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Earthquake Probability and Inelastic Displacement is Proportional to Building Weight

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A B S T R A C T

Elastic displacement is multiplied by deflection amplification factor (C_d) to get maximum displacement under severe seismic conditions. The elastic displacement is determined either by equivalent static analysis or linear time history analysis. In general code specifies certain value of C_d which may be used to estimate maximum inelastic deformation of building. The approved Bangladesh National Building Code (BNBC) has specified 4.5 as C_d value for Intermediate Reinforced concrete Moment Resisting Frames (IMRF). Theoretically, C_d value should vary according to building height, span, stiffness and other properties. To examine the range over which C_d varies for building in different regions of Bangladesh, in this work, 24 Reinforced Concrete buildings with different vertical and plan configuration has been examined. For analysis of these frames, three-dimensional finite element software ETABS has been used.

The 24 buildings considered in this work had bay width of 5 meter and height of 3.2 meter. Building frames of 2, 3 and 4-bay were examined in this work. Each bay has 8 frames having 2, 3, 4, 5, 6, 8, 10, 12 story. At first, structural analysis of these frames has been performed using equivalent static analysis as per BNBC (2020) which is based on zone specified seismic force and weight of the building. Nonlinear time history was been done for PGA 0.2g, 0.3g and 0.36g using the imperial valley earthquake. As peak ground acceleration of Imperial valley earthquake is 0.2605g (at 0.43 sect), it was scaled so that PGA becomes 0.2g, 0.3g and 0.36g.

C_d value was estimated from non-linear and linear top displacement found from the respective analysis. For 12,10 and 8 storied building had C_d value ranged from 4.57 to 4.23, 4.5 to 3.63 and 4.5 to 3.63 for 2,3 and 4-bay building respectively. BNBC specify a flat C_d value of 4.5 for buildings of all configurations. However, from this analysis work, it is evident that C_dvalue is very much dependent on building height, number of bays etc. C_d values suggested in this work may be useful for practicing engineers and researchers to estimate ultimate displacement of buildings due to severe earthquake from linear analysis of building for different regions of Bangladesh.

Keywords: Elastic displacement, Bangladesh. Earthquake, Building, Seismic Zone.

1. Introduction

1.1 General

"When the earth is shaken by its (final) earthquake. And the earth discharges its burdens. And man says, what is with it?" (99:1-3). An earthquake is a sudden movement of the earth-crust, caused by the abrupt release of strain, accumulated over a long time. Bangladesh is situated in a seismically active region. Part of the country extended from Sylhet to Chittagong is in the high seismic zone whereas Dhaka is in the moderate seismic zone. Major metropolitan cities of our country are under serious threat because of inadequacies in design and construction of structures.

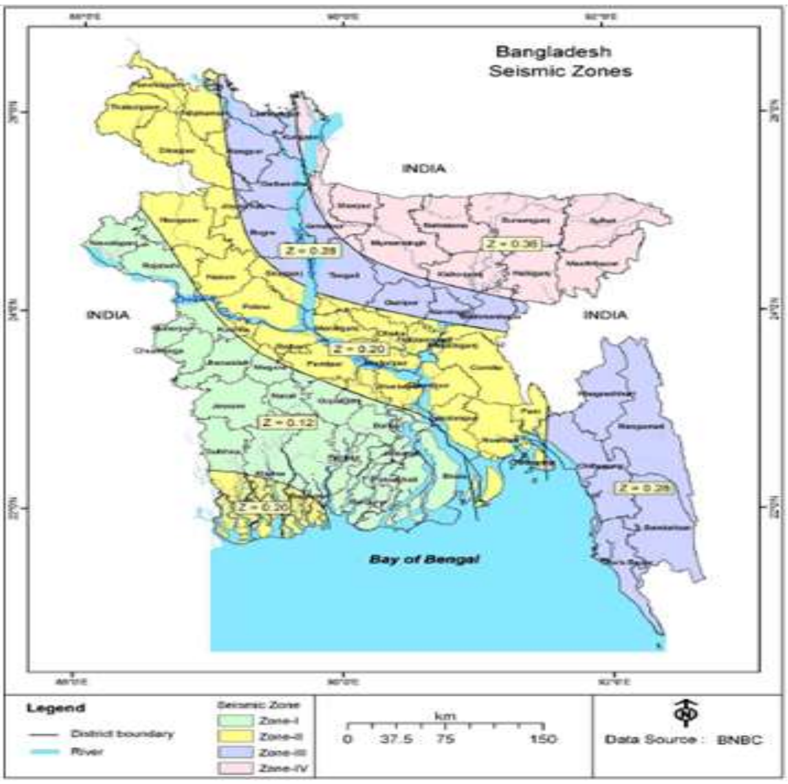

Figure 1.1. Seismic Zoning Map of Bangladesh (BNBC, 2020)

Materials remain elastic at certain level. The ground motion applied on a structure exerts force which becomes nonlinear at certain level. To bring down the ground motion force at inelastic level, Response modification factor is applied. Again, for assessing for total displacement and energy absorbed deflection amplification factor is applied.

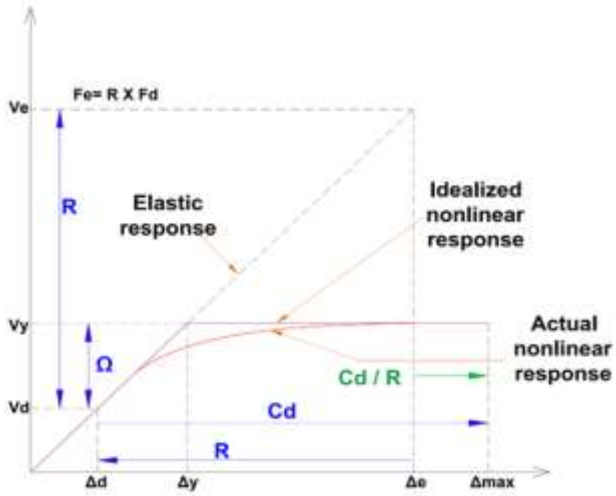

Figure 1.2. Relation Between $\boldsymbol{C_d}$ and $\boldsymbol{R}$ (Astrid et al., 2014)

For estimating the maximum inelastic deflection that might occur during an earthquake, the design deflections computed from an elastic analysis are usually amplified by a deflection amplification factor (C_d). This process is referred to as force-based design method.

1.2 Background and Present State of the Problem

There was no written building code in Bangladesh until 1993. In 1993, Bangladesh National Building Code (BNBC) was published by Housing and Building Research Institute (HBRI) which is commonly known as BNBC. The seismic design provisions of BNBC were based on the UBC (UBC, 1991). For the regular structures, the Code defines a simple method to represent earthquake induced inertia forces by Equivalent Static Force for static analysis. For very tall structure, the Code provisions require Time History Analysis. All these methods detailed in BNBC are force-based methods. As in many other codes, the level of forces prescribed by BNBC for a structure is rather arbitrarily set and aimed at damage control performance objectives i.e., no damage under small earthquake and no collapse under extreme earthquake. This BNBC was gazetted in 2006 as BNBC 2006. Bangladesh National Building Code 2020 (BNBC 2020) is the latest version of building code in Bangladesh. This code is very much similar to ASCE 7-05.

The purpose of this study is to investigate deflection amplification factor of intermediate RC moment frames based on the ratio of maximum inelastic to equivalent static and linear time displacement. Therefore, nonlinear, linear and equivalent static analysis are performed on the 24 models of reinforced concrete moment frames to determine the maximum seismic deflections at all the stories when subjected to the scaled earthquake records.

There are many researches on $C_{d,}$ but as per proposed BNBC no research has been found. In the newly proposed Bangladesh National Building Code (BNBC, 2020), different values for C_d are proposed for different types of RC structures. However, a more detail analysis may be performed to show the variation of C_d due to changes in different RC building parameters like story height (Typical storey height 3.2 meter and bottom storey height 2.13 meter), plan geometry, distribution of mass etc. This would be helpful in understanding the inelastic behaviour of RC building of different configuration designed as per BNBC (2020).

It is to be remembered that the length to breadth ratio of the building in plan not to be higher than 4. In buildings, floors (including the roof) act as horizontal diaphragms that collect and transmit the inertia forces to the vertical structural systems and ensure that those systems act together in resisting the horizontal seismic action.

1.3 Objectives and Scope of the Study

The main objectives of the paper is to determination of elastic and inelastic displacement ratio ($\boldsymbol{C_d}$) and elastic to inelastic storey drift ratio for RC building of different configuration and provide relationship between variations of $\boldsymbol{C_d}$ with different building parameters

1.4 Outline of Methodology

Structural modelling of RC buildings of different configuration to be done in finite element analytical software. 24 intermediate reinforced concrete moment frames to be designed based on BNBC (2020) and ACI 318 (2002) (where needed) provisions. To cover wide range of building geometries, several frame models with two, three and four bays will be selected. Height range of building will vary from 2 to 12 stores, in 1-storey increments except for the frames more than 6 stories, which will have 2-storey increment. The typical bay span and story height will be 5 and 3.2 meters, respectively.

2. Literature Review

2.1 Existing Analysis and Design Procedure

2.1.1 Equivalent Static Analysis

The evaluation of the seismic loads starts with the calculation of the design base shear which is derived from the design response spectrum, S_a. The building period in the two main horizontal directions to be smaller than both $4T_c$ and 2 seconds and the building does not possess irregularity in elevation.

SC type soil is used in analysis. The parameters in BNBC and Etabs of SC soil has difference. That is why site class F has been used in Etabs for Equivalent static analysis. The parameters of Soil type SC has been taken from Appendix C of BNBC.

2.1.1.1 Design Base Shear

The seismic design base shear force in a given direction to be determined from the following relation:

$$V = S_a W \qquad (2.1)$$

where,

S_a= Design spectral acceleration (in units of g) corresponding to the building period T.

W = Total seismic weight of the building.

2.2.1 Dynamic Analysis Methods

Spectral acceleration is measured in g that describes the maximum acceleration in an earthquake on an object. Dynamic analysis should be performed for regular buildings with height greater than 40m in Zones 2,3,4 and greater than 90 m in Zone 1. Dynamic analysis may be carried out through response spectrum and linear and nonlinear time history analysis.

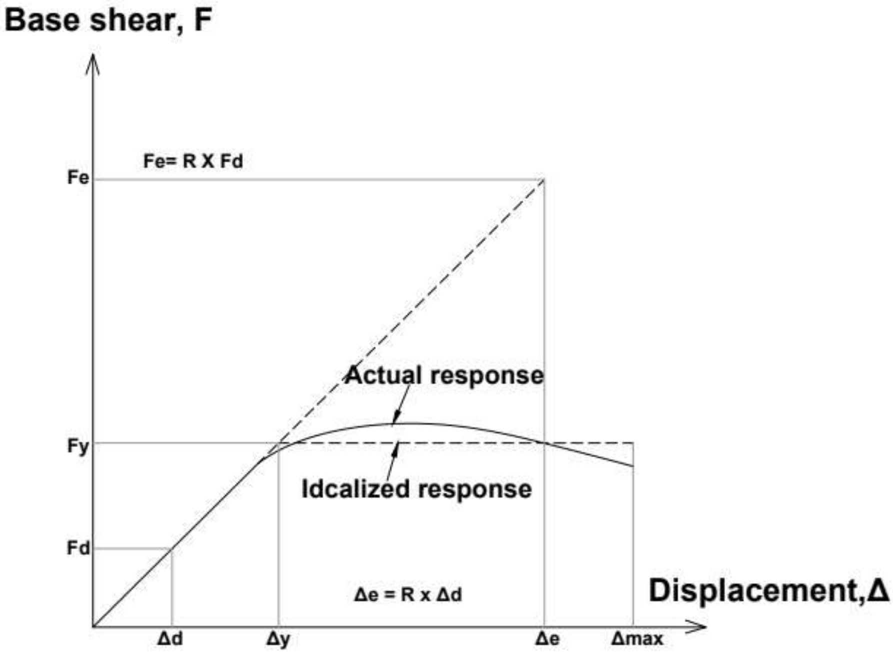

Figure 2.1. General Structural Response under the Effect of Lateral Loading (Elfath, 2019)

Figure shows global inelastic response of a structure under the effect of lateral loading. The actual inelastic response is idealized by a bilinear relation between the base shear and a lateral displacement component of the structure. Δ_{max} represents the maximum displacement demands under inelastic earthquake analysis. The elastic force and displacement demand F_e and Δ_e are related to the design force and displacement demands F_d and Δ_d according to the following relation:

$$\frac{F_e}{F_d} = \frac{\Delta_e}{\Delta_d} = R \qquad (2.15)$$

According to the definition presented by FEMA P695 (2009) and by various researchers such as Uang and Maarouf (1994), the inelastic displacement ratio ρ is calculated according to the following equation:

$$\rho = \frac{DAF}{R} = \frac{(\Delta_{max}/\Delta_d)}{R} = \frac{\Delta_{max}}{\Delta_e} \qquad (2.16)$$

3. Methodology

3.1 General

Numerical modelling of Reinforced Concrete frames has been presented in this chapter. In this research, total 24 reinforced concrete frame structures have been analysed using finite element method. Firstly, structural analysis of these frames has been performed using equivalent static analysis as per BNBC 2020. Using same geometrical, material and loading data, nonlinear time history analysis has been performed for all cases. There are mainly two methods to evaluate deflection amplification factor. Ratio of nonlinear time history displacement with Equivalent static displacement and ratio of nonlinear time history displacement with linear time history displacement (BNBC, 2020).

3.2.2 Design Considerations

Structural analysis and design have been performed according to BNBC (2020). Other codes, standards, specifications have been utilized as required in structural design.

A. Structural Geometry Considerations

Initially shape, size, story height and number of stories of the building have been considered as per design requirement and checked as per BNBC (2020). The buildings having bay width of 5 meter and height of 3.2 meter. There are frames of 2,3 and 4 bay. Each bay has 8 frames having 2, 3, 4, 5, 6, 8, 10, 12 story. Typical column location, beam location is shown in the following layout (Figure 3.1).

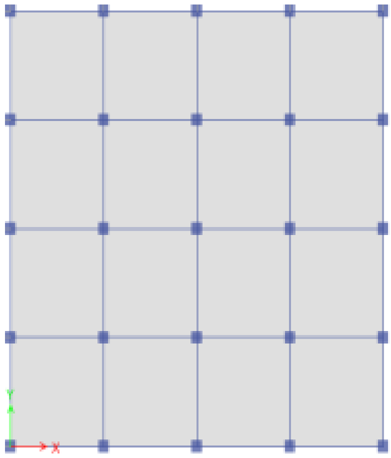

Figure 3.1. Column Layout of Four Bay Twelve Story

3.4 Ground Motion and Analysis Procedure

3.4.1 Peak Ground Acceleration of Imperial Valley Earthquake

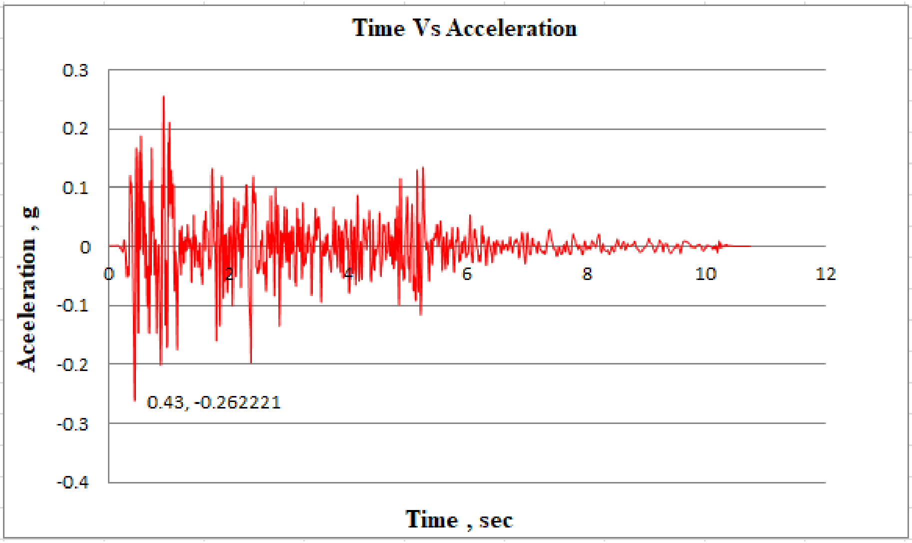

Figure 3.2. Peak Ground Acceleration of Imperial Valley Earthquake

PEER NGA Strong Motion Database Record

Imperial Valley-02, 5/19/1940, El Centro Array #9, 180

Acceleration Time Series in units of g.

No of Points = 5372, Difference of Time = .0100 Sec

Scale Factor = I_g/R

Here, g = 32.2 ft/sec^2 = 386.4 in/sec^2

Scale Factor of Nonlinear Analysis , I_g/R_x = (1x386.4)/1=386.4

Linear Time History Analysis, I_g/R_x = 1×386.4/5 = 77.28

3.4.2 Scale Factor for Dhaka Region

Peak Ground Acceleration/ Maximum Considered Earthquake of Dhaka = 0.2g

Peak Ground Acceleration of Ground Motion = $0.2605g$;

To scale down acceleration to $0.2g$ (Peak Ground Acceleration of Dhaka); let equalizing factor is A.

$0.2605g \times A = 0.2g$

So, $A = 0.768$

So, in Nonlinear Time History Analysis, Scale Factor = (386.4) (0.768) = 296.66.

In Linear Time History Scale Factor for 0.2g = I_g/R = 296.66/5 = 59.3

3.4.3 Scale Factor for Sylhet Region

Peak Ground Acceleration of Sylhet Region=0.36g

$0.2605g \times A = 0.36g$

So, $A = 1.382$

Scale Factor = 386.4×1.382 = 533.9

In Linear Time History Scale Factor for 0.36g = I_g/R=533.9/5=106.78

4. Result and Discussion

4.1 Introduction

This chapter highlights the analysis and results of 24 different finite element models prescribed in chapter 3. The result includes structural response from equivalent static analysis and nonlinear time history analysis. Results from equivalent static analysis for 24 frames are presented. Nonlinear behavior of 24 frames are discussed including computaion of deflection amplification factor and drift ratio. There are three different geometries/building configurations that includes 10m×10m, 15m×15m and 20m×20m floor area. Deflection Amplification Factor (C_d) and Drift Ratios are determined for all three geometric configuration of finite element.

4.2 Finite Element Analysis Result for 10m×10m Frame Structures

4.2.1 C_d and Drift Ratio of Two Bay Two Story Frame (2-2)

The selected beam of 235.2mm×416.6mm (9.26in×16.4in) and column of 235.2mm×235.2mm (9.26in×9.26in). Rebar percentage is 1%, 1.29% and 2.39% at bottom, first floor and second floor respectively. Demand Capacity Ratio is <1

A. Deflection Amplication Factor (C_d)

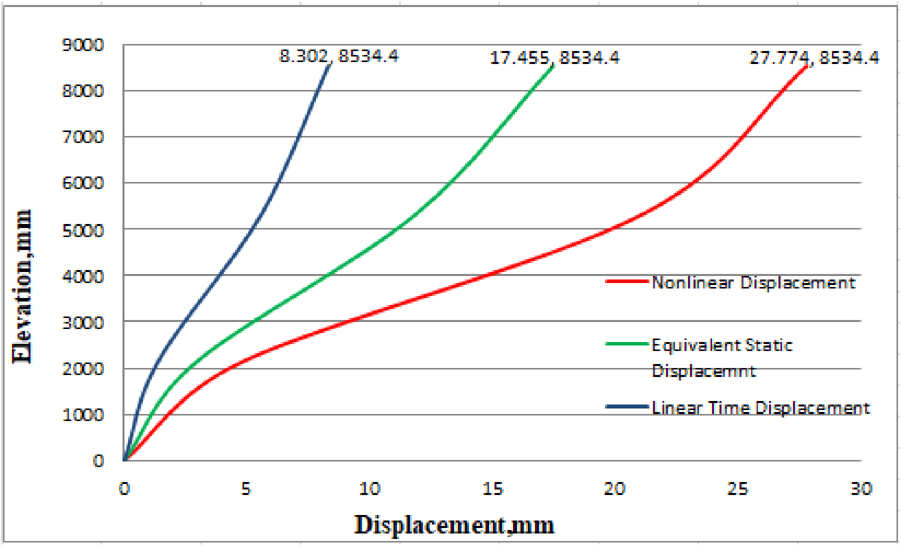

Figure 4.1. Maximum Story Displacement of 2 Bay 2 Story Frame

C_d = 1.59 and 3.35 respectively with respect to equivalent static displacement and linear time displacement.

B. Story Drift

As per BNBC, drift limit is 0.02. Here static linear, linear and nonlinear drifts are less than specified limit.

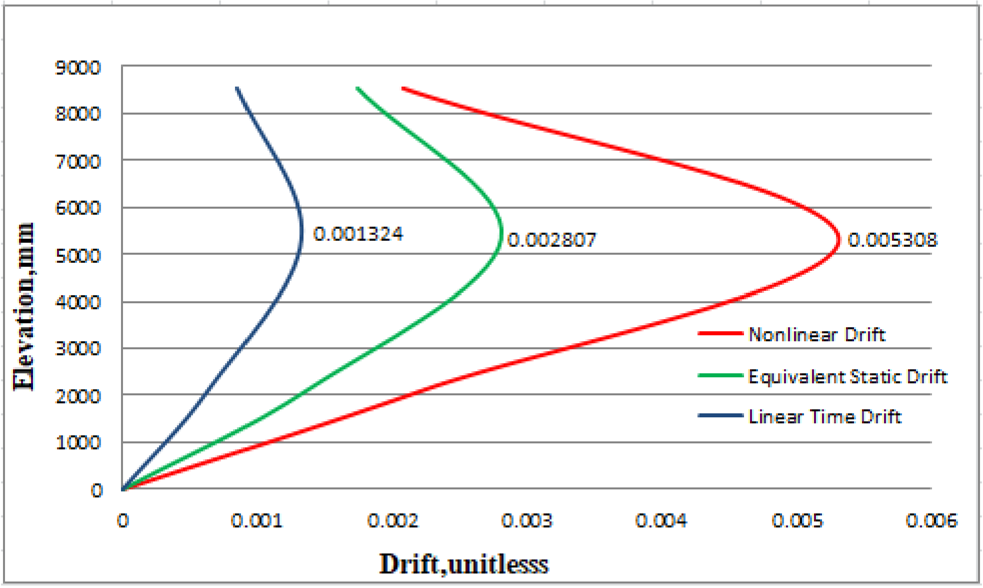

Figure 4.2. Maximum Story Drift of 2 Bay 2 Story Frame

C. Relationship between Displacement and Load

Two bay two story has maximum roof displacement of 27.8 mm where under load condition culumn has maximum displacement of 27.8 mm.

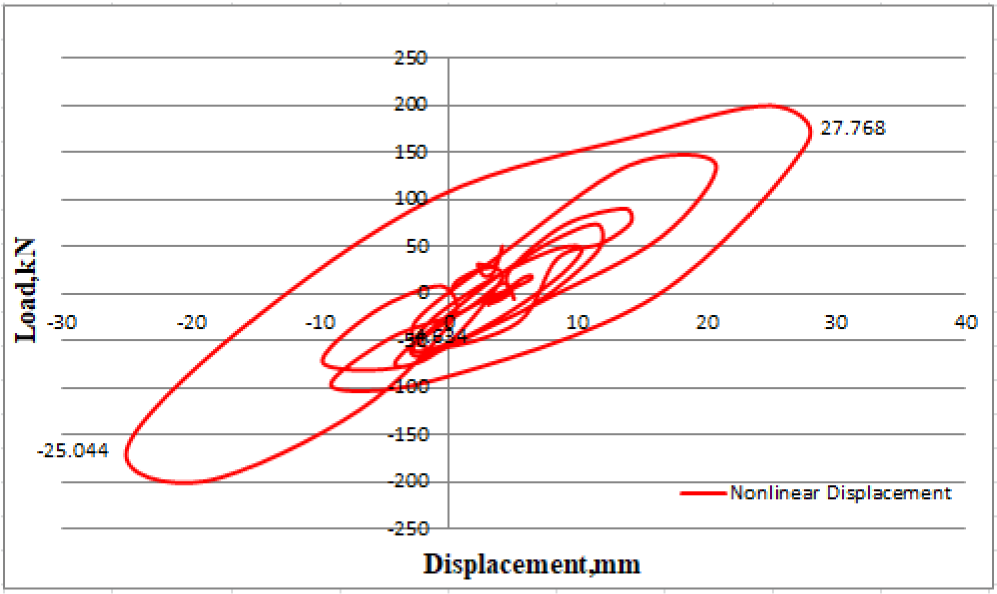

Figure 4.3. Relationship between Displacement and Load of 2 Bay 2 Story Frame

D. Hinge Result

The hinge result (Figure 4.4) shows that it is in plastic zone. Plastic rotation in negative direction.

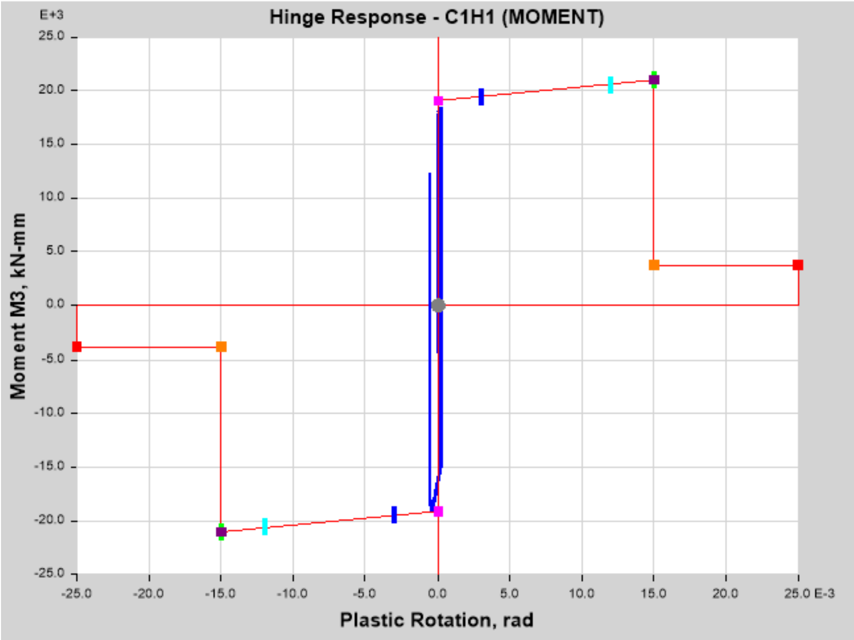

Figure 4.4. Hinge Result of 2 Bay 2 Story Frame

4.3 Evaluation of C_d for Sylhet (PGA = 0.36g)

4.3.1 Two Bay Two Story in Sylhet (2-2)

The selected beam of 235.2mm×416.6mm (9.26in×16.4in) and column of 235.2mm×235.2mm (9.26in×9.26in).

A. Deflection amplification factor (C_d)

The evaluated nonlinear displacement is 51.497 mm,the equivalent static displacement is 17.455 mm and linear time displacement is 14.944 mm. Therefore deflection amplification is found to be 2.95 and 3.45 with respect to equivalent static displacemnt and linear time displacement respectively.

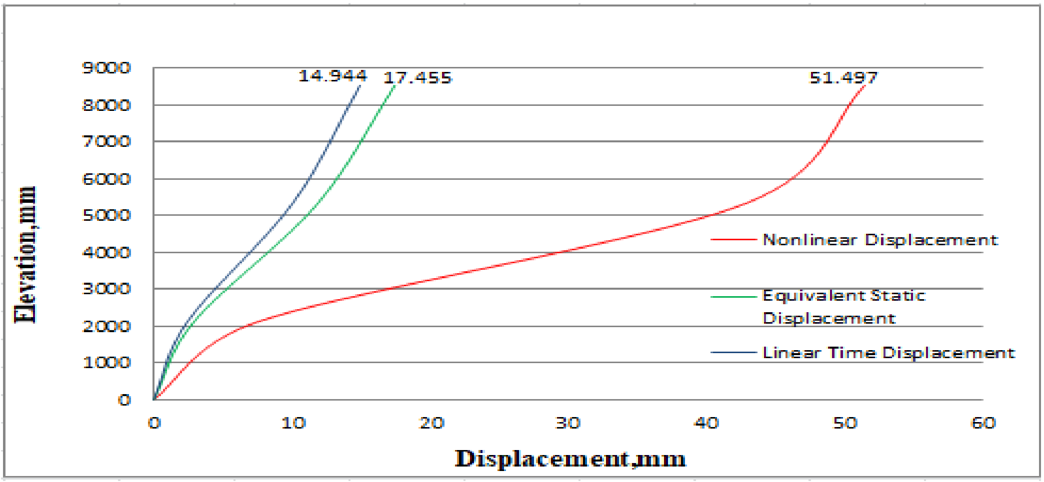

Figure 4.5. Relationship between Displacement and Load of 2 Bay 2 Story Frame

B. Hinge Result in Sylhet Region

The Load case is nonlineardynamic. The column is in ground floor. Hinge degree of freedom M3. Hinge relative distance is 0.1. The hinge has moved to plastic zone. Rotation is in positive and negative direction.

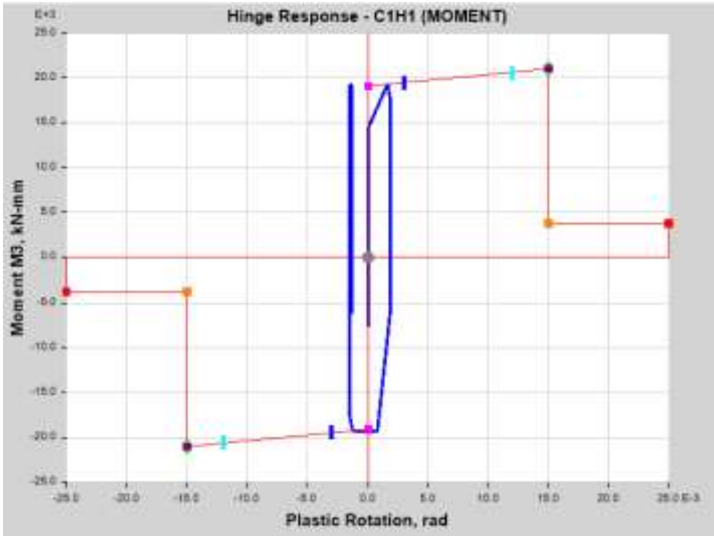

Figure 4.6. Hinge Result of 2 Bay 2 Story in Sylhet Region

4.4 Summary of C_d with respect to Equivalent Static Displacement and Storey Drift Characteristics (PGA = $0.3g$)

Table 4.1. Summary of Inelastic Displacement Ratios and Storey Drift Characteristics

Frame	Analysis	Top Deflection (mm)	Story Drift	Inelastic Displacement Ratio
4 Bay 12 Story	Nonlinear Time History	110.13	0.008834	4.098
	Equivalent Static	26.873	0.000968	
4 Bay 10 Story	Nonlinear Time History	124.788	0.010601	3.03
	Equivalent Static	41.154	0.001804	
4 Bay 8 Story	Nonlinear Time History	85.494	0.00778	2.26
	Equivalent Static	37.772	0.002119	
4 Bay 6 Story	Nonlinear Time History	56.01	0.005339	1.84
	Equivalent Static	30.415	0.002287	
4 Bay 5 Story	Nonlinear Time History	49.443	0.00512	1.7
	Equivalent Static	29.112	0.002643	
4 Bay 4 Story	Equivalent Static	44.671	0.005402	1.79
	Nonlinear Time History	24.977	0.002801	
4 Bay 3 Story	Nonlinear Time History	42.229	0.006231	1.91
	Equivalent Static	22.096	0.003138	
4 Bay 2 Story	Nonlinear Time History	39.769	0.007563	2.02
	Equivalent Static	19.658	0.003652	
3 Bay 12 Story	Nonlinear Time History	103.313	0.006398	3.99
	Equivalent Static	25.888	0.000832	
3 Bay 10 Story	Nonlinear Time History	120.915	0.008206	2.98
	Equivalent Static	40.537	0.001638	
3 Bay 8 Story	Nonlinear Time History	82.916	0.006366	2.2

	Equivalent Static	37.717	0.001942	
3 Bay 6 Story	Nonlinear Time History	58.578	0.004579	1.81
	Equivalent Static	32.404	0.002192	
3 Bay 5 Story	Nonlinear Time History	49.935	0.004383	1.676
	Equivalent Static	29.795	0.002418	
3 Bay 4 Story	Nonlinear Time History	45.682	0.004768	1.736
	Equivalent Static	26.312	0.002632	
3 Bay 3 Story	Nonlinear Time History	41.99	0.005593	1.92
	Equivalent Static	21.87	0.002837	
3 Bay 2 Story	Nonlinear Time History	38.934	0.006694	2.07
	Equivalent Static	18.839	0.003179	
2 Bay 12 Story	Nonlinear Time History	173.152	0.006497	2.87
	Equivalent Static	60.388	0.001956	
2 Bay 10 Story	Nonlinear Time History	118.099	0.005895	1.87
	Equivalent Static	63.2	0.002554	
2 Bay 8 Story	Nonlinear Time History	75.478	0.00496	1.415
	Equivalent Static	53.332	0.002781	
2 Bay 6 Story	Nonlinear Time History	58.199	0.004473	1.17
	Equivalent Static	49.789	0.003521	
2 Bay 5 Story	Nonlinear Time History	74.167	0.00739	
	Equivalent Static	48.035	0.03758	
2 Bay 4 Story	Nonlinear Time History	53.85	0.006234	1.55
	Equivalent Static	34.72	0.003313	
2 Bay 3 Story	Nonlinear Time History	45.497	0.006903	1.78
	Equivalent Static	25.61	0.00309	
2 Bay 2 Story	Nonlinear Time History	40.808	0.008468	2.34
	Equivalent Static	17.455	0.002807	

.5 Base Shear, Weight, Inelastic Displacement Ratios, and Storey Drift of Two Frames (PGA=0.3g)

Table 4.2. Base Shear, Weight, Inelastic Displacement Ratios, and Storey Drift of Two Frames

Frame	**Analysis**	**Top Deflection (mm)**	**Story Drift**	**Base Shear, V (KN)**	**Total Weight, W (KN)**	**(V/W) %**	**Axial Load on Column (KN)**	**Column End, Rebar (%)**	**Column and Beam Size(in)**	**Inelastic Displacement Ratio**
4 Bay 12 Story	Nonlinear Time History	110.13	0.008834	3728	50645	2.7	58174	0.82	21.75×21.75 and 12.30×24.75	4.098
	Equivalent Static	26.873	0.000968	1368						

4 Bay 10 Story	Nonlinear Time History	124.788	0.010601	2936	39310	3.7	45572	0.98	19.97×19.97 and 12.13×19	3.03

5. Conclusion

5.1 General

In this study the deflection amplification factor of Reinforced Concrete frames has been investigated and compared with values suggested in BNBC. For this, 24 frames were modelled in finite element software ETABS. These 24 frames were varied with respect to story height and bay configuration. Eight different story from 2 to 12 were considered in this work. Three types of bay arrangements were used, i.e., two by two bay, three by three bay and four by four bay.

The buildings were first designed using equivalent static analysis as per BNBC. From that beam and column sizes were determined. From this static analysis of 24 frames, maximum top deflection and storey drift were recorded. Afterwards, nonlinear dynamic analysis of these frames was conducted. For this, imperial valley earthquake data was used. This earthquake data was scaled to fit the BNBC recommendation for Dhaka zone, i.e., peak ground acceleration was seated to $0.2g$. For nonlinearity of members i.e., beams and columns, isotropic hysteresis model which is a built-in function of ETABS was used. From the nonlinear analysis, the top deflection, story drift and hinge results were recorded.

5.2 Conclusions

Following Conclusions may be drawn based on the study:

(i) $\mathrm{C_d}$ value was estimated from non-linear and linear top displacement found from the respective analysis. For 12,10 and 8 storied building had $\mathrm{C_d}$ value ranged from 4.57 to 4.23, 4.5 to 3.63 and 4.5 to 3.63 for 2,3 and 4-bay building respectively. BNBC specify a flat C_d value of 4.5 for buildings of all configuration. However, from this analysis work, it is evident that $\mathrm{C_d}$value is very much dependent on building height, number of bays etc. For most of the cases analyzed in this work, $\mathrm{C_d}$ value was found to be much lower than BNBC specified valued. However, for 12 storied building, $\mathrm{C_d}$ was found to have value slightly more than 4.5 for 2 bay configuration.

(ii) $\mathrm{C_d}$ values suggested in this work may be useful for practicing engineers and researchers to estimate ultimate displacement of buildings due to severe earthquake from linear analysis of building for different regions of Bangladesh.

(iii) Cd value increases when Weight of building increases thereby probability of earthquake increases.

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