The Seismic Performance Evaluation of RC High-rise Buildings Designed to Various Building Codes

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Abstract

This study evaluates and compares the expected seismic performance of a high-rise building when designed according to various international building codes. Using a 40-story reinforced concrete (RC) case study building, the comparison among the three most widely used building codes (ACI 318/ASCE 7-10, BS 8110 and EC-2/EC-8) is presented in terms of structural design and seismic performance. The case study building has a dual structural system (moment-resisting frame and shear walls) and is assumed to be located in a highly active seismic region. First, its linear elastic model was created and analysed to perform the code-based design for gravity and seismic loads. The building is designed separately for three codes following their prescribed load combinations, cracked stiffness modifiers and seismic design factors. Then, the detailed performance evaluation of case study building (separately designed for each building code) was carried out using the nonlinear response history analysis (NLRHA) under different input ground motions. Based on obtained results, a comparison of three building codes is presented in terms of the design, seismic performance and economic considerations.

Keywords: high-rise buildings; dual systems; code-based design; nonlinear dynamic analysis; performance-based seismic evaluation.

1 Introduction

Building codes are a set of rules and regulations specifying the minimum safety, health and energy standards for the design, construction and maintenance of constructed objects such as buildings and non-building structures. These standards are often prepared by the international organizations and their committees based on the general consensus of subject experts, researchers, engineering community and governmental agencies. The codes become the law of a particular jurisdiction when officially enacted by any particular governmental or private authority.

With the rapid economic growth and urbanization, the construction of tall buildings increased in the middle of 20th century. A variety of social requirements for commercial or aesthetic reasons and limited availability of land has resulted in more challenges and difficulties for design and evaluation of high-rise buildings.

Recently, occurrence of actual observed damages especially human lives during earthquakes in various parts of the world has proved that capacity of resisting earthquake loads is quite insufficient. Buildings having non-ductile reinforcement details were the main reason of the structural inadequacy. Low lateral strength, poor proportioning of frame members might also be the one of reason in few countries which reduce seismic resistance in the buildings. For preserving life of public and structure all such important factors should be considered to prevent major damage. Various seismic codes help to improve the behavior of the structures so that they may withstand the earthquake effects without significant loss of life and property. In order to design an earthquake resistant structure, the designer must have a good knowledge about various seismic design codes. The structural design practice in different countries involves the use of different codes. However, the common and major objective is to ensure the life of occupants.

It should also be noted that satisfying a structure from one code may not compliance with the design provisions given by another code. It is expected that a comparative seismic assessment of buildings designed to various codes will help to identify the code which can ensure better seismic performance as compared to others.

Recently, several studies have attempted to perform such a comparison. Karthiga and Titus [1] designed a ten story RC building using four different international codes. It was found that BS code has consumed the highest reinforcement as compared to other codes and the performance of building in terms of displacements is almost same for all other design codes. Similarly, Santos [2] compared design criteria for buildings among various codes. Obtained results were compared by applying several design standards on a regular ten story building. It was observed that difference in design spectra shapes can cause differences in overall results which can be even more than 100 percent in some cases.

More recently, Asmita et al. [3] reviewed seismic design and evaluated high rise structures using various international codes. Main objective was to examine the differences caused by using various international codes during analysis of tall buildings. However, details results showed that building designed using Euro code performs better as compared to Indian and American codes. It was also observed that Euro code serves to be the most economical design and Indian code is the least economical code.

This study will also focus on seismic performance comparison of a case study high-rise building with shear walls, located in a high seismic zone and designed according to three international building codes (ACI, BS and EURO).

2 Methodology

In this study, a 40-story shear wall building structure located in a highly active seismic region (Makati, Philippines) is selected. It is first designed according to three building codes. Then, the seismic performance is evaluated by comparing various key response indicators, both at local (members) level and global (structural) level, by subjecting the building (separately designed according to these codes) to a site-specific suit of ground motion records.

The case study building is a residential tower originally designed by the MKA (Magnusson Klemencic Associates) according to LATBDSC [4]. The lateral forces are mainly resisted by the reinforced concrete structure core wall built around the elevator shaft and special moment resisting frames connecting the core. The typical plan and 3D view is shown in Figure 1, while basic features, dimensions and other structural and non-structural details are shown in Table 1.

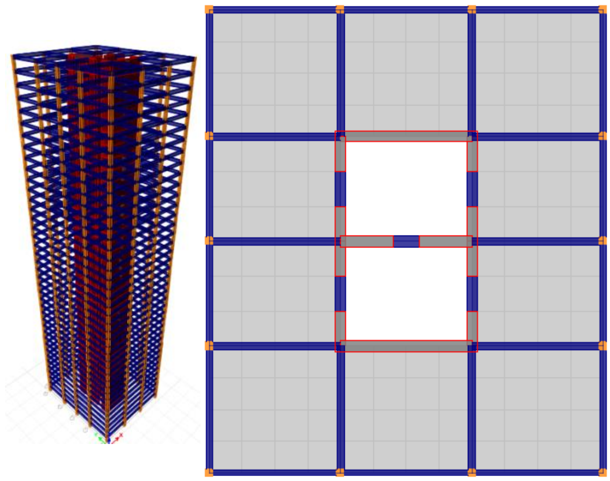

Figure 1. 3D view & typical layout plan of building

Table 1. Basic geometric information of the case study building and section sizes

Description	Dimensions
Location	Philippines
No of Stories	40 m
Width	35 m
Length	30 m
Total Height (40-story)	121.92 m
Width to Length ratio	1.12
Width to Height ratio	3.5
Length to Height ratio	4
Foundation: Fixed support (columns), pinned support (shear walls)	
Total no of lift-cores	2
Dead Load	Self-weight
Live Load	1.5 KN/m^2
Superimposed dead load	2.5 KN/m^2
Core wall	Reinforced concrete shear walls • SW-1: 1000 mm, L01-L20 • SW-2: 750 mm, L21-L40
Columns	Reinforced concrete columns: • 800mm x 800mm (L01-L10) • 700mm x 700mm (L11-L20) • 600mm x 600mm (L21-L40)
Beams	Reinforced concrete Beams: • B-400X750 (L01-L10) • B-400X650 (Inner) (L01-L20) • B-500X750 (T-Inner) (L21-L40)
Coupling Beams	Conventional coupling Beams: • CPB-750X750 • CPB-800X800
Slab	150 mm reinforced concrete slab

Table 2. Selection of codes

Design Codes	Seismic Codes
ACI 318-14	ASCE 7-10
BS 8110-1997	EURO-8
Euro Code-2-2004	EURO-8

The linear elastic model of case study building is created in ETABS [5] and is used to perform code-based design. The model includes shear walls, columns, coupling beams, beams and slabs. Shear walls, slabs, are modeled using shell elements. Columns, coupling beams and beams are modeled using frame elements. The stiffness parameters for various elements are varied in each model for several types of analysis. A critical damping ratio of 5% is used for DBE analysis in compliance with codes. For determining the design seismic demands, the standard Response Spectrum Analysis (RSA) procedure is applied for DBE level for all three codes. Design parameters (e.g. reinforcement ratio) obtained from three widely used building codes i.e. ACI 318 [6]/ASCE 7-10[7], BS 8110 [8] and EC 2/EC 8 [9] (Table 2), were compared in terms of their adequacy for providing better seismic performance as well as for economic considerations.

The detailed nonlinear models were then created in PERFORM 3D [10]. The models include inelastic member properties for elements that were anticipated to be loaded beyond their elastic limits. These include flexural response of coupling beams, girders and shear wall. The shear walls were modeled using nonlinear concrete and steel fibers. The steel fibers are modeled using the Park's model, while concrete is modeled using the Mander's model [11]. Girders, conventional RC beams and coupling beams were modeled with moment hinges at the ends. The deformations capacities are taken from Table 10-7 of ASCE 41-13 [12]. The performance evaluation is carried out using nonlinear response history analysis (NLRHA) under MCE level earthquake with an approximate return period of 2475 years (2% probability of exceedance in 50 years). The input ground motions were obtained from a recent Probabilistic Seismic Hazard Analysis (PSHA) study for the city of case study building (Makati city, Philippines). Seven pairs of ground motions were modified to match with the MCE-level response spectrum shown in Figure 2 and were used in the detailed NLRHA procedure. Table 3 shows the acceptance criteria for MCE-level seismic hazard.

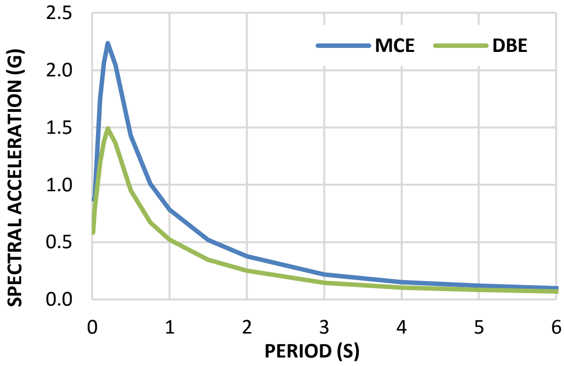

Figure 2. The DBE- & MCE-level response spectra used in this study

Table 3. Acceptance criteria for maximum considered earthquake (MCE)

Item	Value
Peak transient drift	Maximum of mean values shall not exceed 3%. Maximum drift shall not exceed 4.5%.
Residual drift	Maximum of mean values shall not exceed 1%. Maximum drift shall not exceed 1.5%.
Coupling beam inelastic rotation	≤ASCE 41-13 limits
Column Inelastic Rotation	≤ASCE 41-13 limits
Shear wall reinforcement axial strain	≤0.05 in tension and ≤0.02 in compression
Shear wall shear	Remain elastic. (Check for 1.5 times mean value)
Girder inelastic rotation	≤ASCE 41-13 limits
Girders shear	Remain elastic.

3 Results and Discussion

Figure 3 shows the natural periods for first three vibration modes in both directions and torsion.

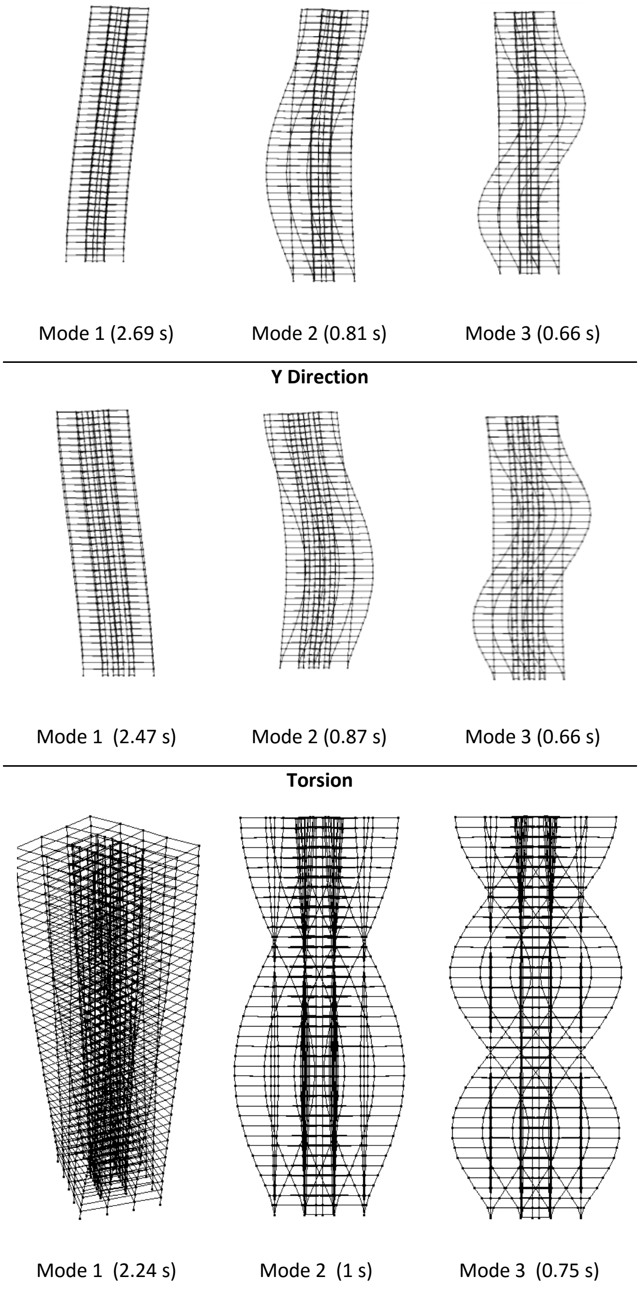

Figure 3. The vibration mode shapes

3.1 DBE-Level Response Spectrum Analysis

It is observed that the base shear computed at DBE level by using ASCE 7-10 was 1.24 and 1.37 times higher than Euro-8 in X and Y direction respectively (Figure 4). Since BS don't have their own seismic code so, Euro-8 were used as a seismic code of BS due to which base shear came same in both cases.

Figure 5 shows the story shear and moment comparison in X-Direction of the case study building. As expected, ASCE 7-10 [7] is resulting in higher story shears and corresponding overturning moments.

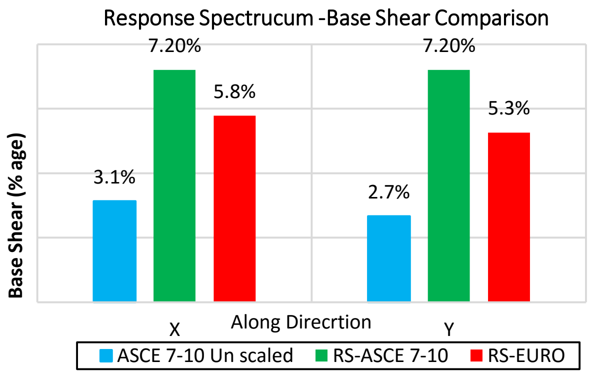

Figure 4. RS-Base Shear comparison (DBE-Level)

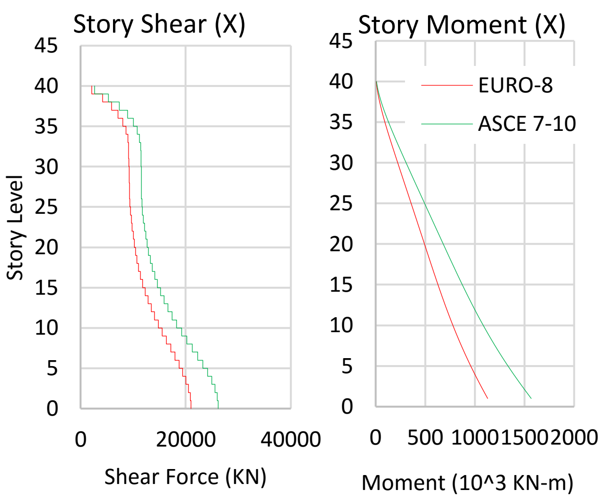

Figure 5. Story shear and moment comparison (X-DBE Level)

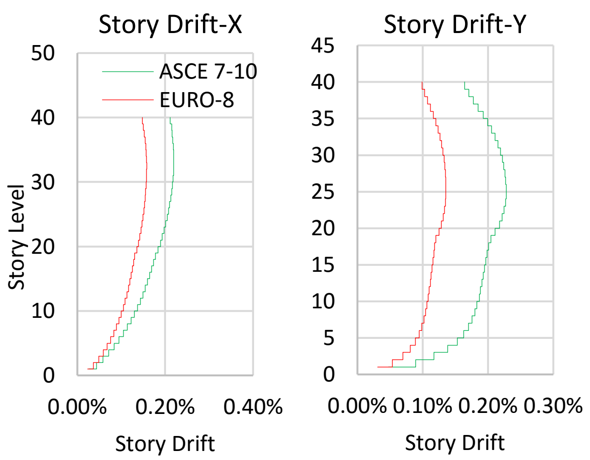

Figure 6. Story drift (X, Y Directions) DBE Level)

The elastic story drifts were also evaluated and compared at the DBE level earthquake in both X and Y directions. Although they are within acceptable limits, ASCE 7-10 has slightly higher more drift as compared to Euro-8 (Figure 6).

The summary of reinforcement requirement for all 3 codes is shown in Figures 7 to 10. BS code has resulted in more reinforcement in selected coupling beams, main beams and columns.

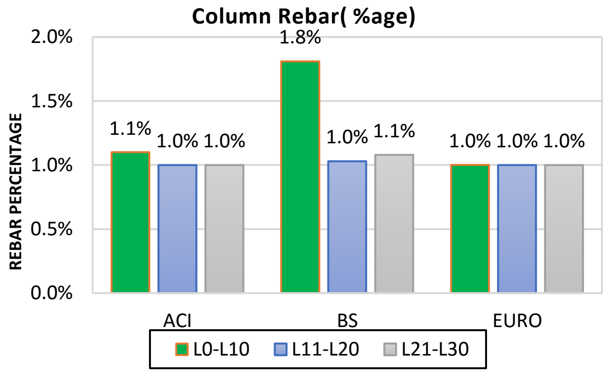

Figure 7. Column reinforcement

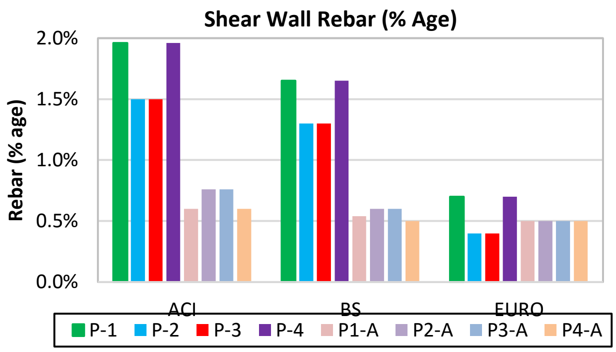

Figure 18. Shear wall reinforcement

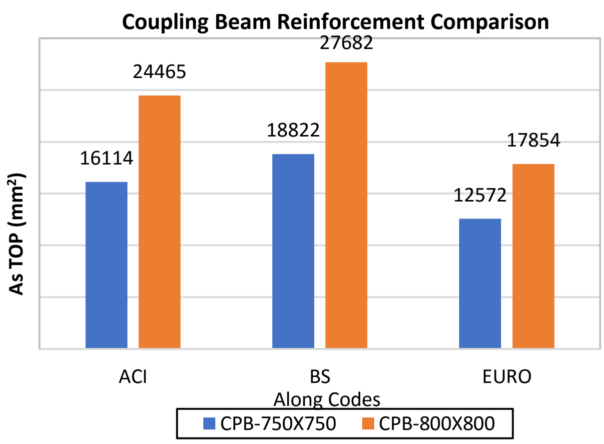

Figure 9. Coupling beams Reinforcement

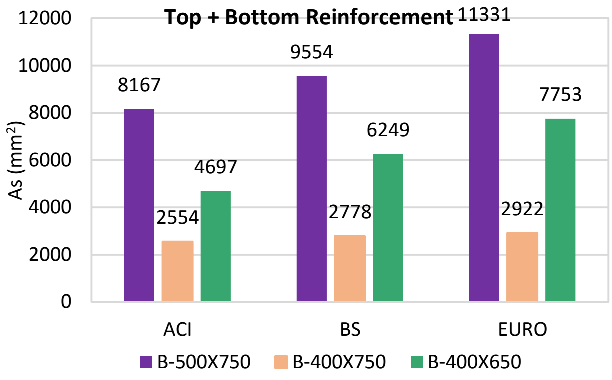

Figure 10. Beams reinforcement

The total amount of longitudinal reinforcement was also compared between three design codes. It was found that Euro code required less reinforcement of about 183 tons as compared to ACI and 200 tons less than building designed by BS code. The comparison between three codes is shown in Table 3.

Table 3. The comparison of reinforcement

Reinforcement Comparison (Weight in Kg)			
	ACI	BS	EURO
Columns	67,598	81,484	64,362
Beams	280,522	334,593	387,196
Coupling Beams	73,784	86,949	60,791
Shear Walls	480,852	412,804	204,048
Total Sum (Kg)	902,756	915,830	716,396

3.2 MCE-Level Nonlinear Response History (NLRHA) Analysis

The detailed NLRHA procedure was carried out using 7 pairs of MCE-level ground motions. It is observed that the computed base shear for Euro code is lower than those of ACI & BS codes in both X and Y directions (Figure 11).

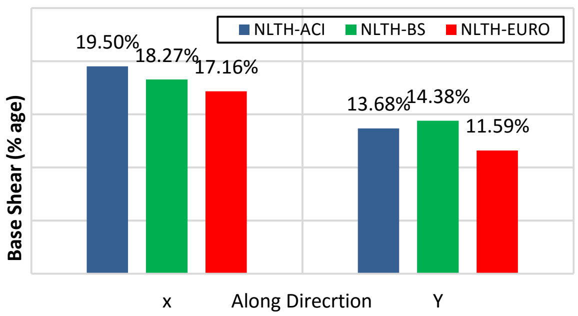

Figure 11. Nonlinear (NL) base shear expressed as a percentage of total seismic weight

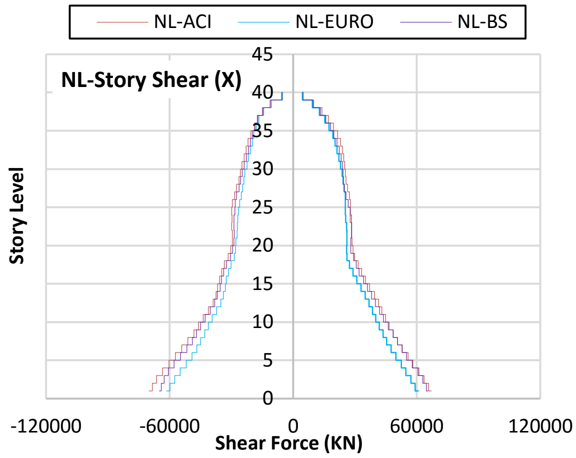

Figure 12. NL story shear (X-MCE level)

Figures 12 and 13 show the comparison of story shear and overturning moments in both X and Y-directions.

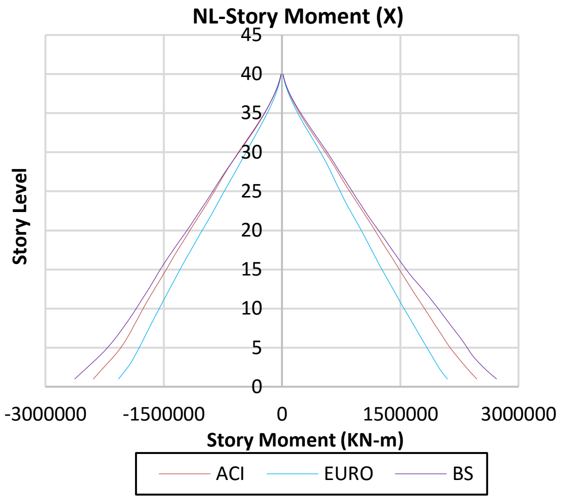

Figure 13. NL story moment (X-MCE level)

Under MCE level earthquake, the story displacements and drifts (averaged value from 7 pairs of ground motions) in both X & Y direction were compared among three models. Mean values of peak transient drift ratios were also compared under MCE level earthquakes and were checked against the limit of 0.03. The maximum story drift ratio from any ground motion was compared against the limit of 0.045. It is observed that all models performed satisfactorily in transient drifts and residual drift ratios and remained within the acceptable limits (Figures 14 and 15).

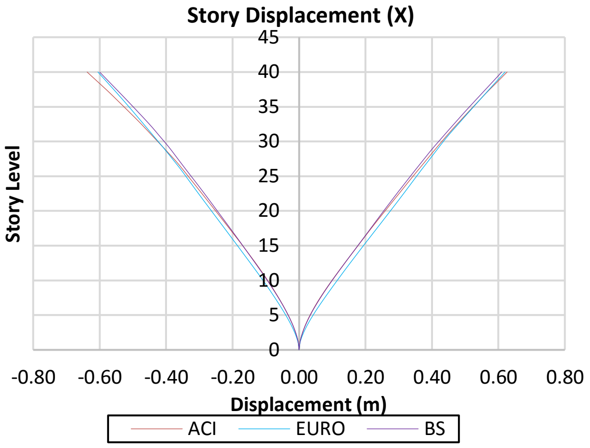

Figure 14. NL story Displacement (X-MCE level)

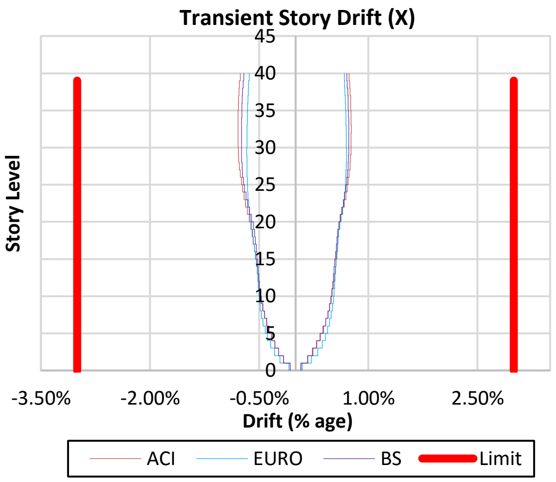

Figure 15. Transient Story Drift (X-MCE level)

4 Conclusions

This study presented the design and expected seismic performance of a case study high-rise building according to three most widely used building codes (ACI 318/ASCE 7-10, BS 8110 and EC-2/EC-8). The building is designed separately for three codes following their prescribed load combinations, cracked stiffness modifiers and seismic design factors. Then, the detailed performance evaluation of the building (separately designed for each building code) was carried out using the nonlinear response history analysis (NLRHA) under different input ground motions. Based on obtained results, a comparison of three building codes is presented in terms of the design, seismic performance and economic considerations. It is observed that all of structural members evaluated from three models are within allowable limit and performed satisfactorily under MCE level. However, designing a building by Euro code can save 185 tons of longitudinal steel as compared to building designed by ACI & BS codes. Therefore, Euro standards can comparatively serve to be the most economical design codes for the site specific hazard at the site of case study building (Makati city, Philippines).

5 References

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