-3story | 5.63 | 2.00 |
| C3-3story | 6.05 | 1.97 |
| C4-3story | 6.47 | 2.10 |
| C1-4story | 5.21 | 1.09 |
| C2-4story | 5.63 | 1.34 |
| C3-4story | 6.05 | 1.37 |
| C4-4story | 6.47 | 1.53 |
| C5-2story | 6.32 | 2.23 |
| C6-2story | 6.74 | 2.70 |
| C5-3story | 6.32 | 1.26 |
| C6-3story | 6.74 | 1.29 |
| C5-4story | 6.32 | 1.03 |
| C6-4story | 6.74 | 1.04 |

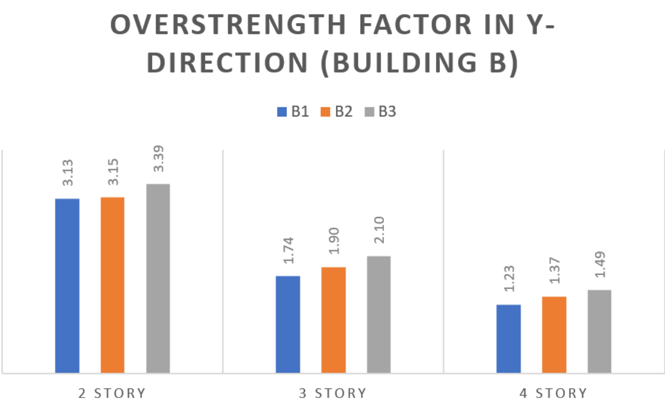


**Figure 7:** Overstrength factors for buildings B1, B2, B3

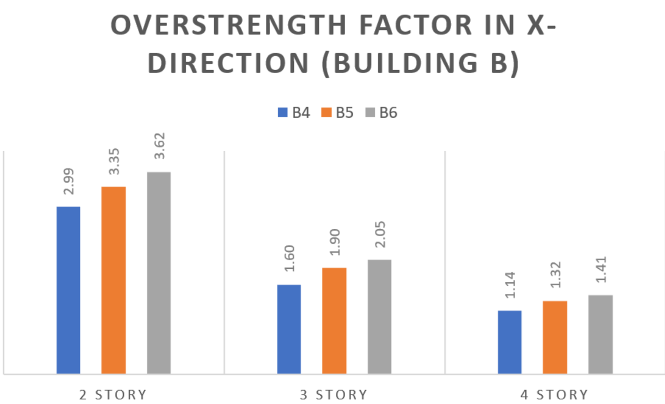


**Figure 8:** Overstrength factors for buildings B4, B5, B6

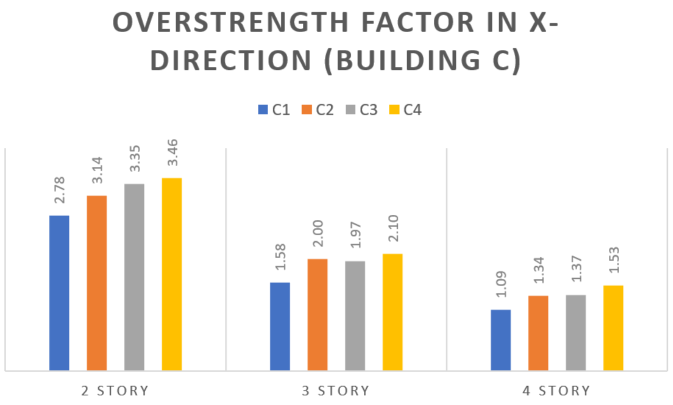


**Figure 9:** Overstrength factors for buildings C1, C2, C3, and C4

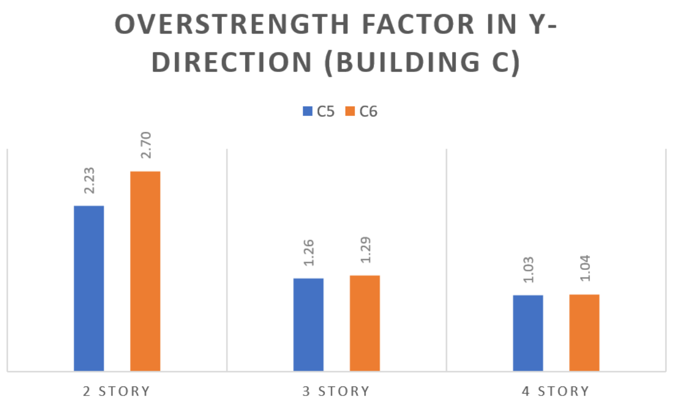


**Figure 10:** Overstrength factors for buildings C5, C6

**Table 6:** Ductility factor for buildings B1 to B6

| Building | WDI(%) | Ductility factor |
|---|---|---|
| B1-2story | 6.42 | 1.54 |
| B2-2story | 7.37 | 1.62 |
| B3-2story | 8.20 | 1.53 |
| B1-3story | 6.42 | 1.49 |
| B2-3story | 7.37 | 1.45 |
| B3-3story | 8.20 | 1.34 |
| B1-4story | 6.42 | 1.46 |
| B2-4story | 7.37 | 1.39 |
| B3-4story | 8.20 | 1.33 |
| B4-2story | 7.91 | 1.67 |
| B5-2story | 8.38 | 1.56 |
| B6-2story | 8.86 | 1.47 |
| B4-3story | 7.91 | 1.69 |
| B5-3story | 8.38 | 1.51 |
| B6-3story | 8.86 | 1.43 |
| B4-4story | 7.91 | 1.65 |
| B5-4story | 8.38 | 1.50 |
| B6-4story | 8.86 | 1.41 |

**Table 7:** Ductility factor for buildings C1 to C6

| Building | WDI(%) | Ductility factor |
|---|---|---|
| C1-2story | 5.21 | 1.69 |
| C2-2story | 5.63 | 1.60 |
| C3-2story | 6.05 | 1.48 |
| C4-2story | 6.47 | 1.47 |
| C1-3story | 5.21 | 1.60 |
| C2-3story | 5.63 | 1.36 |
| C3-3story | 6.05 | 1.41 |
| C4-3story | 6.47 | 1.32 |
| C1-4story | 5.21 | 1.59 |
| C2-4story | 5.63 | 1.37 |
| C3-4story | 6.05 | 1.39 |
| C4-4story | 6.47 | 1.22 |
| C5-2story | 6.32 | 2.15 |
| C6-2story | 6.74 | 1.89 |
| C5-3story | 6.32 | 2.08 |
| C6-3story | 6.74 | 2.12 |
| C5-4story | 6.32 | 1.86 |
| C6-4story | 6.74 | 1.87 |

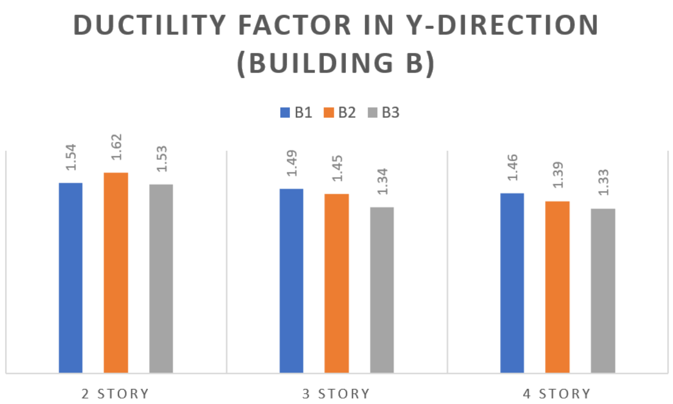


**Figure 11:** Ductility factors for buildings B1, B2, B3

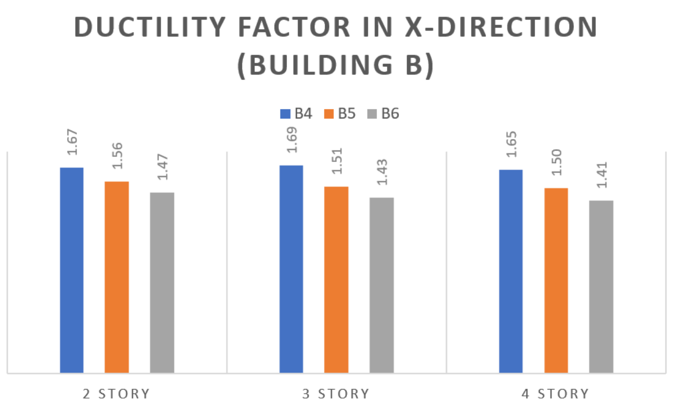


**Figure 12:** Ductility factors for buildings B4, B5, B6

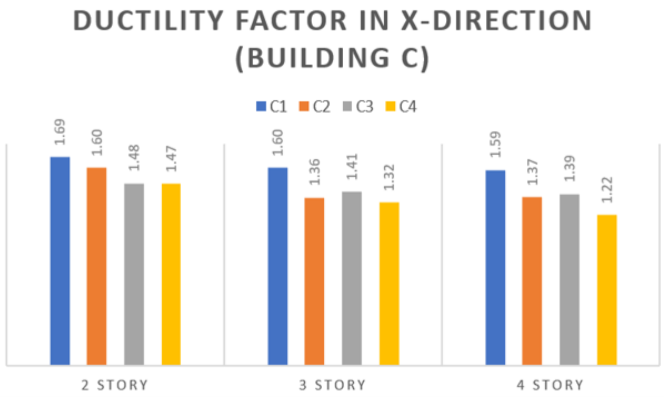


**Figure 13:** Ductility factors for buildings C1, C2, C3, C4

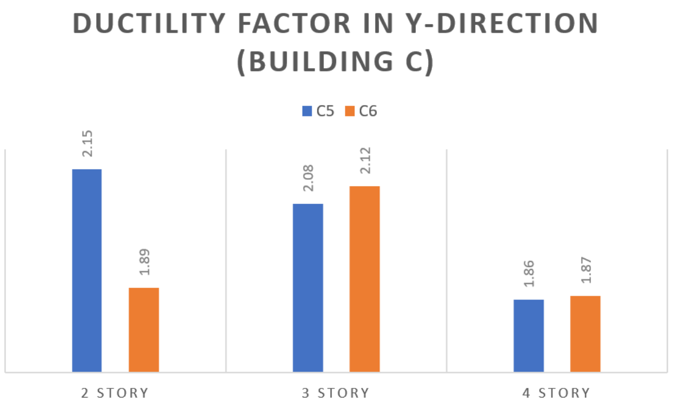


**Figure 14:** Ductility factors for buildings C5, C6

From table 6 to 7 table and figure 11 to figure 14, it can be seen that a clear pattern cannot be observed whether the value of ductility factor either increases or decreases with the increases in wall density and number of stories. However, the value of ductility factor obtained is lower than that prescribed in NBC 105:2020.

**Table 8:** Response reduction factor for buildings B1 to B6

| Building | WDI(%) | R-factor |
|---|---|---|
| B1-2story | 6.42 | 4.82 |
| B2-2story | 7.37 | 5.10 |
| B3-2story | 8.20 | 5.17 |
| B1-3story | 6.42 | 2.59 |
| B2-3story | 7.37 | 2.76 |
| B3-3story | 8.20 | 2.82 |
| B1-4story | 6.42 | 1.79 |
| B2-4story | 7.37 | 1.92 |
| B3-4story | 8.20 | 1.99 |
| B4-2story | 7.91 | 4.99 |
| B5-2story | 8.38 | 5.22 |
| B6-2story | 8.86 | 5.32 |
| B4-3story | 7.91 | 2.71 |
| B5-3story | 8.38 | 2.87 |
| B6-3story | 8.86 | 2.92 |
| B4-4story | 7.91 | 1.88 |
| B5-4story | 8.38 | 1.98 |
| B6-4story | 8.86 | 1.98 |

**Table 9:** Response reduction factor for buildings C1 to C6

| Building | WDI(%) | R-factor |
|---|---|---|
| C1-2story | 5.21 | 4.71 |
| C2-2story | 5.63 | 5.05 |
| C3-2story | 6.05 | 4.95 |
| C4-2story | 6.47 | 5.10 |
| C1-3story | 5.21 | 2.54 |
| C2-3story | 5.63 | 2.73 |
| C3-3story | 6.05 | 2.78 |
| C4-3story | 6.47 | 2.77 |
| C1-4story | 5.21 | 1.73 |
| C2-4story | 5.63 | 1.84 |
| C3-4story | 6.05 | 1.90 |
| C4-4story | 6.47 | 1.86 |
| C5-2story | 6.32 | 4.81 |
| C6-2story | 6.74 | 5.11 |
| C5-3story | 6.32 | 2.61 |
| C6-3story | 6.74 | 2.73 |
| C5-4story | 6.32 | 1.91 |
| C6-4story | 6.74 | 1.95 |

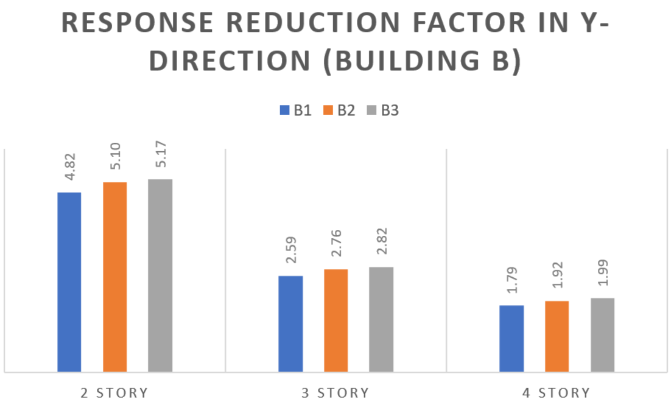


**Figure 15:** Response reduction factors for buildings B1, B2, B3

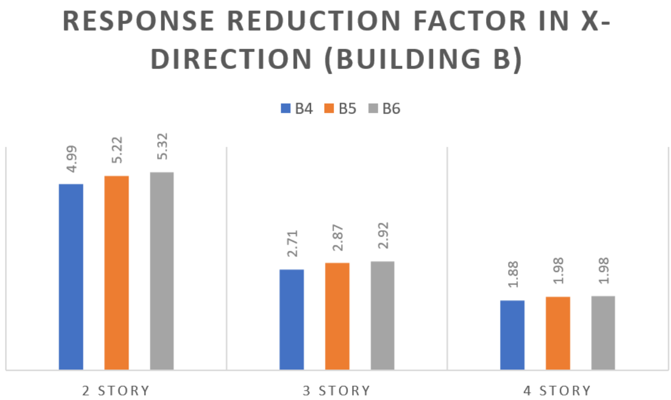


**Figure 16:** Response reduction factors for buildings B4, B5, B6

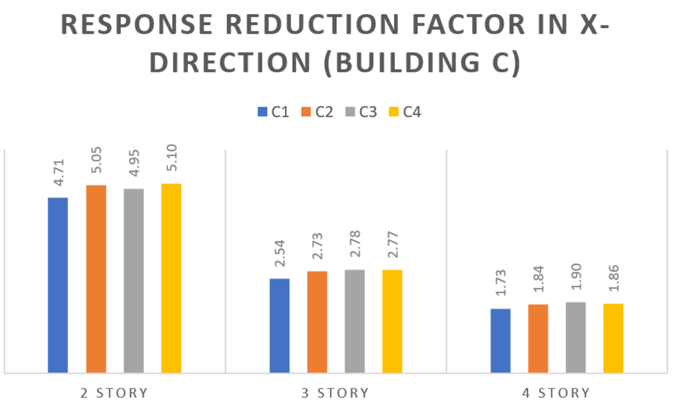


**Figure 17:** Response reduction factors for buildings C1, C2, C3, C4

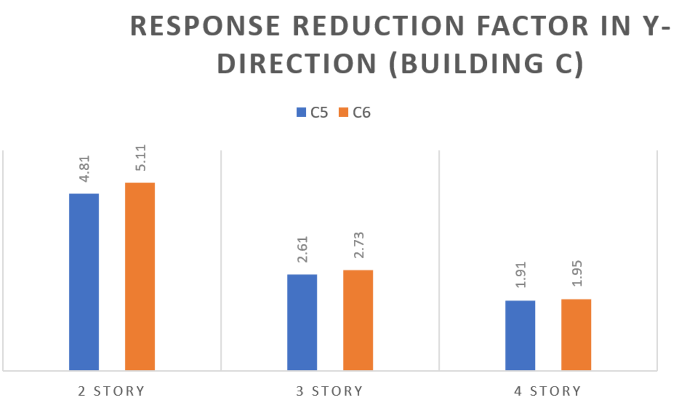


**Figure 18:** Response reduction factors for buildings C5, C6

In the overall, from table 8 to table 9 and figure 15 to figure 18, we can observed that response reduction factor increases with the increase in wall density index. Moreover, with the increasing the number of stories, response reduction factor decreases. The variation in the response reduction factor is generated primarily due to the variation in overstrength factor.

## 8. Conclusions

In this study, overstrength factor, ductility factor, and response reduction factor have been determined with the help of equivalent static analysis and nonlinear static analysis methods of 36 different building models. The conclusions that can be derived from this study are as follows:

- As the wall density index increases, the pattern that can be observed is that overstrength factor also increases significantly. The values of overstrength factor range from 1.22 to 3.39.
- As the wall density index increases, response reduction factor also increases. The main increase in response reduction factor is due to the significant increase in overstrength factor. Response reduction factor were calculated from 1.73 to 5.32.
- A significant pattern cannot be observed regarding the trend of the ductility factor with the increase in wall density index. However, the values obtained range from 1.09 to 2.15, which is below the value prescribed in NBC 105:2020.
- With the increasing number of stories, both overstrength factor as well as response reduction factor decrease.

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