SEISMIC PERFORMANCE EVALUATION OF REINFORCED CONCRETE WALL FRAME MIXED BUILDING SYSTEMS

Mohammad Al Amin Siddique*[1] and Md. Foysal Meah*[2]

[1] *Professor, Bangladesh University of Engineering and Technology, Bangladesh, e-mail: alamin@ce.buet.ac.bd*
[2] *Graduate Research student, Bangladesh University of Engineering and Technology, Bangladesh, e-mail: foysal.bdtech@gmail.com*

***Corresponding Author**

ABSTRACT

It is evident that Bangladesh lies in a region with low to moderate seismic hazard that increases in the northern and eastern parts of the country. The seismic design guideline by Bangladesh National Building Code (BNBC) has been modified to a large extent in BNBC 2020 from the previous BNBC 2006 to ensure ductile behavior and safe performance of the designed structures under possible future earthquakes. In this paper, numerical analyses have been conducted to figure out the shear force and bending moment distribution along the height of the shear wall of wall-frame mixed buildings. Non-linear static pushover analyses have been conducted and R values for different structural systems have been evaluated for all the considered buildings. These models are different in plans [Plan A (3×3 bay), B (3×5 bay) and C(5×3 bay)] having 15-storied and three different framing systems like building frame system with the shear wall, M1 (100% lateral force to be resisted by the shear wall), dual-frame system, M2 where the frame is capable of resisting at least 25% of prescribed seismic forces and general wall system, M3 (percentage of lateral force to be resisted by the shear wall based on their stiffnesses. The response reduction factor, R has been evaluated for all these structures and the results were obtained and compared among each other. From the results, it was found that R-values are non-conservative for 15-storied building systems for the considered three plan configurations.

Keywords: *Response reduction factor, building frame system, dual-frame system, mixed frame and intermediate moment-resisting frame, pushover analysis.*

1. INTRODUCTION

To resist lateral force in the structural system presently reinforced concrete framing buildings with shear walls have been widely used because walls and frames can interact with each other and thereby play important roles in earthquake resistance. Dual systems with intermediate moment frames must be capable of resisting at least 25% of prescribed seismic forces (with bracing or shear wall), as per BNBC 2020 as well as ASCE 7-10. The equivalent lateral force (ELF), described as the Equivalent Static Analysis procedure in BNBC 2020 (Art 2.5.7), is one of the most common seismic design methods adopted in current codes (e.g., ASCE 7-10 and Eurocode 8). As per BNBC 2020, categorizes of framing systems can be divided according to their type to resist earthquake lateral loading. For instance, 'Building frame systems' have high lateral stiffness, such as shear walls and braced frames; 'Moment-resisting frame systems' include those that resist lateral seismic forces by frame action; and 'Dual systems with special or intermediate moment frames' include those that resist lateral seismic forces by a combination of shear walls (or braced frames) and moment frames. Mondal et al. (2013) designed and detailed reinforced concrete (RC) moment resisting frames (MRF) following Indian Standard for seismic analysis suggested by design code IS 1893. Values of response modification factor, R obtained for four realistic designs at two performance levels. The structural systems considered for their study were four typical symmetric-in-plan RC frame structures having two, four, eight, and twelve storied configurations, intended for a regular office building in the seismic zone IV as per IS 1893. The seismic demands on these buildings were calculated following IS 1893. The RC design for these buildings was based on IS 456 guidelines and the (seismic) ductile detailing of the RC sections is based on IS 13920 provisions. The studied buildings were assumed to be located in zone IV, which was the second most seismically intensive zone covering a large part of the country including the national capital New Delhi and several other state capitals. The results showed that the Indian Standard provides a higher value than that of the obtained value of R, which is potentially dangerous. Kim and LaFave (2017) investigated the feasibility of the new design method to use the shear wall on the analysis of five-storied nine buildings. Their study focused on reinforced concrete ordinary walls in mixed building systems and specifically those with plans having fairly limited bays with walls, which makes it difficult to separate the walls and frames. To investigate the performance of buildings designed by the simple new method based on elastic analysis, nonlinear static pushover and nonlinear dynamic analyses were conducted. Results indicated that buildings designed by the new method have good performance even for very conservative failure criteria. This shortcoming could be compensated by a slight decrease in the response modification factor, R or by specifying a lower bound wall area ratio or an upper bound wall axial load ratio. Abou-Elfath and Elhout (2018) performed an analysis on nine different moment resisting frames to evaluate response modification factors as per the Egyptian code. These buildings were assumed to be located in Alexandria, Egypt (seismic zone 2), with a PGA of 0.125 g which was associated with 10% probability of exceedance in 50 years. Soil type “C” and sub-urban exposure conditions were considered in the lateral load calculations. Six, nine, and twelve storied buildings with a bay width of 6m were considered. The R factors calculated for the frames considered in their study vary from 6.18 to 9.85. The minimum limit of the calculated R-factor of 7.0 specified by the Egyptian code for the design of RC-MRFs with adequate ductility. R factor decreases with the number of stories. R factor decreases with an increase in the story height and its value varied from 7.74 for 3 m story height to 6.31 for the 4 m story height. From other research, it was observed that there is a scope of research for response reduction factors specially with RC buildings with frame and wall systems. Therefore, the objective of the current paper is to assess the response reduction factor, R for mixed building systems consisting of wall and framing systems. Nonlinear static analysis is conducted to determine the R values for such building systems and is compared with the code values. Lateral load is applied monotonically under prescribed seismic load and the applied load distribution is followed first fundamental mode shape.

2. RESPONSE REDUCTION FACTOR (R)

Response reduction factors were first proposed by the Applied Technology Council (ATC) in the ATC 3-06 report published in 1978. The National Earthquake Hazard Reduction Program (NEHRP) provisions, first published in 1985, are based on the seismic design provisions outlined in ATC 3-06. Similar factors, modified to reflect the allowable stress design approach, were adopted in the Uniform Building Code (UBC) a decade late in 1988.

The concept of response reduction factor, R was proposed based on the premise that well-detailed seismic framing systems could sustain large inelastic deformations without collapse (ductile behavior) and develop lateral strength over of their design strength (often termed as reserve strength). The R factor was assumed to represent the ratio of the forces that would develop under the specified ground motion if the framing system were to behave entirely elastically (termed hereafter as elastic design) to the prescribed design forces at the strength level (assumed equal to the significant yield level). The commentary to the 1988 NEHRP provisions (BSSC, 1988) defines the R factor as an empirical response modification (reduction) factor intended to account for both damping and ductility inherent in a structural system at displacements great enough to approach the maximum displacement of the system. The components of R can be defined in several ways, each depends on the performance level under consideration. In this report only the life-safety performance level was considered explicitly.

The impact of R on the seismic design is seen from the below equation:

$V_e = Se,5 \times W$

where V_e = base shear for elastic response
$S_{e,5}$ = inelastic 5% damped pseudo-acceleration,
W = Seismic weight of the structure

A typical force-displacement relationship for a building frame is shown in Figure 1, which is used to estimate yield force and yield displacement relationship.

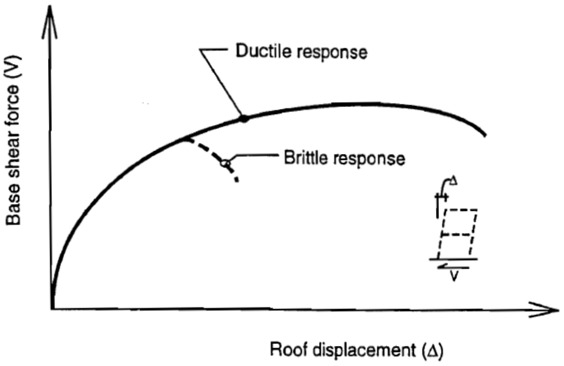
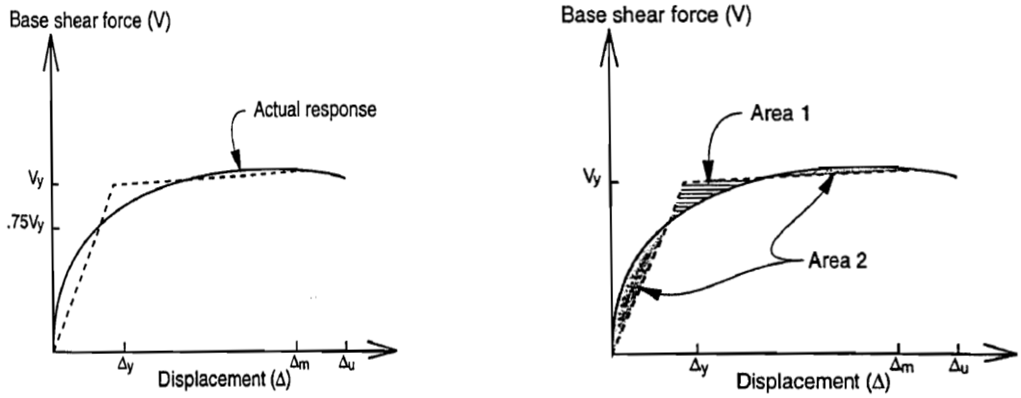


Figure 1: Sample base shear force versus roof displacement relationship (ATC 19)

Paulay and Priestley (1992) assumed a priori knowledge of the yielding strength, V_y of the frame. The elastic stiffness of the frame was calculated from the force-displacement curve at the force corresponding to $0.75V_y$. Elastic stiffness is defined as the slope of the idealized bilinear curve as shown in Figure 2(a).



a) Paulay & Priestley (1992)

b) Equal energy

Figure 2: Bilinear approximations to a force-displacement relationship (ATC 19)

The second method (equal energy method) assumed that area enclosed by the curve above the bilinear approximation is equal to the area enclosed by the curve below the bilinear approximation, Fig. 2 (b). Here, V_y = Yield force, Δ_y = yield displacement, Δ_m = displacement corrosponding to a limit state, Δ_u = displacement immediately prior to failure

The ability of a building frame to be displaced beyond the elastic limit is termed ductility. From Figure 2, displacement ductility ratio is defined as the ratio of Δ_m to Δ_y namely $\mu_\Delta = \frac{\Delta m}{\Delta y}$.

In the mid-1980s, The University of California at Berkeley researchers proposed splitting reduction factor R into three factors that account for contributions from reserve strength, ductility and viscous damping, as

$R = R_s \times R_\mu \times R_\zeta$

where, R_s = overstrength factor, R_μ = ductility factor and R_ζ = damping factor.

Figure 3 shows base shear vs. roof top displacement relationship curve to calculate response reduction factor R. Damping factor, R_ζ at 5% damping is considered $R_\zeta = 1$, Ductility factor, $R_\mu = \frac{Ve}{Vy}$

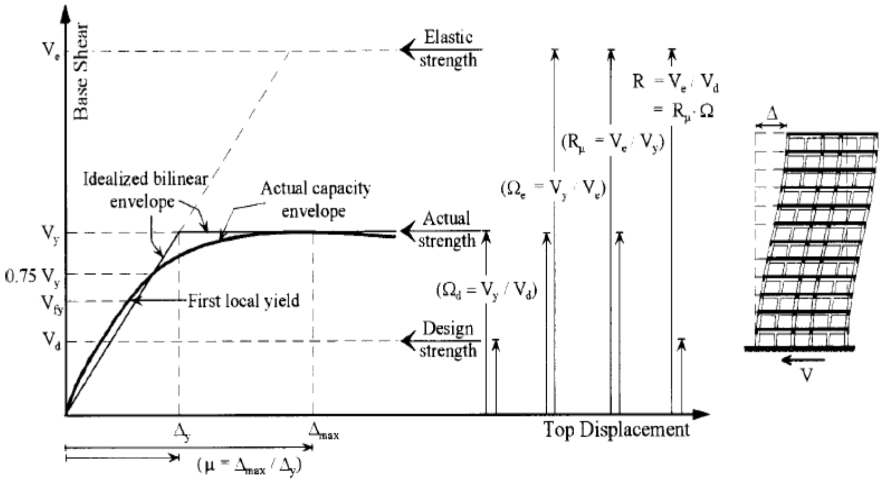


Figure 3: Top displacement vs. base shear relationship (Elnashai and Mwafy, 2002)

R_μ can also be estimated approximately from the structural ductility ratio (μ), the fundamental period of vibration (T) and the characteristics of the earthquake. Here relationship proposed by Newmark and Hall (1982) to estimate R_μ, is used in the present study.

$R_\mu = 1$ for $T < 0.2$ s

$R_\mu = \sqrt{(2\mu - 1)}$ for $0.2\ s < T < 0.5$ s

$R_\mu = \mu$ for $T > 0.5$ s

The structural ductility (μ) can be defined as:

$\mu = \frac{\Delta max}{\Delta y}$

The overstrength factor (Rs) is defined as the ratio of the yield base shear (V_y) to the design base shear (V_d) as follows:

$R_s = \frac{Vy}{Vd}$

Finally, the response reduction factor, $R = R_s \times R_\mu \times R_\zeta$

which turns to $R = \frac{Vy}{Vd} \times \frac{\Delta max}{\Delta y} \times 1 = \frac{Vy}{Vd} \times \frac{\Delta max}{\Delta y}$ and this formula will be followed for all R-value evaluation in the present study.

3. BUILDING MODELS:

In this study, analyses have been performed for three different planned buildings having 15-storied with three different framing systems (M1, M2 and M3). The floor area of those buildings varies from 216 m^2 to 366 m^2 per floor. Ground floor height is 4m and the remaining heights are 3m on each floor. All the analyses have been conducted considering these buildings are for residential use. Figure 4 shows the typical floor plan for the considered buildings. Materials properties for the considered buildings for columns, beams, slab, shear wall, bracing are 24.1 MPa (3500 psi). Rebar strength for column, beam, and shear wall are considered 415 MPa (60,000 psi). Live load, floor finish, partition wall, and lateral load (Seismic load) are considered as per BNBC 2020 guidelines for Residential Type. Live load (Floor) 2 kN/m^2, live load (Roof) 1 kN/m^2, Floor finish 1.25 kN/m^2, Partition wall (floor) 2.5 kN/m^2 have also been accounted. Column base supports have been considered as fixed supported for all the models.

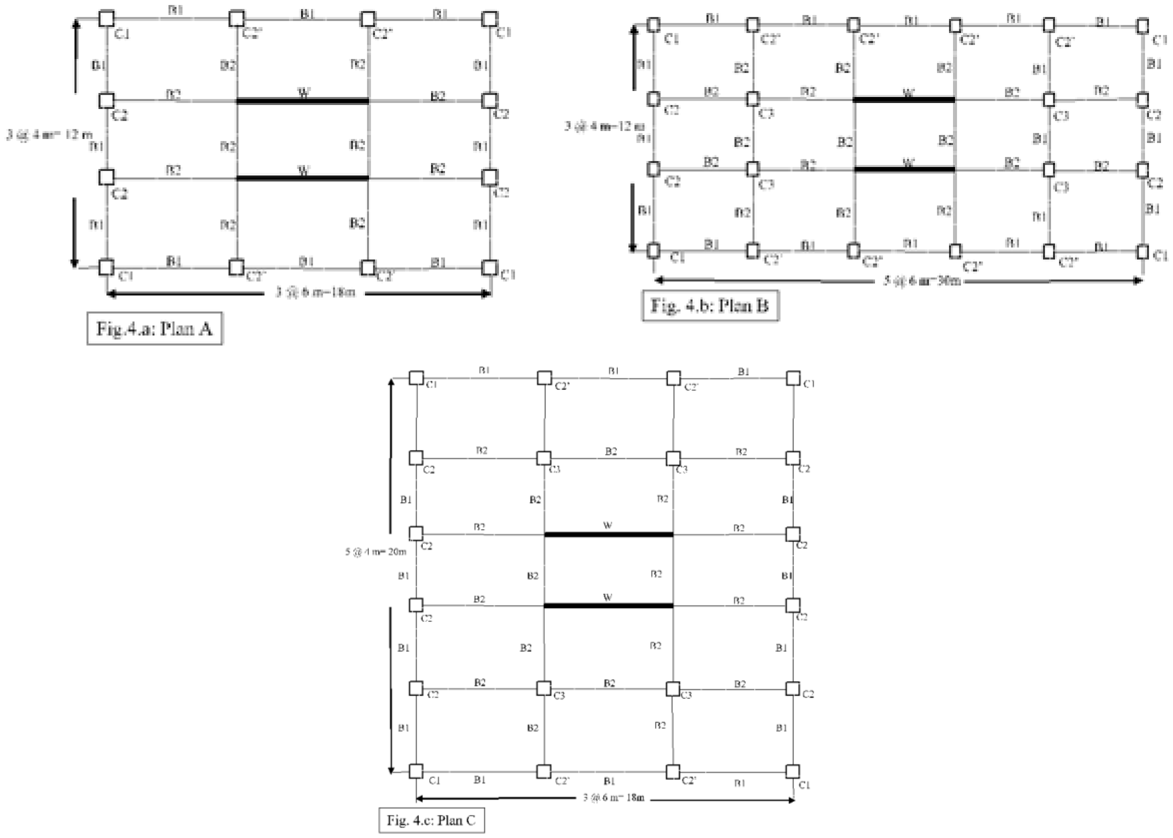


Fig.4.a: Plan A

Fig. 4.b: Plan B

Fig. 4.c: Plan C

Figure 4: Floor plan of buildings

All the buildings are located in seismic Zone 2, Z = 0.20. Response reduction factor (R) for building frame systems (with bracing or Shear wall) R = 5, for ordinary concrete shear walls, for dual systems: Intermediate Moment Frames, R = 5.5 for ordinary concrete shear walls, for general wall framing system R =5. Structural importance factor, I = 1.0. Site co-efficient (S) for SC type soil, S = 1.15. The fundamental period of vibration, T is of 0.862 sec for 15-storied buildings as per BNBC 2020. Diaphragm eccentricity is assumed 0.05 times * width of the structure perpendicular to direction considered. Figure 5 shows the plan view of 3D building models considered for three different plans. Cracked section stiffness as shown in Table 1 is considered for the design and analysis of the building models. Table 2 shows the Spectral accelerations, S_s and S_1 values for soil class C and seismic design category C.

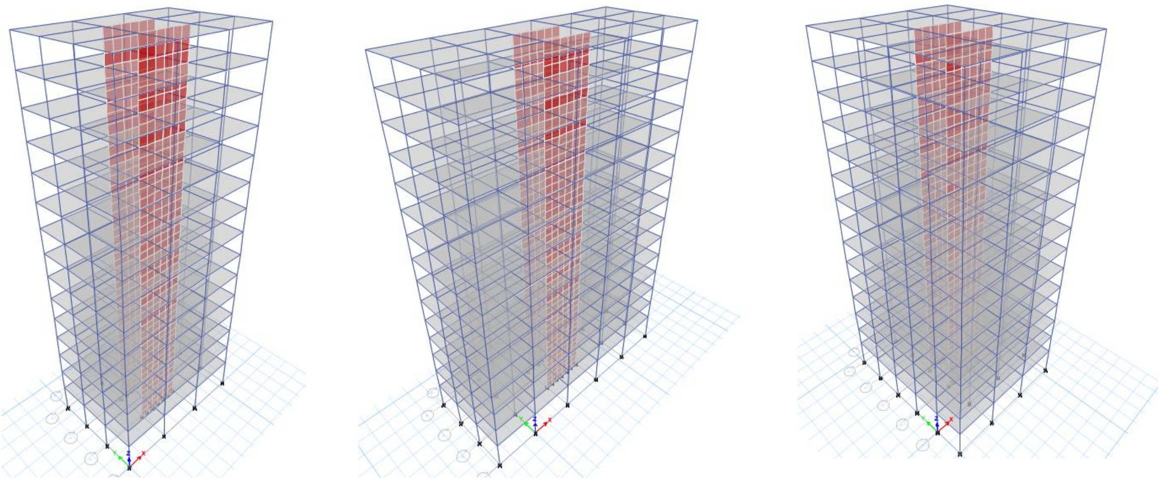
Nonlinear static procedure (NSP) for the seismic assessment of existing structures (or design verification of new ones) has gained considerable popularity in the recent years, backed by a large number of extensive verification studies that have demonstrated its relatively good accuracy in estimating the seismic response of buildings. Pushover analysis is carried out considering default-hinge properties for beams, columns and shear walls available in commercial software ETABS. Hinges are provided at the end of flexural members and bottom third locations of the shear wall.

Table 1: Modified moment of Inertia, I for cracked sections

Compression members	**Value of I**
Columns	0.70 Ig
Wall – Cracked	0.35 Ig
Flexural members	0.35 Ig

Table 2: Seismic design category, design spectral acceleration and site class

Seismic design category	**S_S**	**S_1**	**Site Class**
C	0.50	0.2	C



(a) Plan A: (b) Plan B (c) Plan C

Figure 5: 3D building models of plan A (a), plan B (b) and plan C (c) - 15-storied building

Table 3 provides the shear wall thickness for the three different plan views of the building models as per BNBC 2020. Periphery beam and column sizes are presented in Tables 4 and 5, respectively.

Table 3: Shear wall thickness (mm)

Plan	**Story**	**M 1**	**M 2**	**M 3**
	15 story	300	300	300
	15 story	300	300	300
	15 story	300	300	300

Table 4: Beam sizes (in mm)

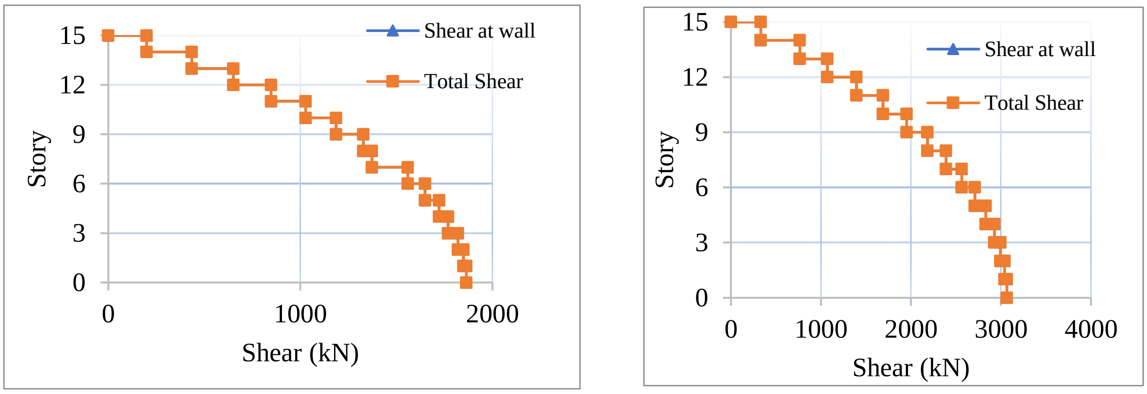
Beam	Periphery Beam, B 1 (250 × 400 mm)	Middle beam, B 2 (300 × 550 mm)

Table 5: Column sizes (in mm)

Sl.	Plan	Model	Story no.	Column type	Size (mm)
1	A	M 1	15	C 1	300 × 300
2	A	M 1	15	C2	400 × 400
3	A	M 1	15	C2′	450 × 450
4	A	M 2	15	C 1	300 × 300
5	A	M 2	15	C2, C2′	450 × 450
6	A	M 3	15	C 1	300 × 300
7	A	M 3	15	C 2, C 2′	400 × 400
8	B	M 3	15	C 3	450 × 450
9	B	M 1	15	C 1	350 × 350
10	B	M 1	15	C 2, C2′	400 × 400
11	B	M 1	15	C 3	650 × 650
12	B	M 2	15	C 1	350 × 350
13	B	M 2	15	C 2	550 × 550
14	B	M 2	15	C2′	500 × 500
15	B	M 2	15	C 3	650 × 650
16	B	M 3	15	C 1	300 × 300
17	B	M 3	15	C 2	450 × 450
18	B	M 3	15	C 2′	450 × 450
19	B	M 3	15	C 3	550 × 550
20	C	M 3	15	C 1	300 × 300
21	C	M 3	15	C 2, C 2′	350 × 350
22	C	M 3	15	C 3	450 × 450
23	C	M1	15	C 1	350 × 350
24	C	M1	15	C 2, C 2′	400 × 400
25	C	M1	15	C 3	600 × 600
26	C	M 2	15	C 1	400 × 400
27	C	M 2	15	C 2	400 × 400
28	C	M 2	15	C 2′	500 × 500
29	C	M 2	15	C 3	600 × 600
30	C	M 3	15	C 1	400 × 400
31	C	M 3	15	C 2, C 2′	450 × 450
32	C	M 3	15	C 3	600 × 600

4. RESULTS AND DISCUSSIONS:

Figures 6 and 7 show the distribution of shear force on the wall and total shear force for three plans with M1 and M3 structural systems, respectively.



(a) Plan A (M1)

(b) Plan B (M1)

(c) Plan C (M1)

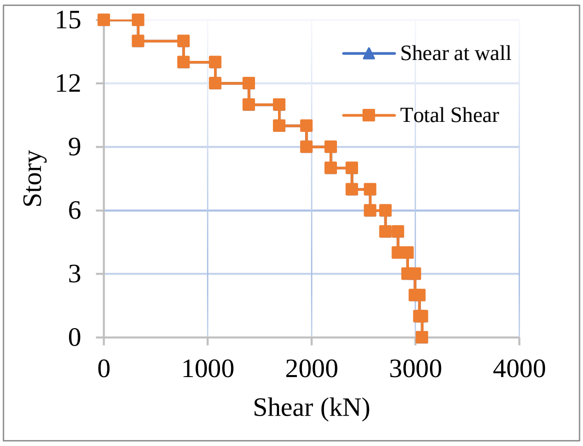
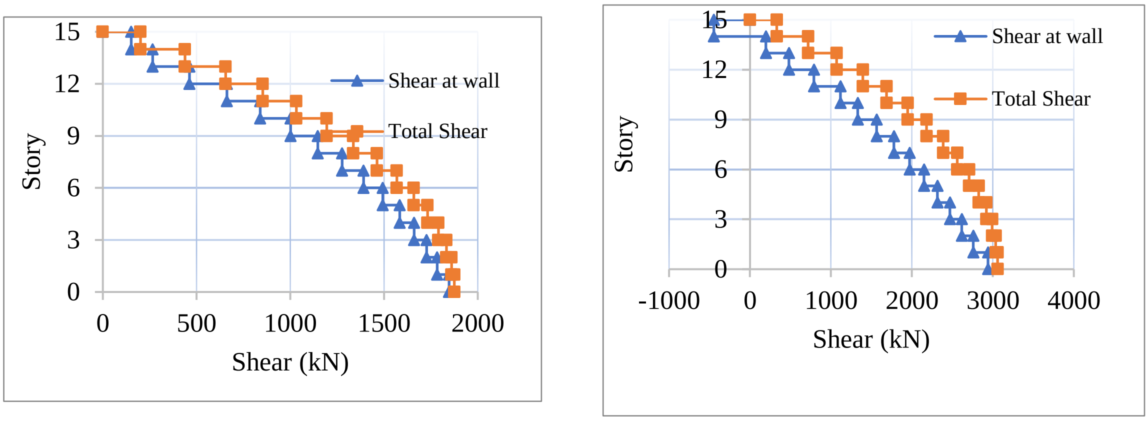


Figure 6: Shear force distribution along the height of the buildings (M1)


(a) Plan A (M3)

(b) Plan B (M3)

(c) Plan C (M3)

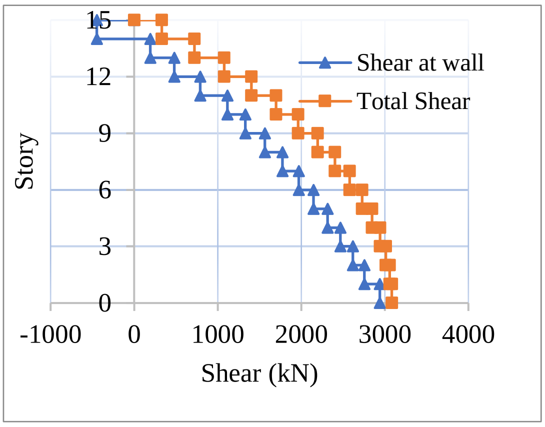
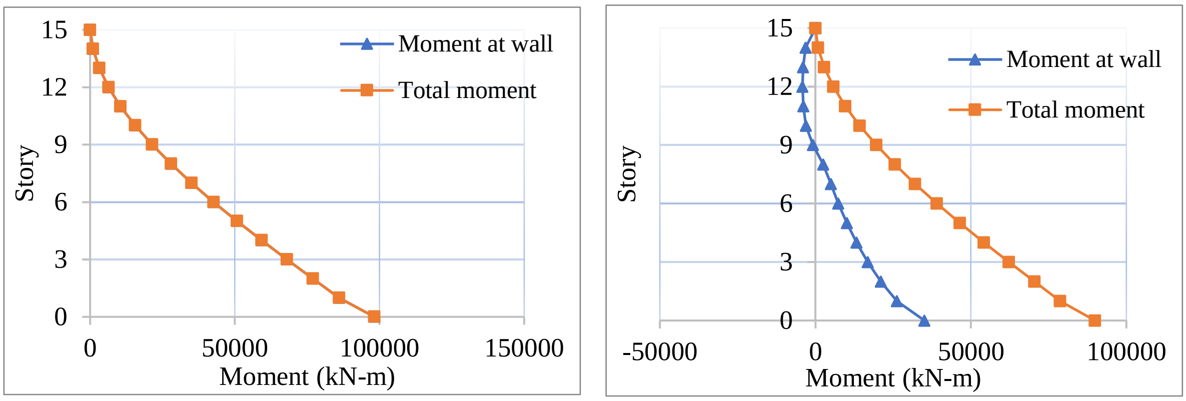


Figure 7: Shear force distribution along the height of the buildings (M3)

From the figures, it is observed that for M1 systems all the shear has been carried by the shear walls whereas for M3 systems interaction between the walls and frames are shown. Figure 8 shows the moment distribution of Plan C buildings with three different structural systems. Similar patterns are obtained for Plan A and B buildings. Table 6 shows the hinge formation details for Plan A building.


(a) Plan C (M1)

(b) Plan C (M2)

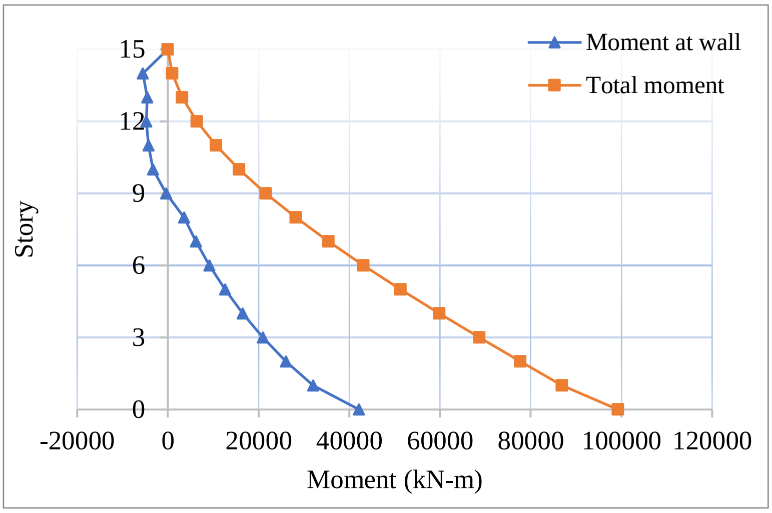

(c) Plan C (M3)

Figure 8: Moment distribution of the Plan C buildings with three structural systems

Table 6: Base-shear, top displacement and hinge formation details for plan A (M 1) 15-storied building

Step	Monitored displacement (mm)	Base Shear force (kN)	A-B	B-C	C-D	D-E	>E	A-IO	IO-LS	LS-CP	>CP	TOTAL
0	0	0	1140	0	0	0	0	1140	0	0	0	1140
1	1	19	1140	0	0	0	0	1140	0	0	0	1140
2	3	38	1140	0	0	0	0	1140	0	0	0	1140
105	141	1629	1138	2	0	0	0	1140	0	0	0	1140
106	142	1636	1138	2	0	0	0	1140	0	0	0	1140
107	144	1643	1136	4	0	0	0	1140	0	0	0	1140
158	212	1926	1130	10	0	0	0	1140	0	0	0	1140

159	213	1931	1130	10	0	0	0	1140	0	0	0	1140
177	238	2006	1128	12	0	0	0	1140	0	0	0	1140
178	239	2010	1128	12	0	0	0	1140	0	0	0	1140
224	301	2114	1126	12	0	0	2	1136	4	0	0	1140
225	302	2114	1126	12	0	0	2	1136	4	0	0	1140
258	339	2027	1124	14	0	0	2	1132	6	2	0	1140
259	339	2027	1124	14	0	0	2	1132	6	2	0	1140

Figure 9 shows load vs. Deflection curve (capacity curve) from pushover analysis for plan A (M1) 15 storied building. Figure 10 shows the formation of hinges at different load steps of the building.

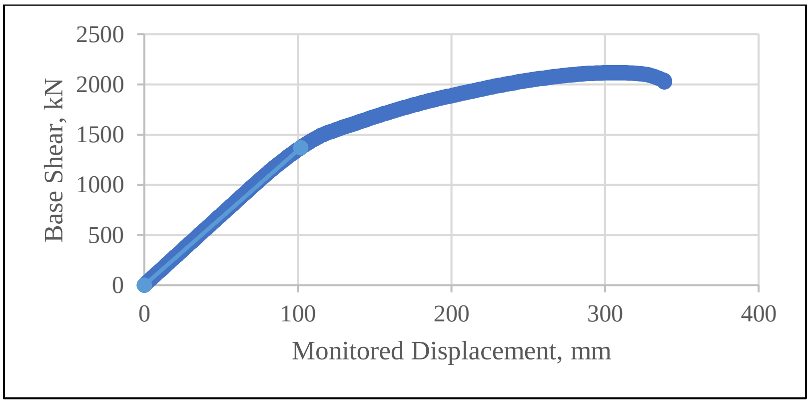
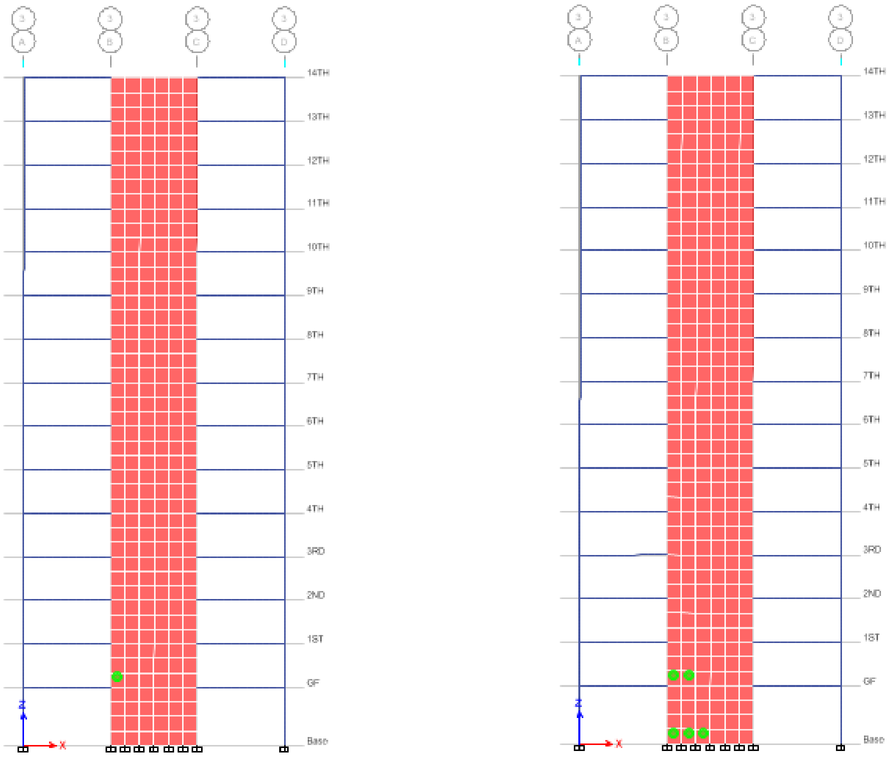
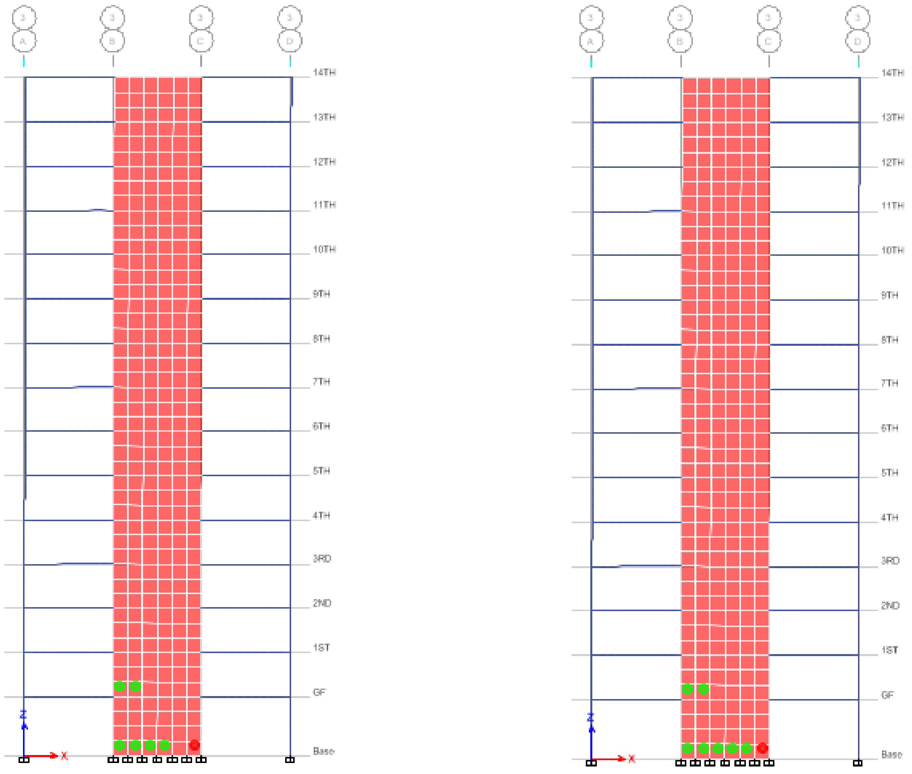


Figure 9: Capacity curve of plan A (M1) 15 storied building



At Step no. 105

At Step no. 157



At Step no. 224

At Step no. 259

Figure 10: Hinges at flexural members and shear wall at different steps for plan A (M1) building

Similar pattern of pushover curves and hinge formation is shown for the M2 and M3 structural systems. This pattern is also applicable for different plans of the building models considered in the study.

5. EVALUATION OF RESPONSE REDUCTION FACTOR (R)

Table 7 shows the response reduction factor (R) which was calculated for different plan configurations and structural framing systems following the guidelines ATC19 and ASCE 41-2013. From the obtained values it is shown that all the considered building models result in lower R than that considered code specified values. In addition, the building does not satisfy the requirement for target roof displacement as per BNBC 2020.

Table 7: Response Reduction Factor (R) for different buildings

Plan	Model	15 Story
A	M 1	2.18
A	M 2	2.97
A	M 3	2.53
B	M 1	1.58
B	M 2	2.28
B	M 3	2.02
C	M 1	2.72
C	M 2	2.90
C	M 3	2.65

6. CONCLUSIONS

A comprehensive numerical analyses has been conducted on three different plan configurations of wall frame mixed building systems. All the building models have been designed as per BNBC 2020. Nonlinear static analysis has been conducted to assess the response reduction factors for 15-storied buildings. From the analysis results, it is observed that all the building models provided lower values than that of the code provisions. In addition, design of the walls using M1 system requires larger sizes and reinforcements in comparison to the dual-frame system (M2) and general wall system (M3). These shear force and bending moment values also increase as the eccentricity of the plan dimension of the building is increased. Advanced structural analysis programs which can easily simulate the walls and frames simultaneously and even three-dimensionally, cannot be used directly without separating the walls and frames considering a minimum required strength for the frame or wall for the considered 15-storied buildings.

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