Nonlinear Time History Analysis for Seismic Effects on Reinforced Concrete Building

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ABSTRACT: A typical Reinforced Concrete (RC) building frame comprising of RC columns and connecting beams that participates in resisting the earthquake forces. Due to earthquake, reversal tension generates at both faces of a beam and column; and hence damage occur in the frame for the disability of tension carrying capacity of concrete. Therefore, the structural performance of RC building for seismic load has been analyzed by nonlinear time history analysis method for this study. A residential building located in Dhaka, Bangladesh subjected to various types of gravity load and seismic load was considered to analyze using ETABS software as per the guideline of BNBC (2020). According to the guideline of ATC 40 (1996), the seismic performances like maximum displacement and story drift for RC building were evaluated both at structural and element levels by applying El Centro (1940) ground motion at the base of the structure. Formation of plastic hinges is used as the basis to evaluate the local performance and story drift is used to evaluate the global performance. At first, the considered building was designed only for gravity load, and then for both gravity and seismic load according to BNBC (2020). Further studies have been performed on that building considering double height column at a story level. It was observed that the maximum displacement and story drift exceeds the allowable limit for all the considered cases if seismic load is applied on the structure.

KEYWORDS: Displacement, Ground motion, Plastic hinges, Story drift, Time history analysis

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I. INTRODUCTION

Earthquake is the distortion of the earth's surface caused by the fast release of strain energy held in the earth's crust, which causes seismic waves (Vanshaj and Narayan, 2017). These waves can lead to ground displacement and surface rupture. The surface rupture can cause other hazards, as well as damage to buildings. Also, under strong earthquake shaking, tension develops on either any of the faces of a structural element. Since concrete cannot carry this tension, crack occurs in concrete due to insufficient steel bars on both faces to resist reversals of bending moment. Then the width of these cracks increase due to repeated earthquake shaking and other gravity loads, and tends to failure of the structure. So, it is necessary to know the characteristics of this ground motion to take required precautions to protect the RC structures from damage. Duration, frequency content, and Peak Ground Acceleration (PGA) are the basic dynamic characteristics of earthquake.

These characteristics play a vital role to study the performance of structures subjected to ground motion generated from earthquake (Ghosh, *et al.*, 2019). It is technically conceivable to design and construct structures for rarely happened severe earthquake event. However, it is also being considered as uneconomical and redundant. To limit the damage to a certain extent and make safe the structure are the main objectives of the seismic design. (Gkimprixis, *et al.*, 2020). The structures should be capable of resisting minor levels of earthquakes without damage. Also, yet there is a probability of some nonstructural damage, the structures should withstand a moderate level of earthquake without structural damage. However, if any significant levels of ground motion occur, the structures should withstand without collapse yet there is a probability of some structural and nonstructural damage (Avramidis, *et al.*, 2011).

So, it is important to identify what makes a building strong enough to withstand an earthquake. The three most important properties for earthquake resistance are stiffness, strength, and ductility. Damage occurs when the structure doesn't meet the necessary stiffness, strength, and ductility to resist the forces of an earthquake (Siswanto and Salim, 2018). Structural stiffness describes the capacity of a structure to resist deformations induced by applied loads. Ductile buildings are safer as they dissipate energy from seismic waves. Therefore, a detailed analysis is required to know the maximum deformation of a building structure that can occur due to earthquake.

(In the last couple of decades, analyzing RC buildings for different earthquake intensities and checking for multiple criteria is being done by several researchers as an essential exercise (Romy and Prabha, 2011). A four-story RC framed structure was designed by Kueht and Hueste (2009) using International Building Code and a numerical study was performed on the seismic performance. Also, Panagiotakos

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and Fardis (2004) designed RC buildings as per "Eurocode 8" and evaluated the seismic performance. Sadjadi, *et al*., (2007) used National Building Code of Canada, Arturo, *et al*., (2008) used Mexico Federal District Code, Mehanny and Howary (2010) used Egyptian Seismic Code to analyze the performance of RC structures under seismic load. Several researches have been done to study the seismic performance of RC structures designed with Bangladesh National Building Code (BNBC) is confined mostly to the code developed in 1993 and 2006 (Islam, *et al*., 2011); (Haque, *et al*., 2016); (Rahman, *et al*., 2018)). (As per author knowledge, a very limited studies have been conducted to evaluate the seismic performance of RC building designed with BNBC developed in (2020). Moreover, very limited studies have focused on the nonlinear time history analysis for the seismic performance evaluation. Nonlinear time history analysis is known for simulating a structure behavior under severe earthquake more proper than other methods (Wu, 2014). So, this study has been conducted to know the effects of seismic motion on RC building structures by nonlinear time history analysis method).

II. RESEARCH SIGNIFICANCE

Bangladesh is situated near an active earthquake zone. The analysis and design procedure used in here is according to the BNBC (2020). It generally follows the equivalent static method which is the simplest in nature and requires lower amount of computational efforts (Patil and Kumbhar, 2013); (Duggal, 2010). According to BNBC (2020), firstly the design base shear is calculated for the whole structure and then it is distributed along the height of the structure. As this process does not use the dynamic analysis, the lateral force obtain from this method are approximate in manner. For this reason, a dynamic analysis method is required to be performed to get an actual representation of the performance of the structure under a seismic load. Nonlinear time history analysis is the most important technique for evaluating the seismic response of a structure subjected to dynamic loading (Wilkinson and Hiley, 2006); (Mwafy and Elnashai, 2001). It is a systematic step by step analysis method which clearly reflects the dynamic response of a structure under a certain loading conditions that varies with time.

The main purpose of this study is to incorporate the effects of varying earthquake motions on six-storied RC buildings which are designed following the BNBC (2020). All the performance analysis in this study was performed using nonlinear time history analysis with Extended Three-Dimensional Analysis of Building System (ETABS) software version 2015. Several studies were performed to understand the response under earthquake motions on a building designed only for gravity loading, and building which have variation in story level (double height column).

III. METHODOLOGY

In this study, the structural models were analyzed as Intermediae Moment Resisting Frames (IMRF) by nonlinear time history analysis method using data from the El Centro earthquake. Three different Peak Ground Acceleration (PGA) corresponding to the three earthquake design considerations have been applied in each model. The responses of the structures found from analysis by ETABS-v2015 were compared with Applied Technology Council (ATC-40, 1996). According to (Gunn, 2007) the earthquake at El Centro in 1940 was recorded by using a strong-motion seismograph. It was the first time such a recording was made so close to a fault rupture in the case of a large earthquake. This yielded a comprehensive record of the various types of shaking associated with earthquakes as shown in Figure 1. At first, the obtained ground motion records were normalized to perform nonlinear time history analysis. Then, building responses such as velocity, acceleration, drift, and displacement at story levels and base shear were found after analysis using ETABS-v2015 software. Finally, the obtained results were evaluated by comparing with respect to the three ground motions.

A. *Modeling of the structure*

A 60 ft. × 40 ft. six storied building with 10 ft. floor height was modeled for this study. The center-to-center distance in X-direction was kept 20 ft. and for Y-direction was 20 ft. The properties of the materials were kept nonlinear because the structures need to be analyzed by nonlinear time history analysis.

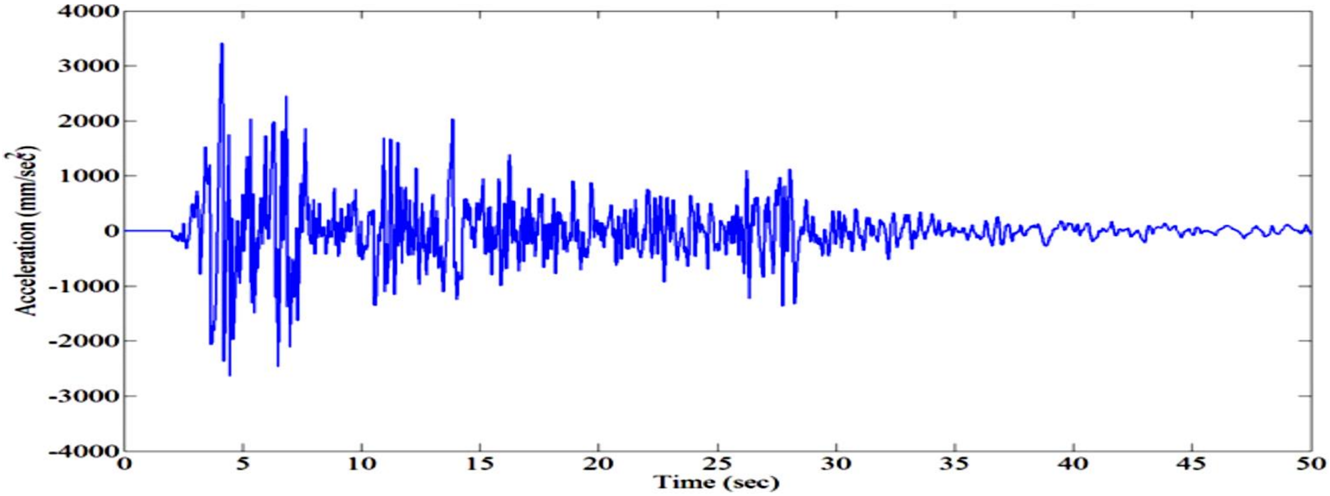


Figure 1: Ground acceleration vs time at El-Centro earthquake (Jiang and Christenson, 2011)

The load cases were defined as per specified code. All the structural models were designed as IMRF. Fundamental period of vibration, damping correction factor, normalized acceleration response spectrum, and design spectral acceleration were calculated using Eqns. (1) to (4) to give input for the analytical model in ETABS. The basic design data of the model are shown in Table 1.

Table 1. Basic design data of the model

Properties name	Value
Concrete strength, f'c	4 ksi
Yield strength of steel, fy	60 ksi
Building location	Dhaka (Zone 2, Z=0.2)
Basic Wind Speed	130.48 mph
Super-imposed dead load	3.4 k/ft
Live load	0.8 k/ft
Soil Classification	SC
Beam section	12 in x 18 in
Column section	18 in x 20 in

For the model, the following calculations were made according to BNBC (2020):

Seismic zone coefficient, $Z = 0.2$

Basic wind speed = 130.48 mph (for Dhaka)

Structure importance coefficient, $I = 1$

Response reduction factor, $R = 5$ for IMRF

Design category $= D$

Fundamental period of vibration, $T = C_t (h_n)^m$

$$T = 0.0466*(18.30)^{0.9} = 0.6374sec \qquad (1)$$

Site coefficient, S =1.35 (soil class SC)

Lower limit of the period of the constant spectral acceleration, $T_B = 0.2$

Upper limit of the period of the constant spectral acceleration, $T_C = 0.6$

Lower limit of the period of the constant spectral acceleration, $T_D = 2.0$

Damping Correction Factor, $$\eta = \sqrt{\frac{10}{5+\xi}} \geq 0.55 \qquad (2)$$

where, ξ is the viscous damping ratio of the structure, expressed as a percentage of critical damping. Considering 5% viscous damping, $\eta = 1.407$

Normalized acceleration response spectrum,

$$Cs = \frac{2.5\ S\,\eta\,T_C}{T} \qquad (3)$$

$$\text{Cs} = 2.61$$

Design Spectral Acceleration,

$$Sa = \frac{2\ ZIC_s}{3R} \qquad (4)$$

$$\text{Sa} = 0.0723$$

So, V = 0.0723*W and K=1.0687 by interpolation.

The distribution of the earthquake load was maintained according to the lateral and vertical distribution of load according to BNBC (2020). Time history load case was defined using the time series function with load type Ux of acceleration. A scale factor of 20.588 (32.2*0.2/0.3128=20.588) was considered to convert the gravitational acceleration ‘g’ unit to incorporate the zone co-efficient for Dhaka. All the number of outputs, time steps and time step sizes were specified. Generally, more output time simply provides more details on output. In this study, 1600 steps per 0.02 second for duration of 32.2 seconds were used. The output data of maximum displacement found from analysis was studied to find out the performance level of the structure. The chance of being at a various performance level in relation to the top displacement of the structure has also been assessed. Three level ground motions were used in this study to investigate the behavior of the structures.

1) *Maximum credible earthquake*

The Maximum Credible Earthquake (MCE) is defined deterministically as the maximum level of ground motion expected at the building site within the known geologic framework due to a specified single event or the ground motion with a 5% chance of being exceeded in a 50-year period. The design procedure for MCE is to allow damage to the structure without collapse.

In this MCE, the used scale factor for nonlinear time history analysis was (0.2/0.3128) *32.2*12 = 247.0588.

2) *Design basis earthquake*

The Design Basis Earthquake (DBE) is defined probabilistically as the level of ground motion with a 10% chance of being exceeded in a 50-year period. Similar calculations were performed for the DBE level. The same factor was used to analyze the structure (2D frame).

The scale factor for DBE was (0.2/0.3128) *32.2*12*(1/1.5) = 164.706.

3) *Serviceability earthquake*

The Serviceability Earthquake (SE) is defined probabilistically as the level of ground motion with a 50% chance of being exceeded in a 50-year period. The maximum earthquake in Dhaka city was scaled for a further 30% to define the SE loading.

The scale factor used for SE case was (0.2/0.3128) *32.2*.70*(1/1.5) *12= 115.27.

B. *Case Study Model*

There were a lot of parameters affecting the results of this study. It is not possible to investigate each parameter. We have focused on the seismic performance of the structure for the following conditions:

Case study I: Designing only for gravity load

Case study II: Variation of story level (inclusion of soft story)

In the Case Study I, at first a 6-storied building was analyzed and designed only for gravity load using ETABS (2015) excluding the earthquake and wind load. Then it was analyzed considering the earthquake and wind load to observe the structural performances. In the Case Study II, the variation of story level was considered to make soft story building. This was considered to investigate the performance of a double ground floor height building which has some design inadequacies.

IV. RESULTS AND DISCUSSION

The structure was evaluated based on global performance and local performance criteria. The global performance of the structure is measured in terms of lateral drift. The analytical deformation results were compared to the deformation limit specified in ATC 40 (1996) as given in Table 2. Each element was examined to see if its individual components satisfy the acceptability requirements for performance point forces and deformation. The uppermost edge joint's displacement time history was then plotted.

Here, h_x = Floor height between two story levels. For nonlinear time history analysis, the story drift or displacement shall not exceed 1.25 times the story drift limit for linear static analysis (BNBC, 2020).

Additionally, it was observed that the plastic hinges (Figure 4) are created at both beam and column hinges. A significant number of hinges are found on beam and columns. During MCE the hinges are in the LS and Collapse Prevention (CP) range which expresses that, the building is collapsed. During DBE, a few amounts of hinges are within the LS and CP range. At the SE level, all the hinges are in the IO and LS range. This means that the building is not capable to withstand the ground motion created by the earthquake. So, the building that is designed only for gravity load is unable to withstand the seismic load and hence design only for gravity load is not recommended.

Table 2: Drift ratio and displacement limits for each performance levels (ATC-40).

Drift ratio limits (ATC-40)				**Maximum displacement limit**	
Intermediate occupancy	Damage control	Life safety	Structural stability	ATC-40	BNBC-2020
0.01	0.01-0.02	0.02	0.33 Vi/Pi	$0.020h_x$ 0.020*10*12 = 2.4 inch	$1.25x0.020h_x$ 1.25*0.020*10*12 =3.0 inch

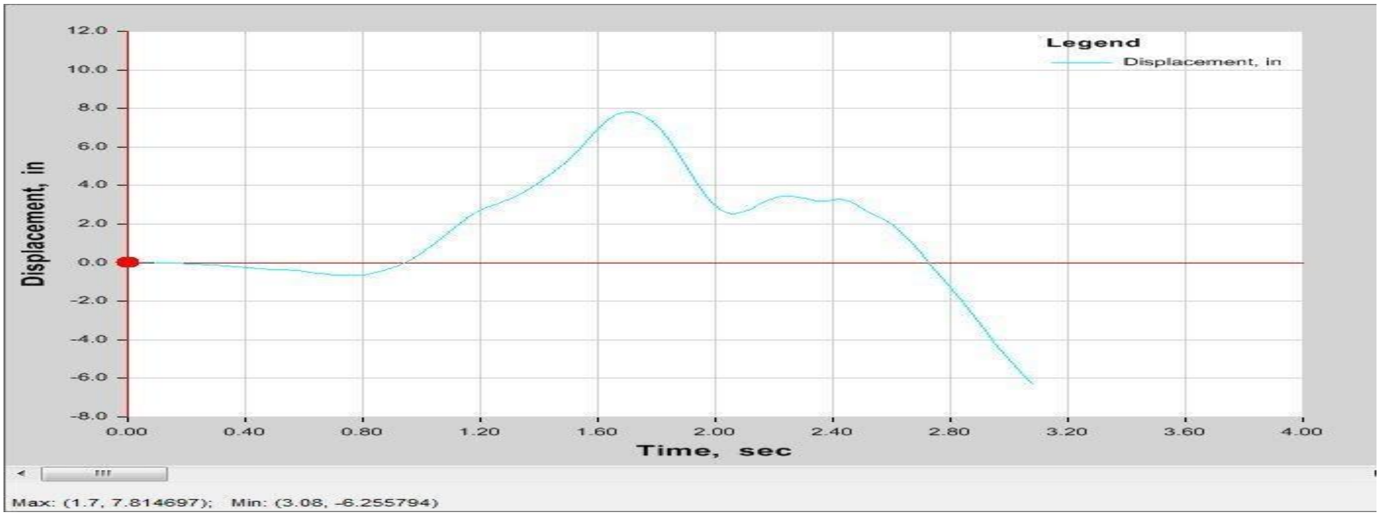
A. *Case Study I: Designing only for Gravity Load*

For Case Study I, joint displacement of the frame under different earthquake levels are shown in Figure 2. Maximum displacement and drift ratios for three different ground motions are given in Table 3. It has been observed from Figure 2 and Table 1 that, the maximum displacements for SE, DBE, and MCE level exceed the allowable limit as per both ATC 40 (1996) and BNBC-2020.

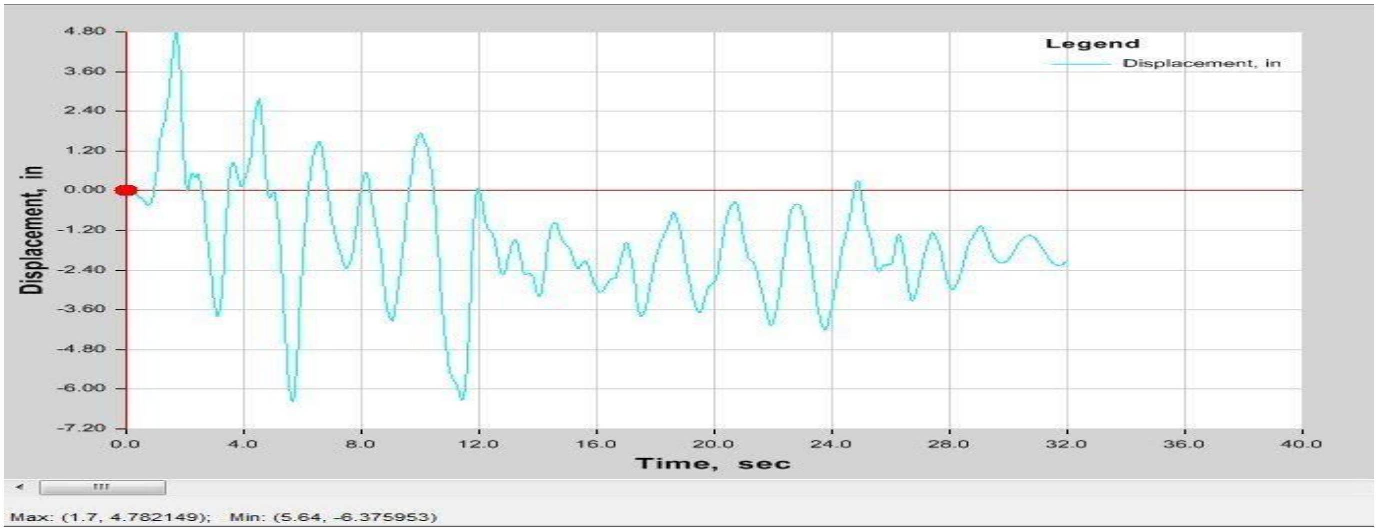
It is also found from Figure 3 that the lateral story drift 0.0142 of the structure in the SE level is not within the drift limit as per Table 2. It goes beyond the Immediate Occupancy (IO) line. During the DBE, the drift of the structure crosses the IO line and almost touches the Life Safety (LS) line. Also, during MCE the drift value 0.0268 exceeds the LS performance level.

Table 3: Maximum displacement and drift ratio for three ground motions (Case study I).

Ground motion level →	**MCE level**	**DBE level**	**SE level**
Maximum Displacement (inch)	7.815	6.376	3.912
Drift ratio	0.0268	0.0193	0.0142

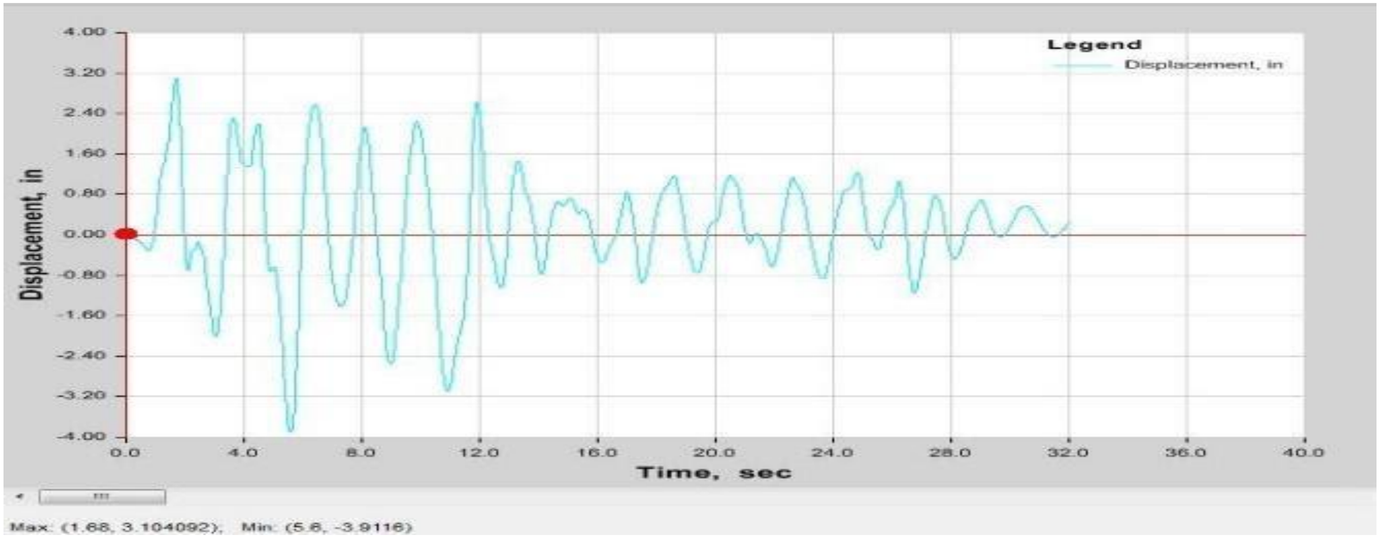


(a) at MCE level



Max: (1.7, 4.782149); Min: (5.64, -6.375953)

(b) at DBE level



Max: (1.68, 3.104092); Min: (5.6, -3.9116)

(c) at SE level

Figure 2: Displacement vs time at different earthquake level (Case Study-I)

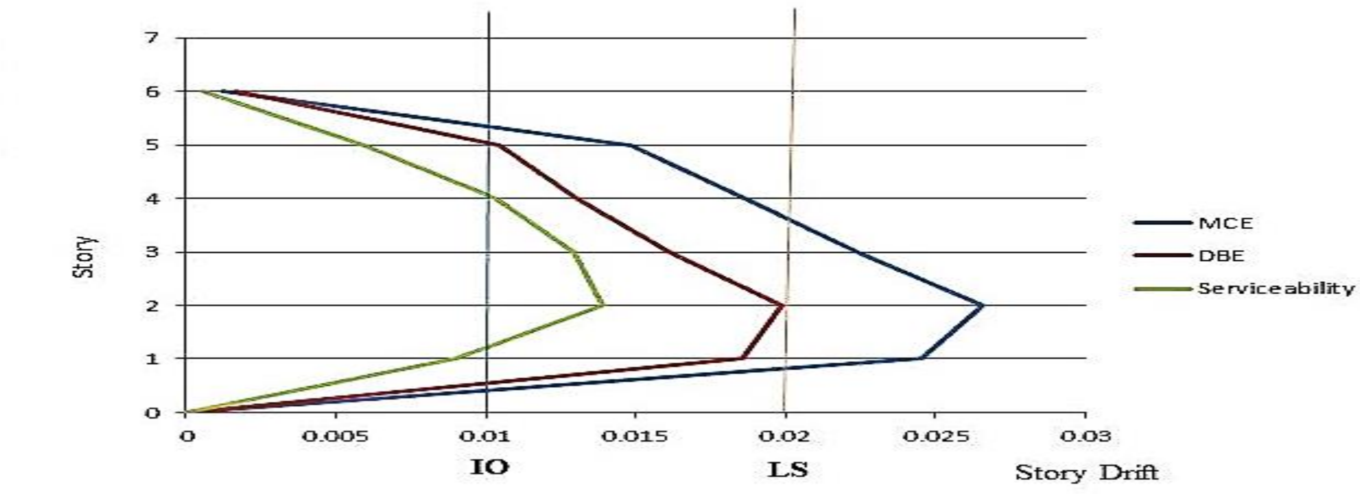
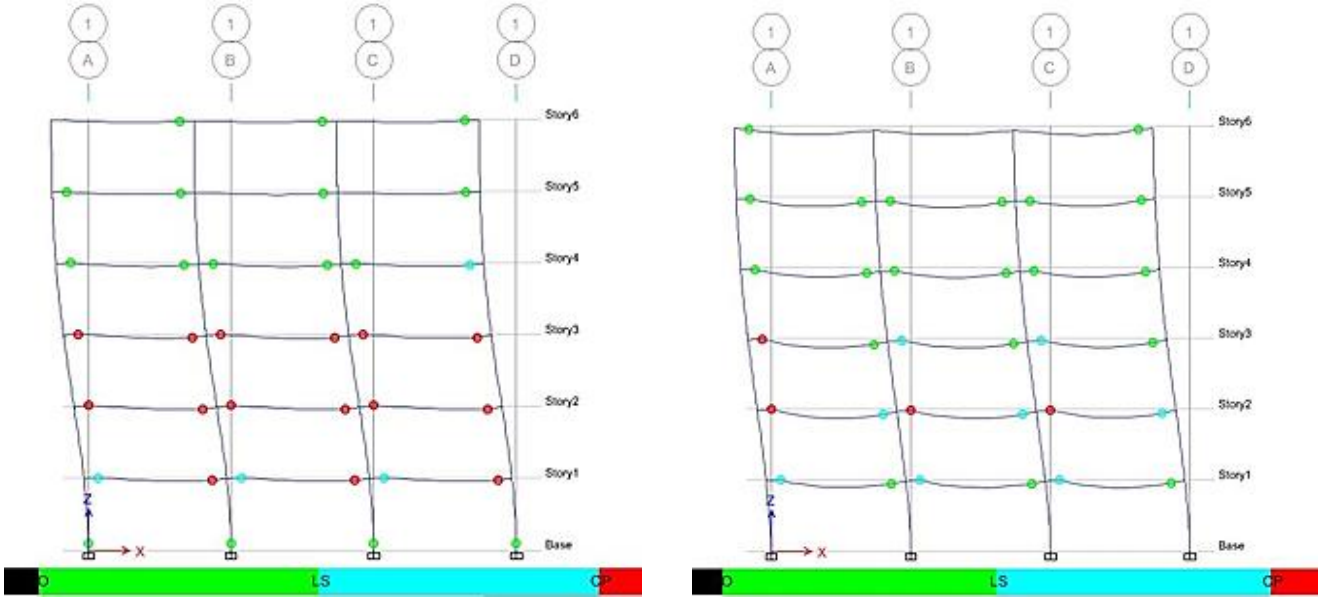
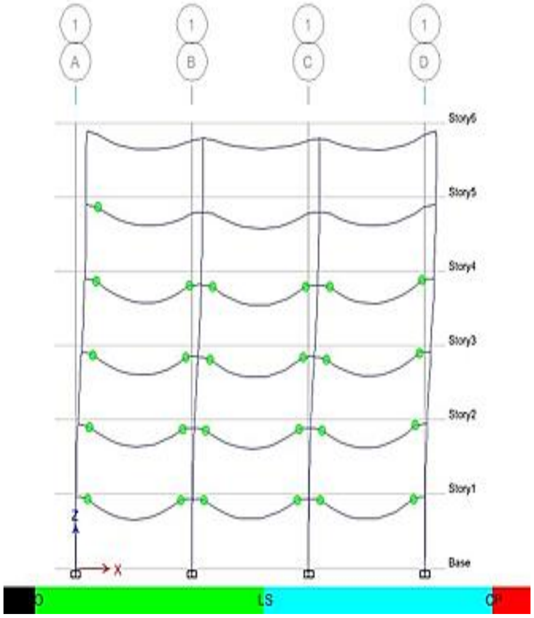


Figure 3: Story drift for gravity loads (Case Study-I).



(a) Hinge formation at MCE level

(b) Hinge formation at DBE level



(c) Hinge formation at SE level

Figure 4: Plastic hinge formation at different earthquake levels (Case Study-I)

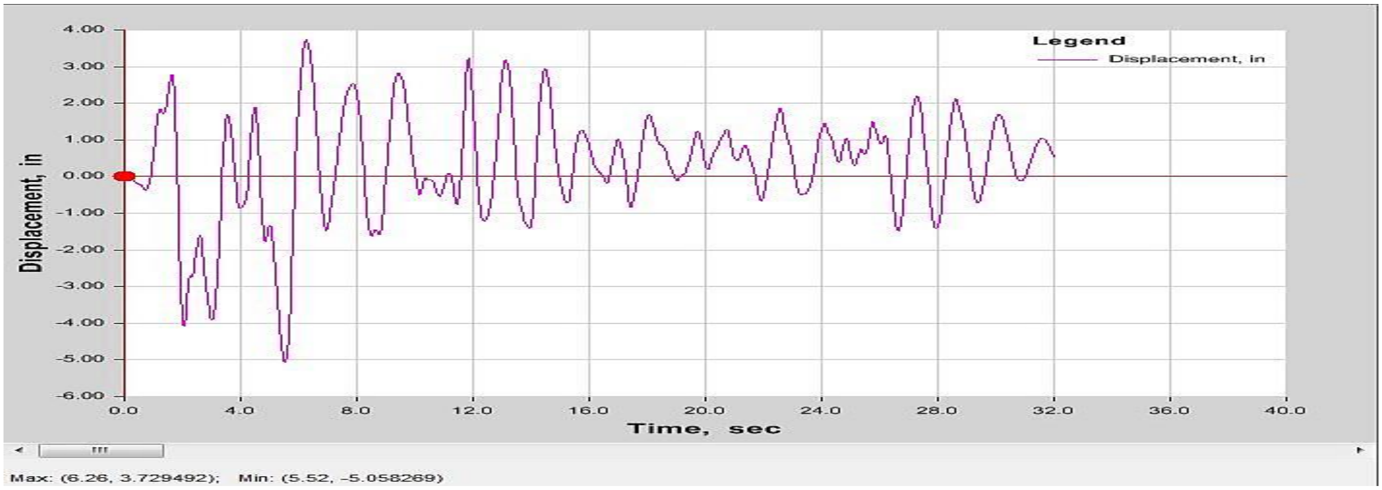
B. Case Study II: Variation of Story Level (inclusion of soft story)

In the Case Study–II, it is observed from Figure 5 and Table 4 for MCE level that the maximum displacement is 5.05 inch which is beyond maximum allowable limit as given in Table 2 and the frame will behave as nonlinear. The maximum displacement is 3.379 inch at DBE level which is just beyond the limit and starts acting as if nonlinear stage. At the SE level, the maximum displacement was satisfied as per limiting value of BNBC-2020 but did not satisfy by ATC-40 as per Table 2. Therefore, double height column is not safe for a building structure because it makes soft story and increase displacement.

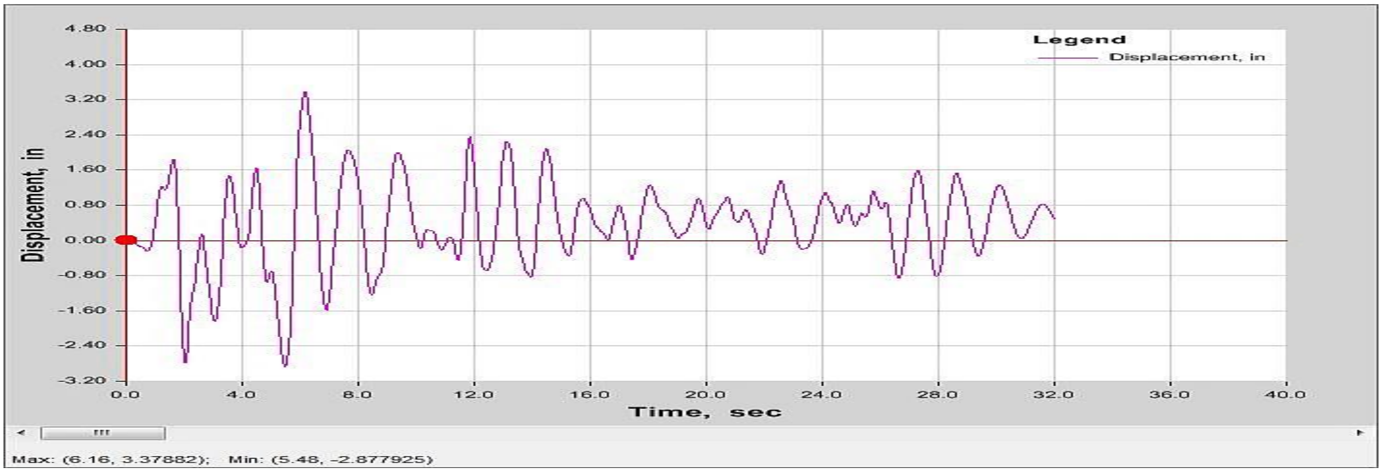
Also, the lateral drift of the structure 0.0015 shown in Figure 6 is within the drift limit as per Table 2 in case of SE. However, at DBE the structure crosses the IO line and far behind from LS line. Also, for MCE the drift of the structure is within the LS line. It is found from the analysis that, a significant number of hinges are created (shown in Figure 7) which is in the range of IO and LS. There is no hinge formation in the SE level.

Table 4: Maximum displacement and drift ratio for three ground motions (Case study II).

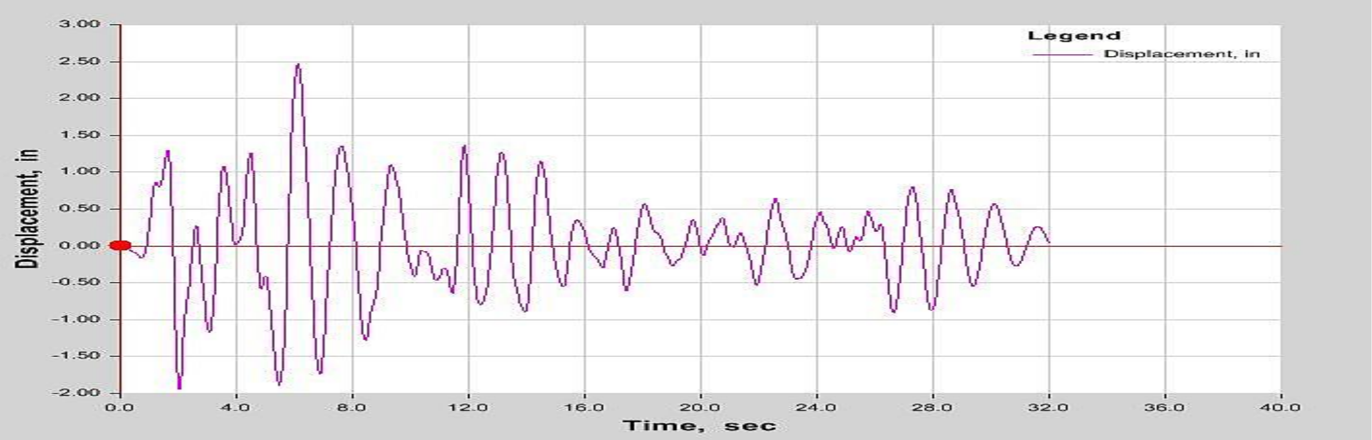
Ground motion level →	MCE level	DBE level	SE level
Maximum Displacement (in)	5.05	3.379	2.482
Drift ratio	0.0187	0.0158	0.0015



(a) Displacement vs time at MCE level.



(b) Displacement vs time at DBE level



(c) Displacement vs time at SE level

Figure 5: Displacement vs time at different earthquake level (Case Study–II).

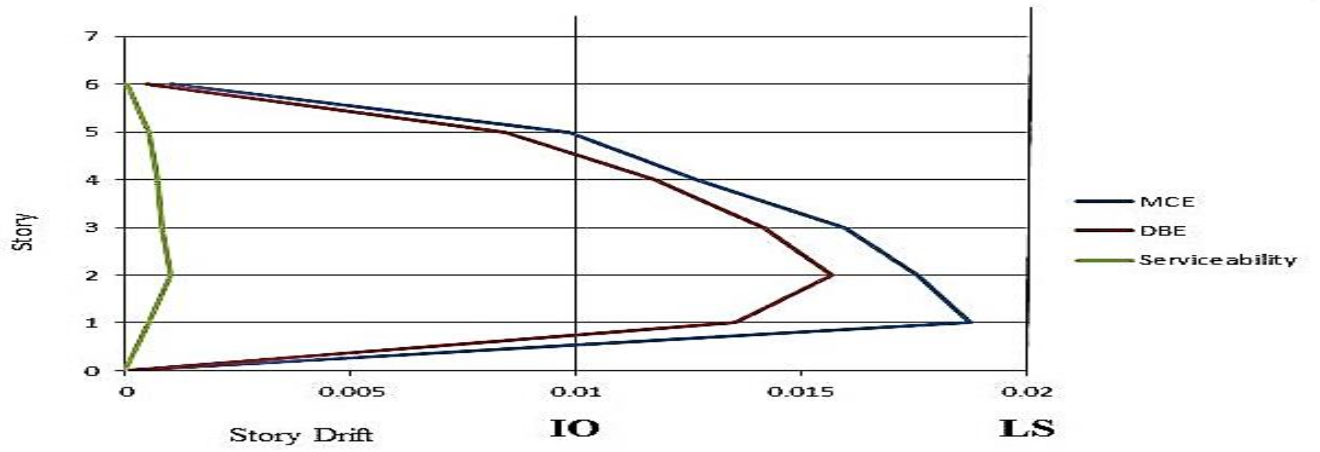
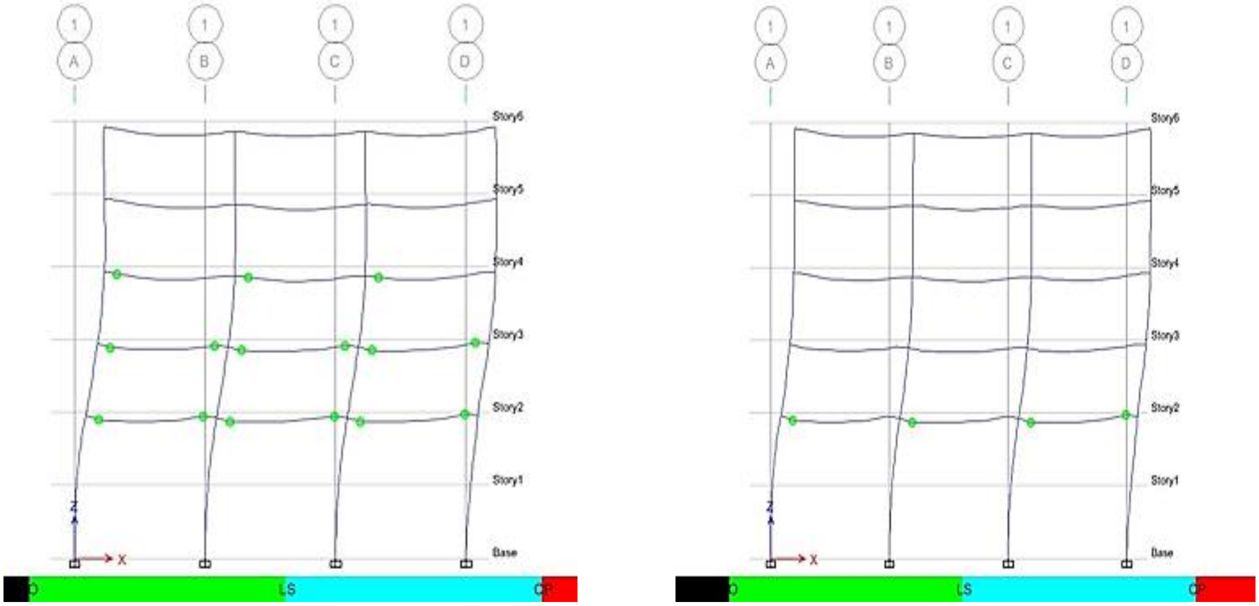


Figure 6: Story Drift for inclusion of soft-story (Case Study-II).



(a) Plastic Hinge Formation at MCE

(b) Plastic hinge formation at DBE.

Figure 7: Plastic Hinge Formation at different earthquake level (Case Study-II).

V. CONCLUSIONS

The following findings have been found as an outcome of the study:

- The assessed structure achieves the performance aim in terms of serviceability earthquakes, design basis earthquake levels, and all other criteria, but it does not maintain its structural stability during maximum earthquake levels. This finding will aid in a better understanding of the BNBC (2020) guideline.
- The investigation of the structure in which reinforcement is provided only for gravity load excluding earthquake load (Case Study I) shows that the structure is very much damage prone. Therefore, a structure should be designed considering all gravity and lateral loads to avoid partial damage or collapse of the structure. If the building construction has already been done, retrofitting can be suggested after detailed engineering assessment.

From Case Study II, it is found that double height column exceeds allowable limit of drift ratio and displacement and makes soft story which is basically an unsafe structure. However, the frame shows all the hinges are in the LS range. So, if we can avoid being a soft story and control story drift, double height column can be used in practice with some measures like lateral bracings, increasing cross sectional dimensions of column etc. at that story.

AUTHOR CONTRIBUTIONS

A. Hasan: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **K. I. M. Iqbal:** Conceptualization, Methodology, Writing – original draft. **S. Ahammed:** Conceptualization, Software, Writing – original draft. **A. Ghosh:** Conceptualization, Software, Writing – original draft.

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