

# Evaluation of Performance-Based Analysis and Design of 44 Stories RC Building Based on EN1998-1 Building Code

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## Abstract

*Inadequate seismic design regulations have a substantial detrimental influence on the overall performance of a structure. The existing code-based prescriptive reinforced concrete design method adopted from developed countries will lead to the failure of structures. Performance-based design (PBD) is a seismic design approach widely used to assess existing buildings and earthquakes for various tall buildings. In this paper, the seismic performance of 3D reinforced concrete models designed per Ethiopian ES8-15 complies with the standards of Eurocode 8-2004 (based on EN1998-1) earthquake code recommendations. This study used sample linear and nonlinear models of 44 stories. It is located in Ethiopia's capital city, Addis Ababa. RC properties are analysed with ETABS vs. 19 software. Response Spectrum Analysis (RSA), Linear Dynamic Time History Analysis (LDTHA) and Classical Modal Analysis with eleven ground accelerations selected from the PEER website. To scale the selected ground motions with target response spectrum as per ES8-15 elastic spectrum type I, both SeismoMatch and ETABS vs. 19.0.0 software were used. The comparison parameters include maximum story displacement, inter-story drift ratios, shear force, overturning moments, and the fundamental period of the buildings for 1st and higher modes. As per Classical Modal Analysis, RSA and LDTHA analysis results of the sample linear 44-story building were found. The result shows that the four global responses of the structure are higher for LDTHA than for the RSA analysis result. The static nonlinear analysis (pushover) methodologies of FEMA 356, ASCE 41-17, and ATC 40 requirements are used to assess their seismic performance. In addition, Nonlinear Time History Analysis (NLTHA) is used to verify the Static Pushover Analysis (SPO) results. The stiffness of the model, the performance levels LS, IO, CP, the target displacement, and the patterns of the plastic hinges are the areas of comparison. The results show that the structures' global and local performance is very similar. Despite this, there were a few notable inconsistencies with shear force and overturning moment capacity results for future earthquake assessment. The study highlighted the benefits of all analysis types except ELF for future research. This comprehensive research process instils confidence in the validity and reliability of our findings.*

**Keywords:** DBE, PBD, MCB, NLTHA, Overturning Moment, Story Drifts, Story Shear, Story Displacement, SPO

## 1. INTRODUCTION

The research details the entire design and operation of a 44-story seismic sample model in accordance with Ethiopian Seismic Design ES8-2015 (hereafter referred to as "ES8-15"), as well as other applicable building regulations based on European Standards 1998-191 and Eurocode 8-2004 [1]. The analysis which was performed on 44-stories model structure, were modal analysis, RSA (Response Spectrum Analysis), and Linear Time History Analysis (LDTHA). Additionally, Static Pushover Analysis (SPO) and Non-Linear Response History Analysis (NLTHA) were done on a 44-story randomized nonlinear sample structure to determine global and local responses such as shear, moment, stiffness, displacement; Comparable areas include the formation of plastic hinges, static and dynamic pushover curves. Ethiopia's rapid appearance of high-rise structures raises worries about the country's present planning and seismic restrictions. Ethiopia lacks a seismic design code, relying instead on European standards [1].

Ethiopia, is susceptible to earthquakes but of a smaller magnitude than on any other continent; The eruption occurred in the Rift Valley, which cuts through the center of Ethiopia. Simultaneously, the region is generating an increasing number of significant economic cities. This may be disastrous for impoverished nations like Ethiopia; which are not prepared for earthquakes like the one with large magnitude that occurred in Haiti. Although Ethiopia doesn't have its own earthquake code, it has embraced the codes used in industrialized western nations.

Additionally, the most recent Ethiopian earthquake code, ES8-2015 (hence referred to as "ES8-15"), as well as additional significant codes are European Standards EN1998-1 which are the same as Eurocode 8-2004 [1]. Gouin published the first earthquake-based map of the possibilities in 1976 as a study of seismic risk assessments in limited regions of Ethiopia, which aided in the development of the first Ethiopian building code, ESCP-1: 1983. Additionally, Kebede and Asfaw examined the map in 1996, and the conclusions were included in the second nation-building code EBCS-8: 1999. Kebede and Van Eck reviewed the dangerous characteristics of Ethiopian and neighboring earthquakes in 1997 and concluded that there were no significant differences in the map and effects of the 1996 Kebede earthquake hazard map; however, it is believed that they analyzed the spectral response in other cities and industrial areas [2].

Additionally, [2] examined an earthquake hazard map for Ethiopia and adjacent countries in 1999, examining the influence of rock formation on a 10% exceedance for over a 50-year period. Later, an examination of the potential for earthquakes in

Ethiopia and neighboring countries incorporates the Poisson earthquake model and the related catalog, which Ayele reported in 2017; 475 return time was used to develop Ethiopia's third-generation building code. Ethiopian research to yet has had a little regional impact or inadequate reaction in terms of topography, groundwater response, or slope. *As a result, the Ethiopian earthquake hazard map needs incorporation of a comprehensive examination of groundwater changes or local soil conditions, climate and slope impacts, groundwater hydrology, operational mistakes, slope and other necessary parameters.* Finally, the further interdisciplinary study is required to enhance the Ethiopian hazard map (e.g., logical tree considerations) [2]. Ethiopian high-rise building design and construction are still in their infancy, and the authorities are worried about the consultant design quality. Since 2005, a variety of initiatives targeted at improving the local building sector have been implemented. However, owing to the absence of such measures, the status of the domestic building sector continues to worsen. Local contractors and managers lack the necessary skills, state-owned firms are inefficient, corruption exists, unsustainable employment possibilities, technology is antiquated, and supporting policies are lacking. Unfavorable economic circumstances, for any reason, are all impediments to adoption of building code [2].

## 2. RESEARCH QUESTIONS

- Are the results of RSA and LDTHA analysis identical or different in accordance with Ethiopia's most recent earthquake code, ES8-2015, which is equivalent to Eurocode 8-2004?
- Are the seismic performance assessment and validation of performance-based design approach as per FEMA 356, ASCE41-17 and ATC 40 requirements using Nonlinear Time History Analysis-(NLTHA) & Pushover Analysis-(SPO) results are the same or different?

## 3. THE RESEARCH'S RELEVANCE AND IMPORTANCE

This study aims to advance our knowledge of design issues associated with long-term earthquake-resistant structures and their structural integrity. In addition, it will assist in assessing and understanding ground movement data which includes pick ground velocity (PGV), pick ground acceleration (PGA), spectral acceleration (SA), and other global responses. We studied base acceleration, settlement analysis, pressure distribution, behavioral enhancement, lateral movement, and other problems in RSA study. In addition, this paper aims to explore on the PBD approach, based on (SPO)Nonlinear Statics pushover; and PBD methodology, based on (NLRHA) Nonlinear Response History Analysis. These are the pillars on which the PBD analysis is based. In addition, indirect inelastic studies, quantitative analysis, time history analysis, comprehensive analysis, and model response spectrum analysis were included. These analyzes include participatory features, mass participation and distribution, combination of models, and diaphragm analysis. This information helps engineers working in high-rise buildings to take the necessary steps to solve the design problems of the earthquake and to overcome obstacles.

## 4. LITERATURE REVIEW

Increased emphasis on decoupling structure designs from conformance to prescriptive needs assessment, especially on stiffness, materials, cost, strength, and configuration, has created impetus towards adopting design paradigms that are premised on performance objectives [3]. The efficacy of sustainable and resilient structure designs with specific performance expectations pegged on the spatial and temporal user needs and environmental dynamics has been attested extensively in the literature [3]. Empirical analysis of the performance scale for the new design of structures indicates superior thermal performance [3], improved load-carrying capacity [4], higher durability [5], and impressive response to seismic disturbances [6][7][8]. Performance-based structure designs, the high structural and functional performance notwithstanding, exhibit defragmented implementation criteria due to variability in spatial and temporal performance needs across and along geographical contours.

The resultant incompatibility of the performance-based structure designs between geographical regions introduces complexities in computing loading factors, dead load, wind load, economic value, and design analyses of structures subjected to similar performance conditions [9]. Despite these challenges, the design paradigm offers a quantitative advantage in localizing reinforced concrete (RC) codes and standards, which ultimately increases their responsiveness to local conditions [10]. The transference of the structure design codes between countries and regions can be achieved by adapting to the destination environment to create seamless conformity [11]. Comparative analysis of ACI 318-08 and AASHTO LRFD design criteria for concrete structural designs by [12] indicates the codes exhibit fundamental variances in moment capacity and flexural strength.

Performance-based structure designs necessitate reverse engineering, where the nature of the desired performance results informs the design criteria. In [13], the shift to Performance-based

structure designs simplifies the mathematical modelling of the structure performance. The efficient integration of the design's mathematical models potentially increases the accuracy of performance estimation [14] and harmonization of the local structural designs [15]. It confers greater regulation and control of the structural performance of RC members in different applications [16][17][18][19][20], accurate estimation of structural failure under various load conditions [21] [19], and sustainable development [22].

Design structures supercharged to conform to prescriptive criteria as demonstrated in [23] demonstrate a deficient capacity to respond to seismic disturbances. Similarly, variations in design codes affect the performance of the structures on key indicators, including the packing capacity of the materials, elastic stiffness, global lateral response, peak strength, and target displacement, among others [24] [25]. Flexible design codes allow cost-effective temporary work designs [26] to retain uniformity, clarity, consistency, and repeatability in structure design and analysis [27][28] and simplify designs [29]. Generally, the impressive performance parameters of the design paradigm facilitate the seismic fragility analysis of the structures [30][31], the temporal dynamic behavior of RC structures [32], and the seismic function of the interactivity between structural and non-structural members [33].

Generally, the intrinsic qualities of the codes are determined by the deliberate trade-off made to achieve the desired standards and market demands. In [34], a comparative analysis of European Structural Codes (Eurocodes) and British Standard Codes shows marked differences in effective area, cost performance, and structural performance. Such differences in design codes are reflective of a local need's assessment of structural performance - RC ductility, longevity, sustainability, and durability - in different load conditions [35][36][37][38][39][40][41][42][43][44][45]. The fundamental principles of performance-based structure design codes provide a platform for optimizing the performance indices of the RC members, steel, components, or their combinations.

## 5. METHODS AND SOURCES OF THE STUDY

Reinforced concrete 44-story multi-storied buildings are analyzed and designed by the specifications described in the Ethiopian Earthquake Design Standard ES8-2015, based on the building code Eurocode 8-2004 and PBD with the same local condition. As shown in **Table 1**, **Figure 1** and **Figure 2** both linear and nonlinear models are analyzed and designed. Following that, seismic analysis was performed using a pushover based on **ASCE 41-17 requirements, FEMA 356 and ATC 40**. Pushover analysis is a practical way to perform seismic analyses in buildings. Compared to conventional elastic analysis, it gives much valuable information about future structural reactions and an understanding of the structural features that influence capacity during major future earthquakes. Additionally, it exposes design flaws that the elastic analysis process cannot capture; for example, it can detect the most critical portions of a structure regardless of its limits. It is suggested as the benchmark for typical models examined, particularly in the first dominant mode. Additionally, nonlinear dynamic analysis was used to validate the pushover static analysis findings. These are essential components of PBD (Performance-based Design) research conducted using the ETABS 2019 program.



Figure 1-44 Story Linear and Non-Linear Sample Building 3D Models.

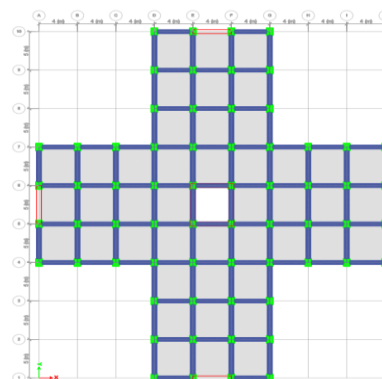


Figure 2- Ground Floor Plan 45mx 36m.

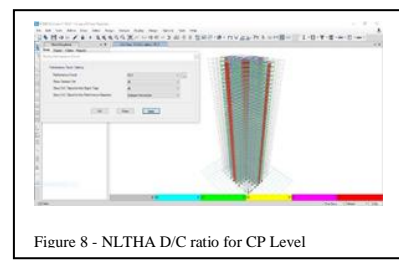
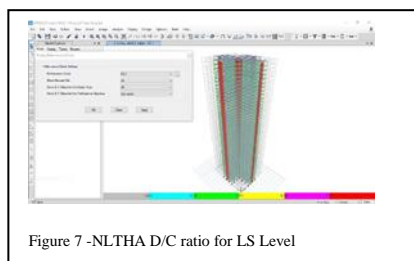
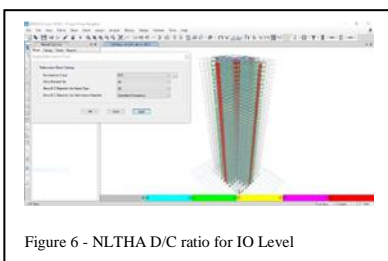
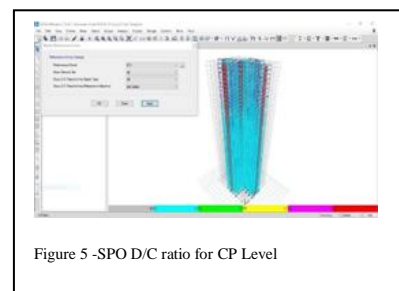
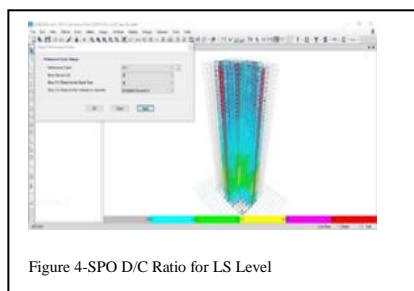
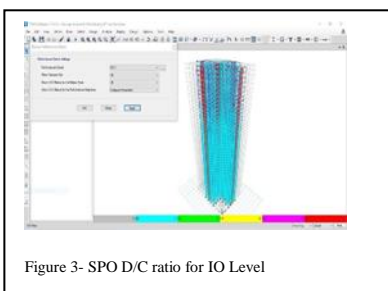
Table 1. General Sample 44 Stories RC Building Detail

Building Detail	44 stories, 132 m
BM section	700x500 mm
Colum Section	850x700mm
Slab Section	150mm
Shear Wall section	200 mm
Building Detail	44 stories, 132 m
28 days Compressive Strength	C-30
Seismic Zone	III
Elastic Modulus, EC	31 x 106 kN/m <sup>2</sup>
Concert unit wight	25 kN/m <sup>3</sup>
Re-bar Steel Strength	S-460/HRB460
Es	200x 106 kN/m <sup>2</sup>
Steel unit weight	78.5 kN/m <sup>3</sup>
Stress-Strain for concrete	H-Rusch formula
Line load on beam	15 kN/m <sup>2</sup>
LL for Dynamic Analysis mass calculation	30 %
28 days Compressive Strength	C-30
Seismic Zone	III
Elastic Modulus, EC	31 x 106 kN/m <sup>2</sup>
Concert unit wight	25 kN/m <sup>3</sup>
Re-bar Steel Strength	S-460/HRB460
Es	200x 106 kN/m <sup>2</sup>
Steel unit weight	78.5 kN/m <sup>3</sup>
Stress-Strain for concrete	H-Rusch formula
Line load on beam	15 kN/m <sup>2</sup>
LL for Dynamic Analysis mass calculation	30 %
DL	2.0 kN/m <sup>2</sup>
LL	3.0 kN/m <sup>2</sup>
Wall load on Beam	15.0 kN/m <sup>2</sup>
CLMOA, LTH, RS, SPO & NLTHA procedure	ES8-15, FEMA 356, ASCE 41-17 and ATC 40.

## 6. RESULT AND DISCUSSION

### 6.1. Plastic Hinge Formation for different performic point levels

Plastic rotation limits in beams and columns for immediate occupancy (IO), life safety (LS), and collapse prevention (CP) are shown in **Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, and Figure 8**; which shows the plastic hinge result at the end of the push steps. The structure is shown with a 2 % target displacement in the roof due to the uniform load pattern.



Plastic hinges were commonly introduced in all part of the building structures for both analysis and conforming to all load patterns. Additionally, when the structure was under the same ground load pattern, plastic hinges were usually appeared on the GF and FF story column. All models, regardless of number of issues, showed the same trend. With the exception of a few systems, the beam-sway method was the famous method, indicating that design meets the predicted requirement of a strong - weak column.

The SPO hinge pattern of the 44-stories model frame result for NLTHA hinge pattern of the 44-story model structure. Although most of the designed columns as per ES8-15 is within the LS and IO Levels, several hinges have passed the CP level on the first to 24th floor, as opposed to the upper floor in the case of SPO than NLTHA. This demonstrates more hinges are formed at the lower part of the model. In addition to that, the result shows that the 44 story RC building **D/C ratios for the performance objective-collapse prevention (CP)** of SPO and NLTHA, respectively; and for this particular sample building, all the frames fall in between 0 to 0.5 safe zone with respect to IO and CP levels.

Similarly, the result shows that 44 story sample RC building **D/C ratios for the performance objective- immediate occupancy (IO)** for SPO and NLTHA respectively, and for this particular sample building some frame elements found in between 0 to 0.5 zone and for 4th to 13 floors some frames fall in between 0.5 to 0.75 zone. Again, in the same region some frames fall in between 0.7 to 0.9 zone, but none of the frames passed CP level in the case of SPO. However, for NLTHA, all the column and beam frame elements fall in between 0 to 0.5 safe zone with respect to IO and CP level.

In the same way the result shows the 44 story RC building **D/C ratios for the performance objective -Life Safety (LS)** for SPO and NLTHA, respectively; and for this particular situation, all frames fall in between 0 to 0.5 zone; none of the frame elements passed this threshold for both analysis methods.

In general, plastic hinge formation of columns in 44-storey buildings under SPO analysis are much larger and closer to the life safety (LS) threshold and few areas observed that collapse faster than NLTHA for all structures exposed to equal roof displacement. Additionally, when SPO-designed structures are compared to NLTHA-designed structures, the creation of plastic hinges occurs earlier in beams than in columns. As a result, it is determined that the ES8-15 structure maintains a strong column-weak beam configuration. Additionally, this demonstrates that the stiffness distribution in ES8-15 is fairly comparable.

In general, we describe the performance evaluation of all components performed using the two analytical techniques. In addition, they show how total no. of hinges in the structure increased as the model was gradually carried out to achieve the 2% roof drift. For example, part of the hinge development is greater in IO than in LS, CP limits. Although all frames designed by ES8-15 using SPO and NLTHA techniques are below CP limits, more than 3% of 44-story frames exceed these limits in both tests. In general, hinges formed with a uniform load pattern are more important than Mode-1 hinges.

## 7. CONCLUSION

In this study the seismic performance of linear and nonlinear 44-story RC sample buildings was designed according to the **ES8-15, FEMA 356, ASCE 41-17, and ATC 40**, recommendations using SPO and NLTHA analysis methods. A complete analysis of the nonlinear timeline history with 11 selected EQ was performed on a 44-Stories RC structure, which ensures good agreement with static analysis. Overall, the findings of this paper are presented as follows: -

- (1) As per Classical Modal Analysis, RSA and LDTHA analysis result of the sample linear 44-story buildings. The result show that the four global responses of the structure are higher for **LDTHA** than for the **RSA** analysis result.
- (2) For 44-story buildings, LDTHA shows a Maximum Story Displacement of 25.68 %, Maximum inter-story Drift ratio of 25.68 %, Story Shear of 15.35%, Story Overturning Moment of 27.5%, and Fundamental time period of 2 % higher than RSA results observed.
- (3) The first mode of the fundamental period found in classical modal analysis for 44 stories was 3.956 sec. However, the result found from the RSA analysis was 3.806 sec. similarly, the fundamental period for DLTHA was found to be 3.883 seconds.
- (4) In addition, for all three analyses, the first two modes are translational, and the third mode was torsional, as required by different coda and guidelines.
- (5) Pushover analysis result for roof target displacement of up to 2% under ATC 40 requirement of Life Safety (LS) performance level were examined and the frames reveal a smaller capacity curve as NLTHA. This proves that the global response results of pushover analysis can be verified using NLTHA.
- (6) The result also showed that formation of column hinges is slightly higher in SPO columns than in the NLTHA column. **It shows the differences in power dissipation methods** between the two model analysis types. Nonetheless, the above sample example results of SPO and NLTHA findings for RC buildings gives important information since the SPO results are compatible with the NLTHA results, suggesting that SPO analysis is practical for the investigated model.

(7) The result also showed that plastic hinge formation in columns in 44-storey buildings under SPO analysis are much higher and closer to the life safety threshold, and collapse faster than NLTHA for all structures exposed to equal roof displacement. Additionally, when SPO-designed structures are compared to NLTHA-designed structures, plastic hinges are created earlier in beams than in columns. As a result, it is determined that the structures designed by ES8-15 maintains a strong column-weak beam configuration. Additionally, this demonstrates that the stiffness distribution in ES8-15 is fairly comparable.

(8) Lastly the result also showed the 44 Story RC sample buildings **ASCE 41-13 SPO performance assessment graph** with the target Displacement and Base Shear results of **114.751 mm** and **16694.9227 (kN)**. In addition to that, the performance point result found as per **FEMA 440 EL** was target displacement **120.294 mm** and Base Shear **17455.2248 kN** with a slighter difference from the ASCE41-13 result. The result was verified with NLTHA, and the **dynamic pushover curve** gives the exact target displacement, which is 2% of the Height of the building, which was around **2358 mm** for a maximum shear force of **0.411445 \* 10<sup>6</sup> KN**; the nonlinear static result gives **2464.3 mm** for a maximum shear force of **0.126002 \* 10<sup>6</sup> KN**. This demonstrates that the performance of the sample building result was verified with NLTHA, and it gives a satisfactory result. Hence, this result shows that the use of SPO is adequate in situations where finding actual ground acceleration is difficult. Thus, until the performance point evaluation study is completed, it may be impossible to determine whether ES8-15 adheres to Eurocode 8-2004 intended structure satisfy or no longer for future seismic force in the nonlinear variety range with the roof drift of 2% may exceed the design limit. It's also worth noting that one of the primary goals of seismic performance analysis is to identify any design flaws. Nonetheless, it is obvious that the ductility of ES8-15 has been exaggerated.

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