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**Research Article**

# Evaluation of performance-based earthquake engineering in Yemen

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**ABSTRACT**

Building codes follow a common concept in designing buildings to achieve an acceptable seismic performance. The objective underlying the concept is to ensure that the buildings should be able to resist minor earthquake without damage, resist moderate earthquake with some non-structural damage, and resist major earthquakes without collapse, but some structural as well as non-structural damage. This study aims to evaluate the performance-based seismic to come up with necessary recommendations for both future practices, essential review, and restoration of existing structures in Yemen. To do this real case studies incorporated, and nonlinear pushover analysis is carried out. The analysis results presented and then assessed to find out the conformity with the required performance. The structural sections assumed at the beginning of the design, then the design repeated many times to achieve the selected performance criteria (the plastic hinge properties and the maximum displacement).

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## 1. Introduction

Earthquakes have long been feared as one of nature's most terrifying phenomena. Early in human history, the sudden shaking of the earth, the death, and destructions that resulted were mysterious and uncontrollable (FEMA 454, 2006).

It may be said that the occurrence of earthquakes is well understood and must be accepted as a natural environmental event. They represent one of the periodic adjustments that the earth makes in its evolution. Arriving without warning, the earthquake can, in a few seconds, create a level of death and destruction that can only be equaled by the most extreme weapons of war. This uncertainty, combined with the terrifying sensation of earth movement, creates a fundamental fear of earthquakes (Ishihara, 2003; FEMA, 2006).

Yemen is generally considered along with its history among countries which subjected from time to time to different natural disasters that comprised earthquakes, flowage, landslides, etc. Besides, many of its areas are located within those recognized with high volcanic activities, and; moreover, several activities are expected to hit back (Almunifi, 1995; Alyafei, 2007; Kulaib et al., 2008; Almunifi and Alameri, 2019).

The location of Yemen in the south of the Arabian plate makes it exposed to seismic attacks. That hazards due to the tectonic Situation of Arab Plate, which make Yemen close to seismic activities in the Red Sea and the Gulf of Aden. Fig. 1 shows the tectonic situation of Arab Plate which gives an illustration of seismic hazards in Yemen (Almunifi, 1995).

Seismic hazards of Yemen are not in the same level in all specialists' considerations (Almunifi, 1995; Alyafei, 2007; Kulaib et al., 2008; Almunifi and Alameri, 2019). Also, there is no formal standard data to specify the hazard magnitude in the different zones in the country. The Uniform Building Code UBC (1997) categorized the capital "Sana'a" in the seismic zone (Z=3) whereas some of the other searches conclude to that hazard in Yemen is characterized by low to moderate seismic activities (Alyafei, 2007; Kulaib et al., 2008).

Despite that seismic hazard in Yemen might not in highly intensive magnitude, the seismic risk is still present. However, Seismic risk is not a function of hazard only, it is based on the vulnerability of structures as well.

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So, although that some researchers conclude that Yemen considered in low to moderate earthquake hazards, and the majority of Yemeni regions might not expect to have a high intensive seismic attack. However, due to wrong construction practices and ignorance for earthquake resistant design of buildings; many of the existing buildings in Yemen might be vulnerable to future earthquakes. That means if the seismic hazard is probable, seismic vulnerability of structures should be considered (Almunifi, 1995; Aldafiry 2005; Alyafei, 2007; Kulaib et al., 2008).

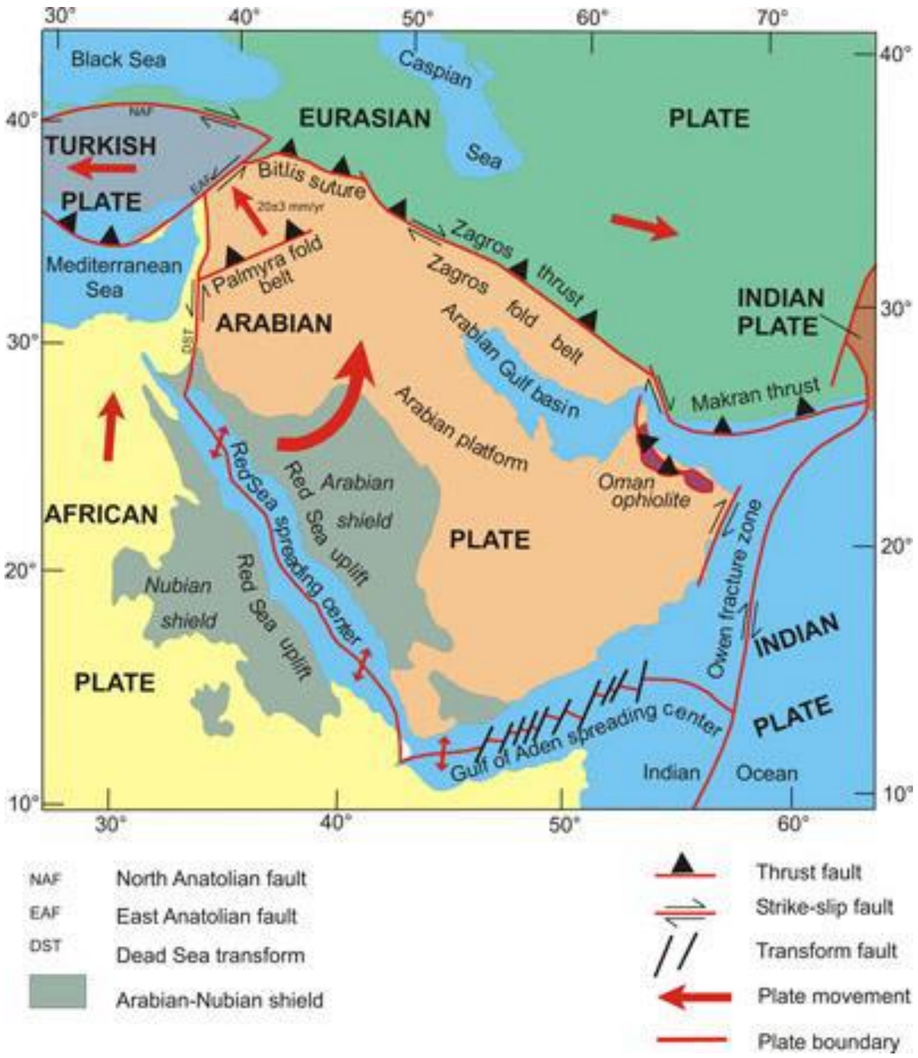


**Fig. 1.** Tectonic situation of Arab Plate.

Performance-based seismic design (PBSD) is a comparatively new concept that was at first developed to be used in predicting the upgrade strategy required for existing buildings. However, it's equally applicable to checking the design of new buildings and may be a paradigm shift in seismic engineering design moving away from the prescriptive code approach. It's presently an evolving methodology with the key difficulties being to reach globally acceptable precise definitions of performance objectives and to quantify performance levels (Manohar and Madhekar, 2015). Generally, in displacement-based or force-based methods of seismic design codes, it is presumed that the structure enters the inelastic phase to dissipate the seismic energy to bear the lateral seismic loads or to attain the performance objectives. In this case, the residual deformations due to inelastic behavior, which are considered as "damages", would depend on the number and layout of the seismic load resisting members and the magnitude of seismic load. These damages would remain in structure in the forms of story drifts or members' deformations (Shoeibi et al., 2017). A lot of studies recommended the performance-based seismic design method to evaluate the damage state of the building. Zeris and Repapis (2018) studied the seismic performance of existing RC buildings designed to different codes and concluded that buildings of the 90s, designed to modern codes exhibit an exceptionally good performance. Ashkezari (2018) proposed a performance based strategy for design of steel moment resisting frames under far range blast loads. For this purpose, he presented an algorithm to calculate the capacity modification factors of frame members in order to simplify design of structures subjected to blast loading. The method provides a simplified design procedure in which the linear dynamic analysis is preformed, instead of the time-consuming nonlinear dynamic analysis. Turker and

Gungor (2018) studied the Seismic performance of low and medium-rise RC buildings with wide-beam and ribbed-slab, The results indicated that the predicted seismic performances were achieved for the low-rise (4-story) building with the high ductility requirements and addition of sufficient amount of shear-walls to the system proved to be efficient way of providing the target performance of structure. Inel and Meral (2016) evaluated seismic performance of existing low and mid-rise reinforced concrete buildings by comparing their displacement capacities and displacement demands under selected ground motions experienced in Turkey as well as demand spectrum provided in 2007 Turkish Earthquake. The results show that the significant number of pre-modern code 4- and 7-story buildings exceeds LS performance level while the modern code 4- and 7-story buildings have better performances. The findings obviously indicate the existence of destructive earthquakes especially for 4- and 7-story buildings. Significant improvements in the performance of the buildings per modern code are also obvious in the study. Almost one third of pre-modern code buildings is exceeding LS level during records in the past earthquakes. Jiang et al. (2017) studied the Seismic performance of high-rise buildings with energy-dissipation outriggers. Two high-rise structures, one with conventional outriggers, the other with energy-dissipation outriggers, were designed. The results show that compared to the ordinary structure, the seismic performance of the new structure is improved significantly. Gorji and Cheng (2017) investigated the plastic behavior and mechanisms of steel plate shear walls with outriggers (SPSW-O), it was shown that such systems are considerably effective in improving the flexural stiffness of conventional SPSWs. Shoeibi et al. (2017) studied the performance for structures with structural fuse system Analyses results showed that in moderate earthquake hazard level, only fuse members yielded and other structural members remained elastic.

Considering these facts, it is imperative to seismically evaluate the existing building and with the present-day knowledge to avoid the major destruction in future earthquakes. This paper aims to evaluate the performance-based seismic in to come up with necessary recommendations for both future practice, essential review, and restoration of existing structures for any underestimated of such obligations.

## 2. Case Studies

In order to study the local practice of earthquake engineering in Sana'a, the selected case studies are real reinforcement concrete buildings situated in Sana'a city. Buildings of case studies are 10, 16, 20 story. The first case study building (10 stories) has a frame structure system, but the others have a shear walls system.

### *2.1. First case study building (10 story building)*

Figs. 2 and 3 show the elevation and some plans of the first case study building (10 story) used as real case study for this investigation. However, the building utilizes frame structural system in both directions to resist the gravity forces. The cubic strength of concrete is $Fc'$= 300 kg/cm$^2$, and $Fy$=4140 kg/cm$^2$ for concrete reinforcement steel. Columns-beam joints analyzed as rigid joints with full transformation of the moments and shear, structural drawings confirmed that in there details. This arrangement may be taken to decrease any undersigned lateral forces, but this manner lead to decrease the designed moments in the middle of beams and increase the moments in joints, and if the joints are not executed well, high moment will developed in the middle which not include in design. Such cases may lead to design sections less than the proper sections, which make serious dangerous to safety under gravity loads (Elghazouli, 2009).

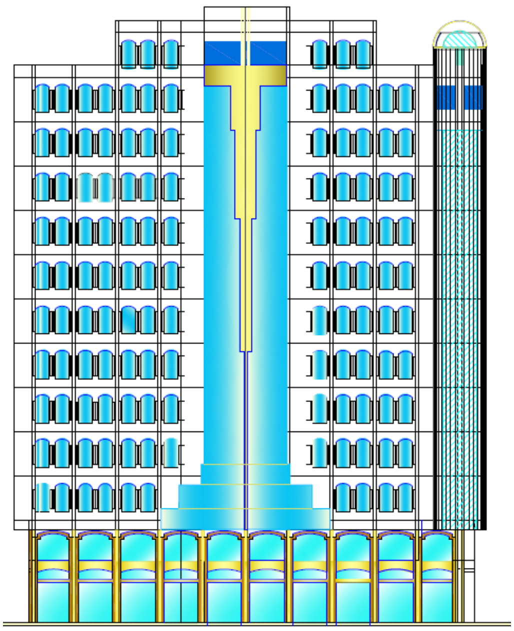

**Fig. 2.** Elevation of the first case study building.

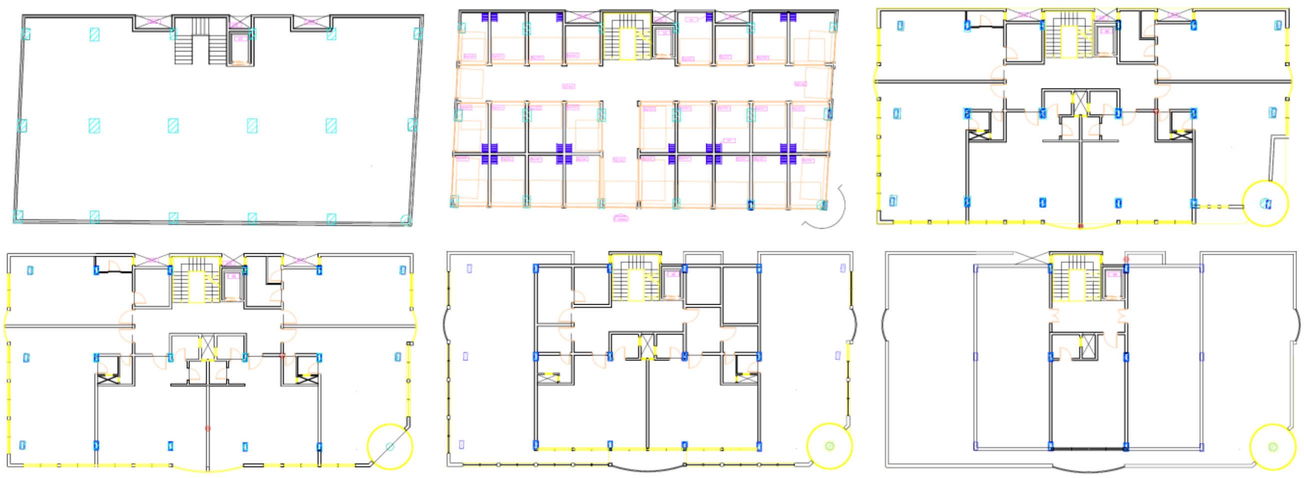

**Fig. 3.** Some plans of the first case study building.

### *2.2. Second case study building (16 story building)*

Figs. 4 and 5 show the plan and elevation of the second case study building (16 story) used; it is situated in Sana'a and it is under construction. The building utilizes a structural system with a dual structural system to resist the lateral forces. Systems are consisting of shear walls and moment-resisting frames in both directions. Lateral forces designed according to the basis of the 1997 UBC Zone 2 (regions of middle seismicity) requirements. The cubic strength of concrete is $Fc' = 400$ kg/cm$^2$, and $Fy$=4200 kg/cm$^2$ for concrete reinforcement steel.

**Fig. 4.** Some elevations of the second case study building.

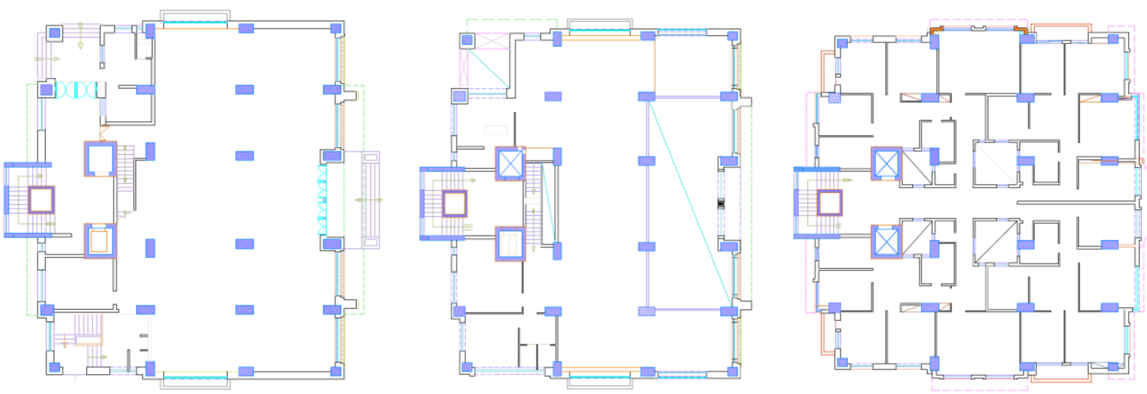

**Fig. 5.** (continued).

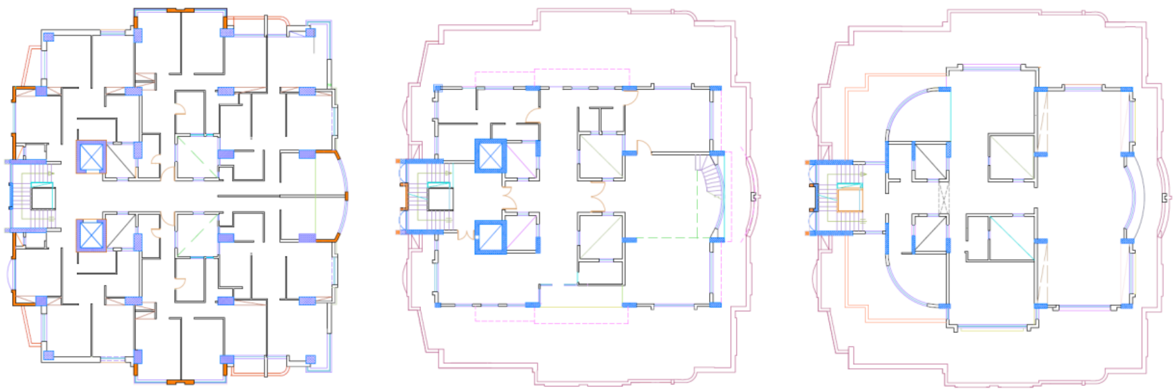

**Fig. 5.** Some plans of the second case study building.

### *2.3. Third case study building (20 story building)*

Figs. 6 and 7 show the plan and elevation of the third case study building (20 story) used. It is situated in Sana'a and it is in design stage. The building utilizes a dual structural system to resist the lateral forces (shear walls and moment-resisting frames in both directions). Lateral forces designed according to the basis of the UBC (1997) Zone 2 requirements.

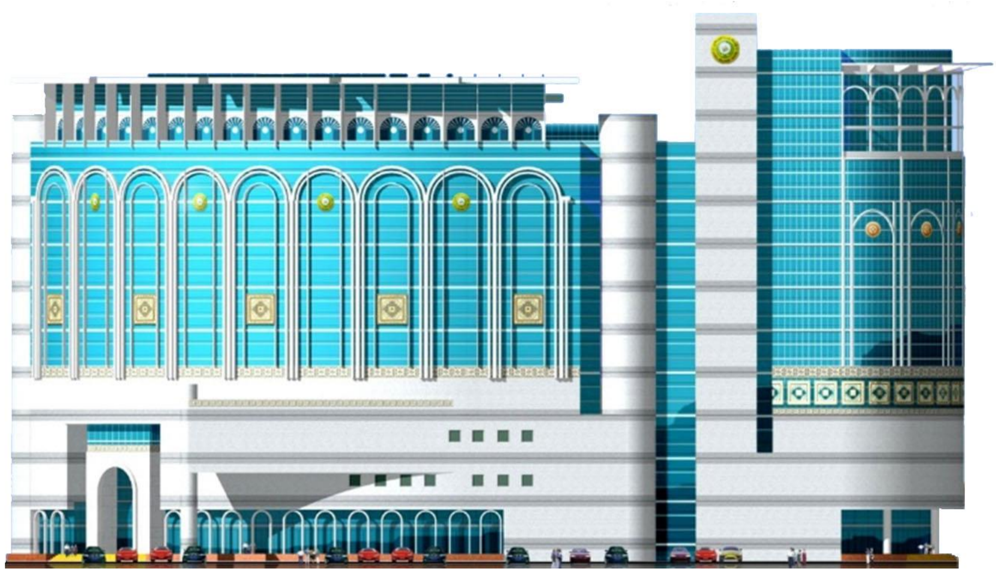

**Fig. 6.** Elevation of the third case study building.

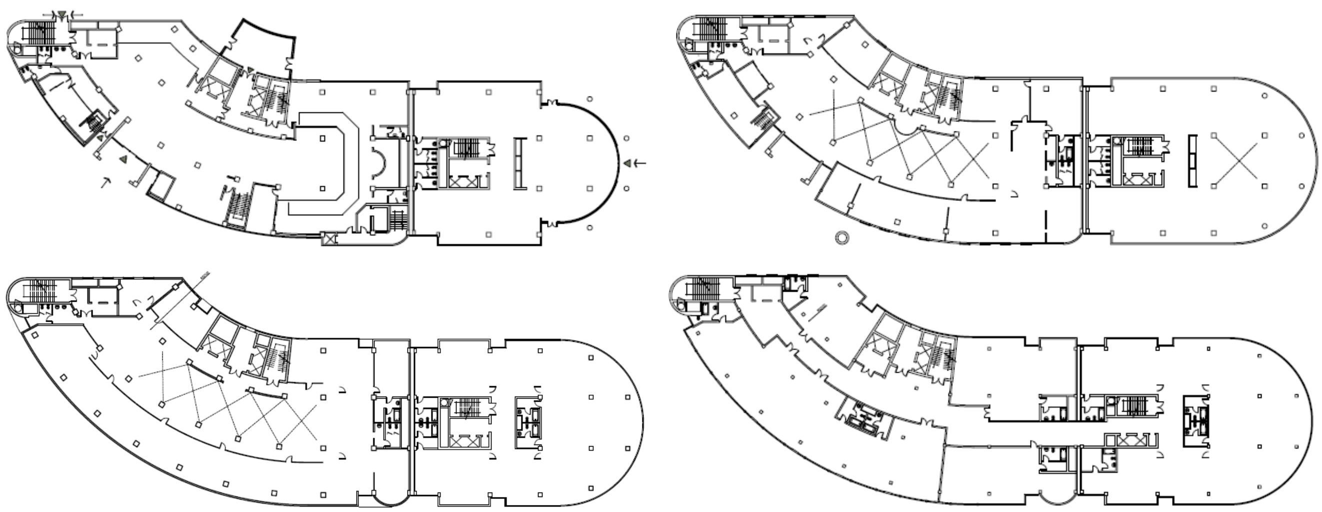

**Fig. 7.** Some plans of the third case study building.

## 3. Non-Linear Static Pushover Analysis

Buildings which used as case studies in this paper are investigated by nonlinear static pushover analysis. The analysis carried by default ETABS nonlinear frame hinge properties. Models used the analysis based to their existing design models with their related specifications, geometric, loads, etc.

### *3.1. First case study building (10 story building)*

Fig. 8 shows the model of the building which developed by ETABS. Earthquake loads has applied in all sides as UBC97 requirements (Z=0.2, Soil Type=SC, R=8.5, I=1). From the static linear analysis results, base shear is $V$=1378.07 kN. Fig. 9 shows pushover analysis results, and relation between the base shear and monitored displacement was drawn.

Results show that pushover accelerations leads to generate hinges in structure which work towards to lose the stability of the structure (Fig. 10).

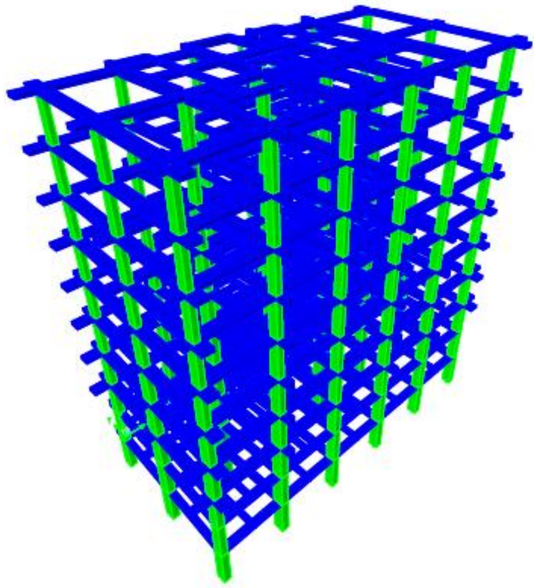

**Fig. 8.** ETABS model of first case study building.

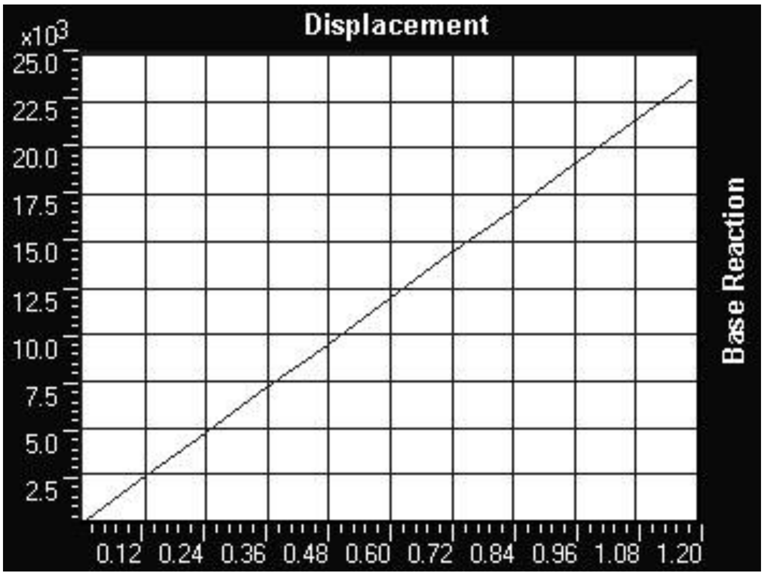


**Fig. 9.** ETABS output of pushover curve.

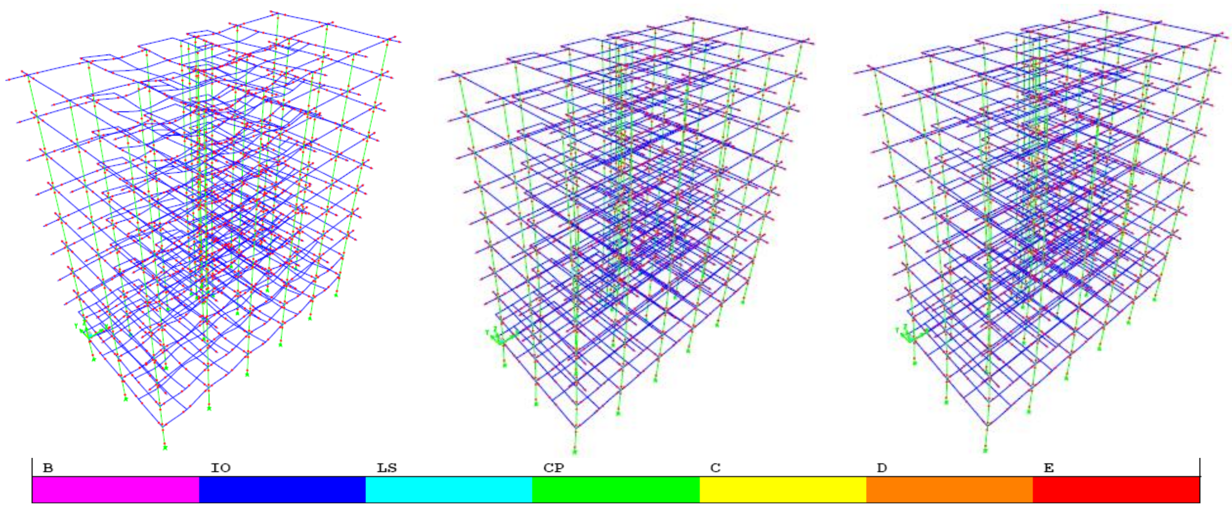


**Fig. 10.** Some steps of pushover analysis and hinges formation (ETABS output).

From intersection of response spectrum and capacity spectrum (Fig. 11), it is deem that the demand curve tends to intersect the capacity curve in elastic response. ETABS identify the performance point indicated to base shear of $V$=6113.784 kN, and target displacement value $D$=0.303 m.

The ratio between base shear of performance point and related shear in elastic is 3 times which suggest acceptable structural behavior. But ETABS identify that the maximum inter-story drift ratio is 2.6%, which suggests "Collapse" performance level according to SEAOC 2000, and "Collapse prevention (S-5)" according to FEMA273 limits.

That result may understandable, because that earthquake requirements not taken in consideration in the design stage. Fig. 12 shows the maximum inter-story drift for case study 1.

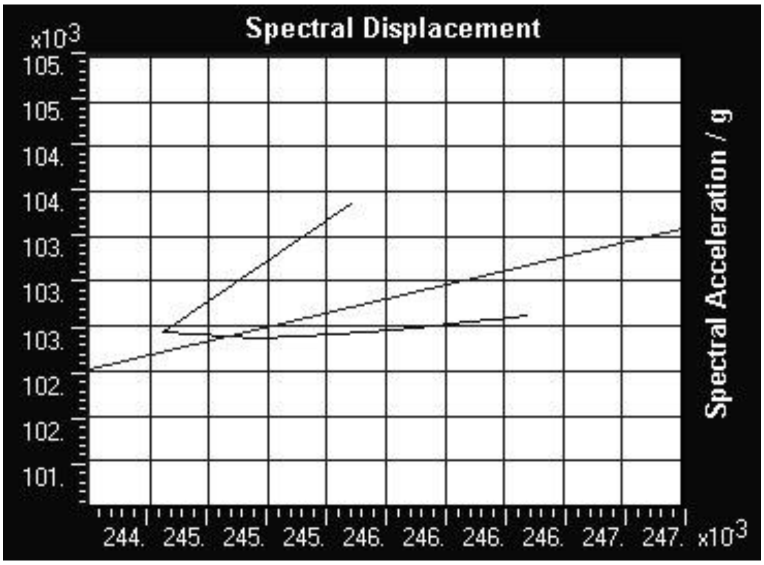


**Fig. 11.** Capacity spectrum and demand spectrum curves (ETABS output).

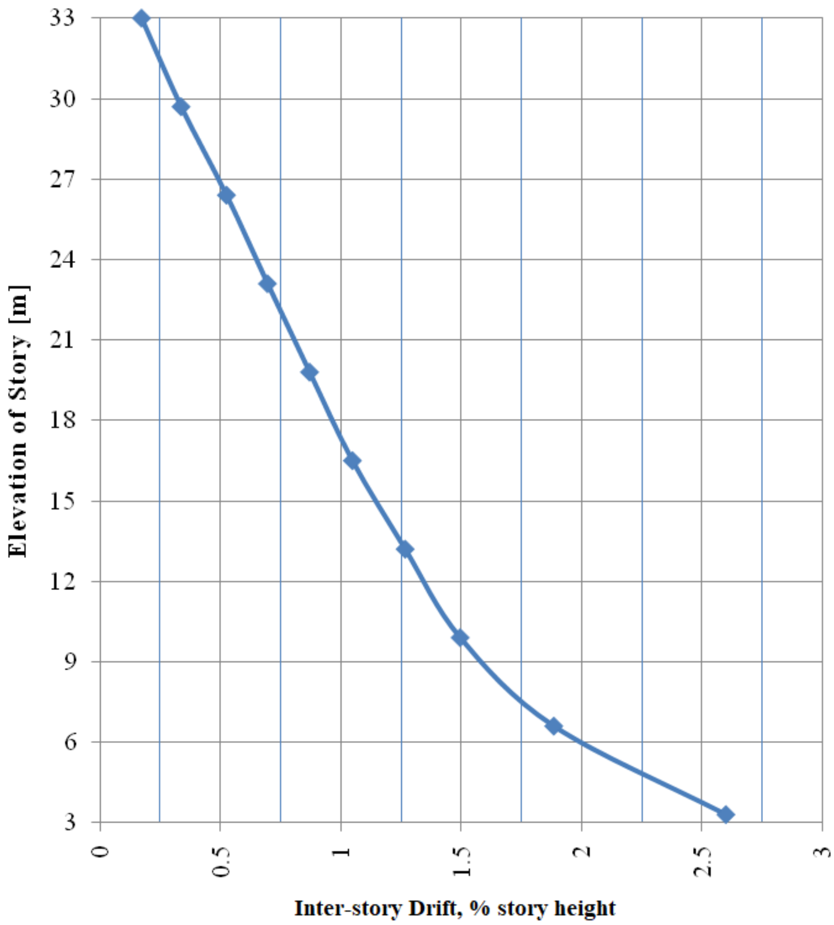


**Fig. 12.** Maximum inter-story drift.

### 3.2. Second case study building (16 story building)

Fig. 13 shows the model of the building which developed by ETABS. Earthquake loads has applied in all sides as UBC97 requirements (Z=0.2, Soil Type=SC, R=8.5, I=1). From the static linear analysis results, base shear is $V$=4607.26 kN. Fig. 14 shows pushover analysis results, and relation between the base shear and monitored displacement was drawn.

Results show that pushover accelerations lead to generate hinges in structure which work towards to lose the stability of the structure (Fig. 15).

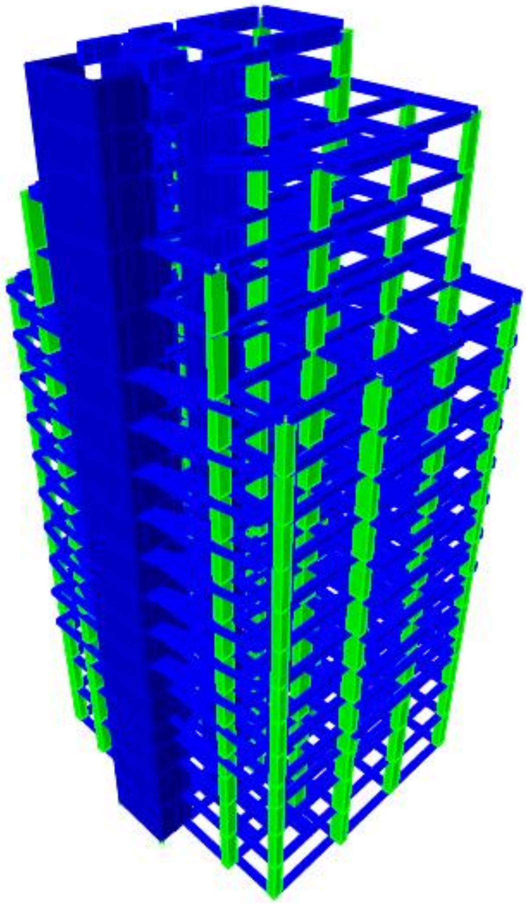

**Fig. 13.** ETABS model of second case study building.

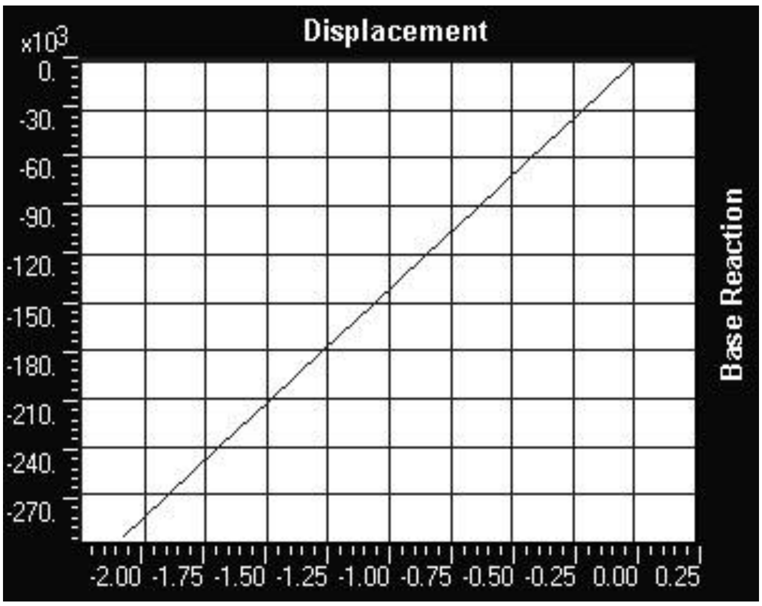


**Fig. 14.** ETABS output of pushover curve.

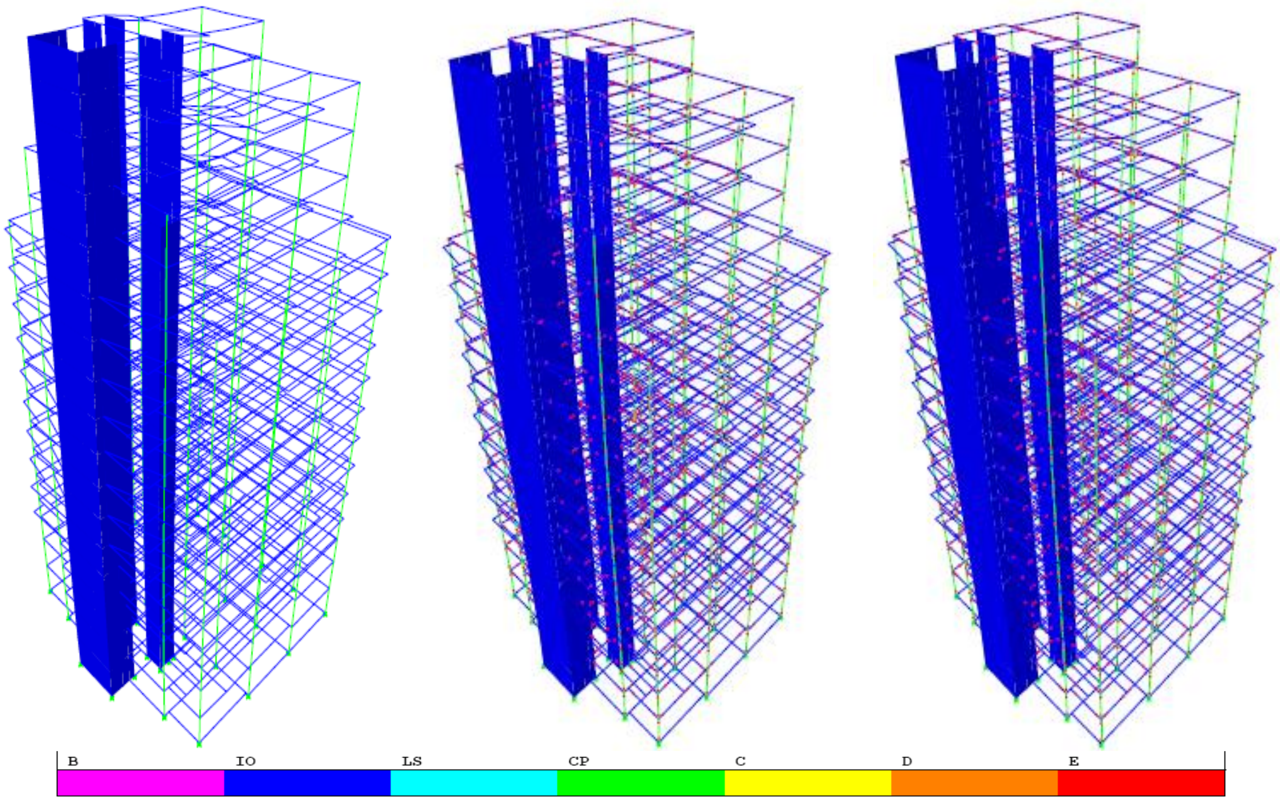


**Fig. 15.** Some steps of pushover analysis and hinges formation (ETABS output).

From intersection of response spectrum and capacity spectrum, it is deem that the demand curve tends to intersect the capacity curve in elastic response (Fig. 16). ETABS identify the performance point indicated to base shear of *V*=23,295.01 kN, and target displacement value *D*=0.165 m.

The ratio between base shear of performance point and related shear in elastic is 5.1 times which suggest acceptable structural behavior. ETABS identify that the maximum inter-story drift ratio is 1.13%, which suggests "Life Safe" performance level according to SEAOC 2000, and "Life Safety (S-3)"according to FEMA273 limits. That result may reasoned that earthquake loads are taken in consideration in the design stage. Fig. 17 shows the maximum inter-story drift of case study 2.

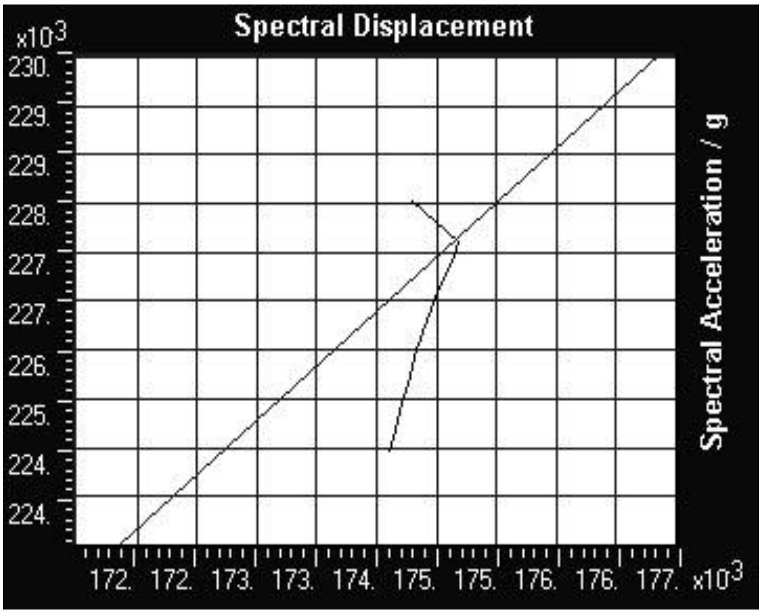


**Fig. 16.** Capacity spectrum and demand spectrum curves (ETABS output).

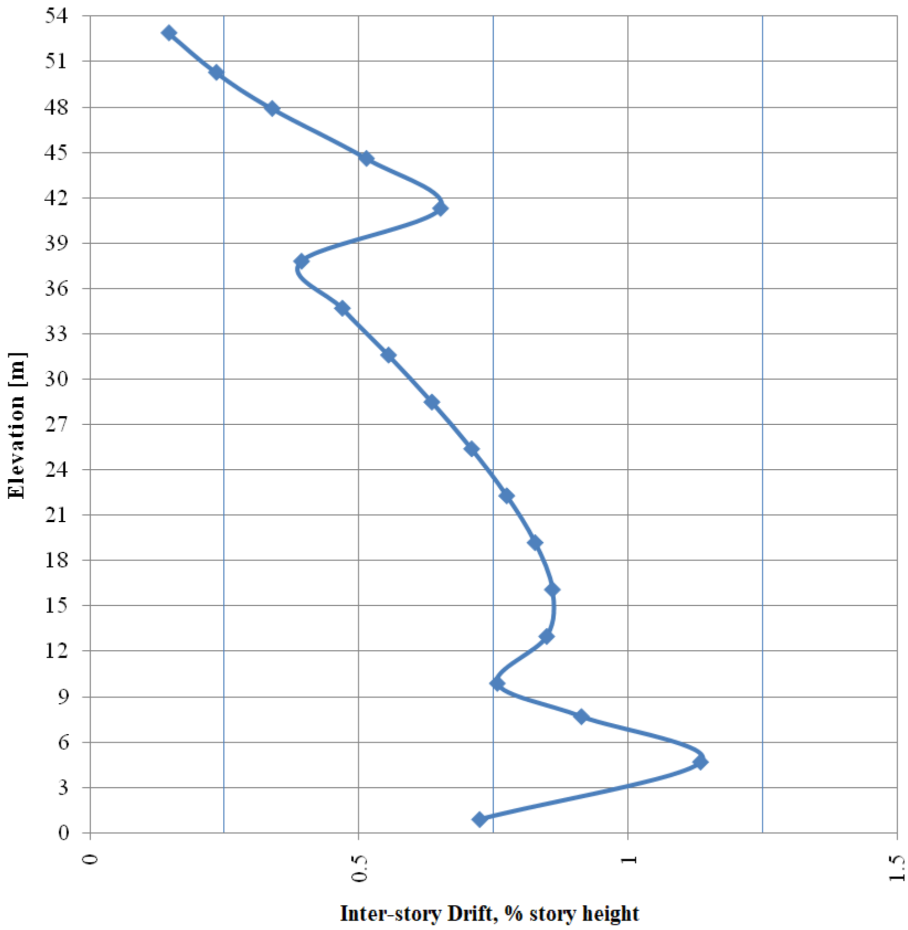


**Fig. 17.** Maximum inter-story drift.

### *3.3. Third case study building (20 story building)*

Fig. 18 shows the model of the building which developed by ETABS. Earthquake loads has applied in all sides as UBC97 requirements (Z=0.2, Soil Type=SC, R=8.5, I=1). From the static linear analysis results, base shear is *V*=7594.28 kN. ETABS results develop pushover curves show the resultant base shear vs. monitored displacement as Fig. 19.

Results show that pushover accelerations leads to generate hinges in structure which work towards to lose the stability of the structure (Fig. 20).

From intersection of response spectrum and capacity spectrum, it is deem that the demand curve tends to intersect the capacity curve in elastic response (Fig. 21). ETABS identify the performance point indicated to base shear of *V*=25,737.34 kN, and target displacement value *D*=0.31 m.

The ratio between base shear of performance point and related shear in elastic is 3.4 times which suggest acceptable structural behavior. The maximum inter-story drift ratio is 0.61%, which suggests "Life Safe" performance level according to SEAOC 2000, and "Immediate Occupancy (S-1)" according to FEMA273 limits. That result may reason that earthquake requirement in regularity and loads are taken in consideration in the design stage. Fig. 22 shows the maximum inter-story drift of case study 2.

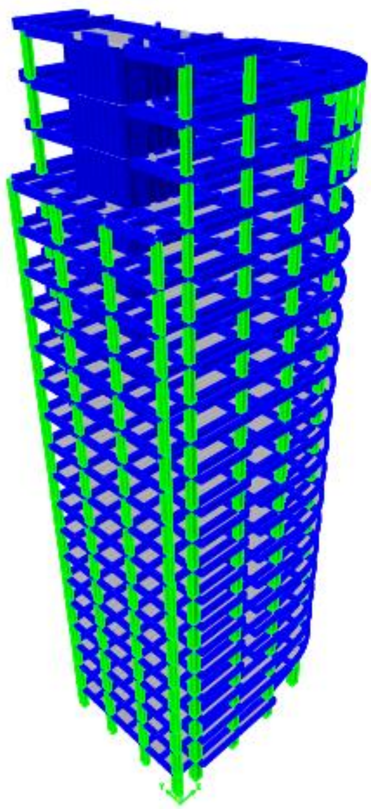

**Fig. 18.** ETABS model of third case study building.

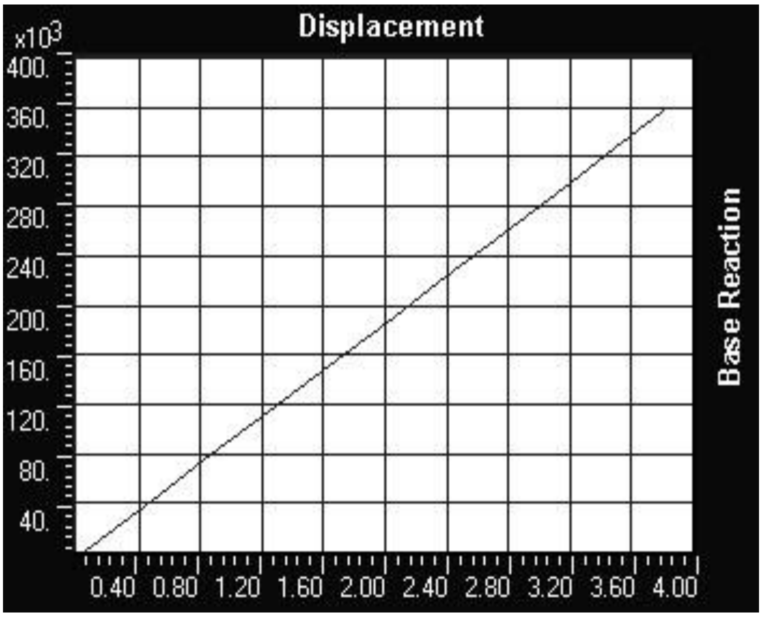


**Fig. 19.** ETABS output of pushover curve.

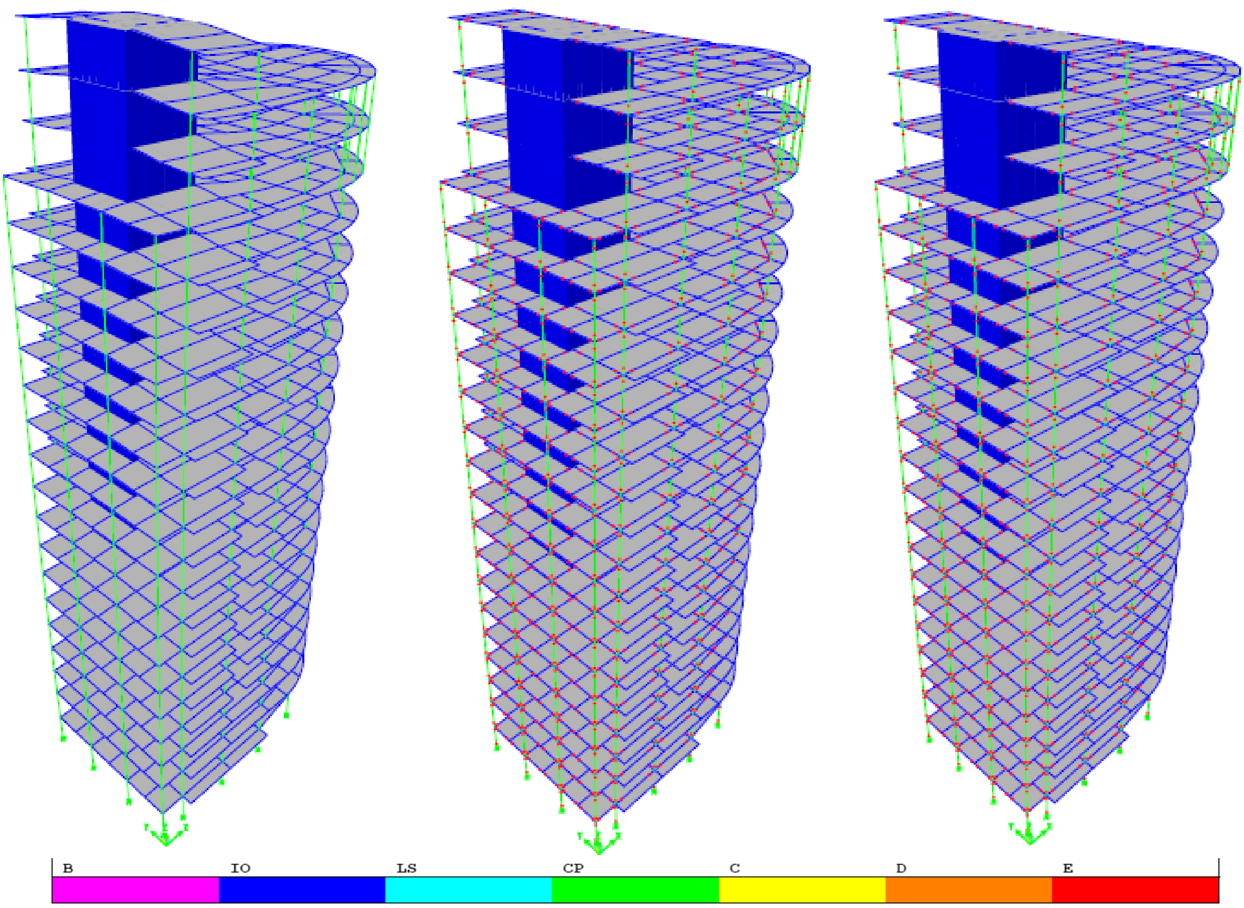


**Fig. 20.** Some steps of pushover analysis and hinges formation (ETABS output).

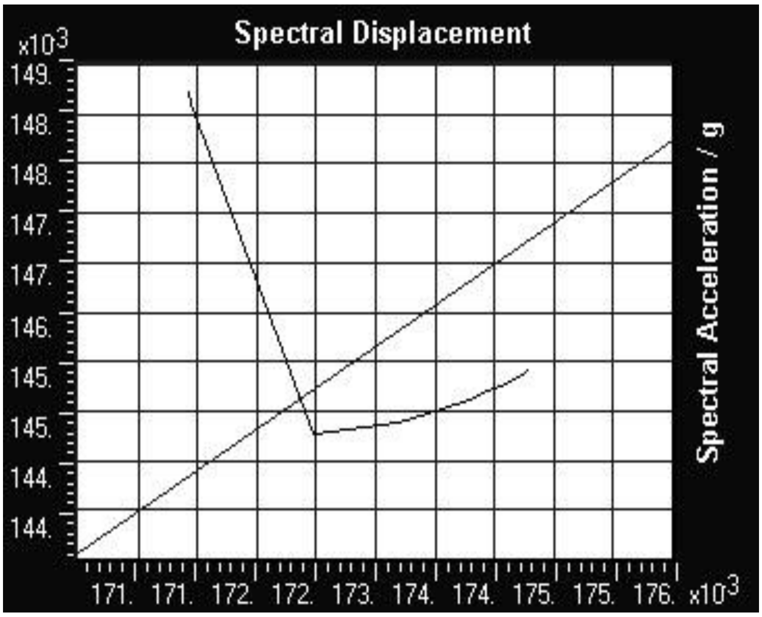


**Fig. 21.** Capacity spectrum and demand spectrum curves (ETABS output).

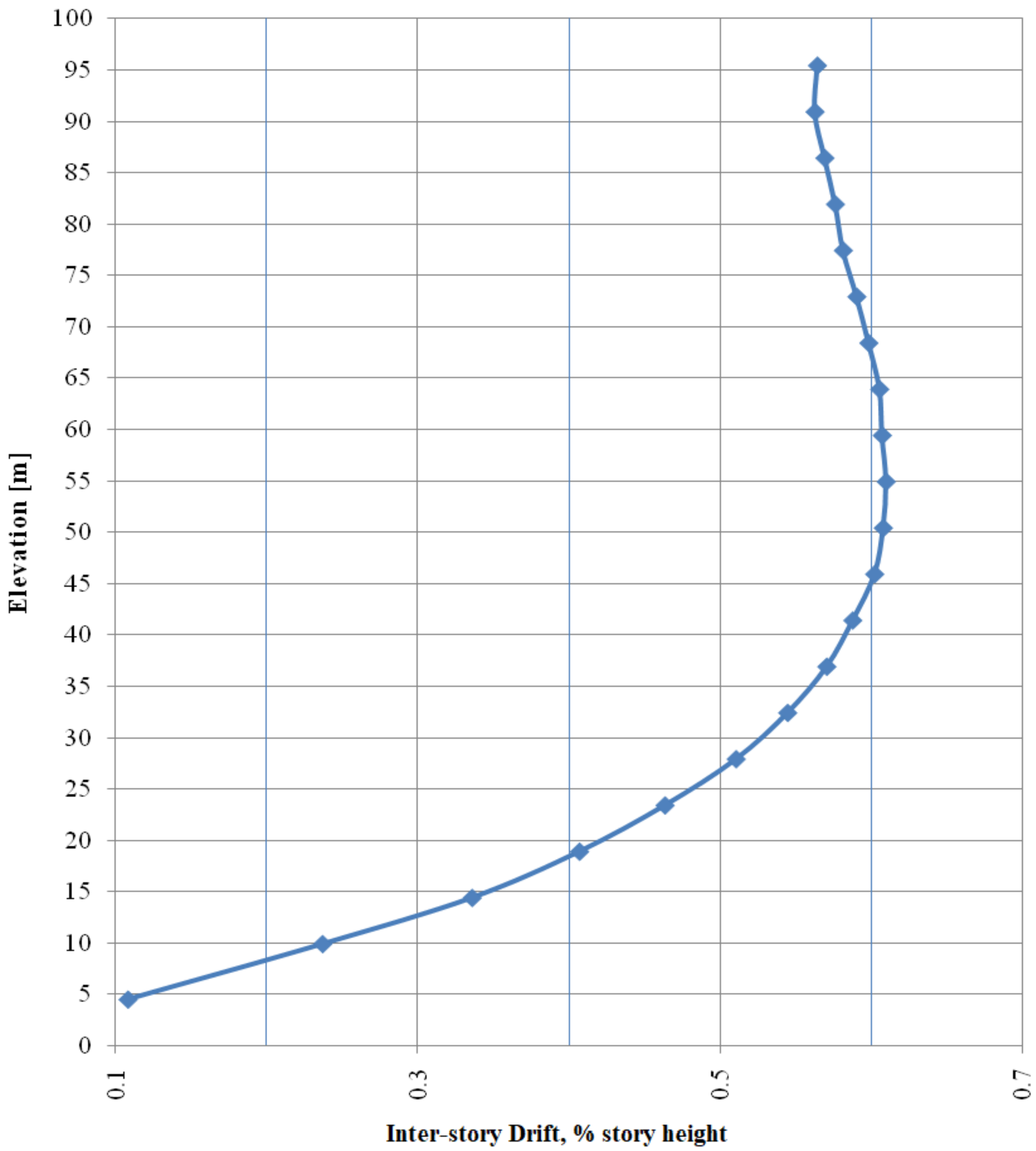


**Fig. 22.** Maximum inter-story drift.

## 4. Conclusions

Since Yemen is not far from earthquakes hazards, evaluation of the vulnerability of existing buildings is among essential priorities. Lack of presence (or availability) of local building code or such obligation may lead to un-implementation of the requirements of seismic buildings resistant which, in turn, may lead to high damage caused by any anticipated earthquake. Therefore, evaluation of performance-based seismic design in Yemen carried out. Evaluation of performance-based seismic design incorporated some case studies in Sana'a, Yemen. The study concerned with the conceptual and analytical three-dimensional modeling of buildings. The evaluation carried utilizing pushover analysis in compliance with the structural requirements for earthquake design. These are the conclusion drawn from this investigation:

- Seismic evaluation by nonlinear static pushover analysis is a useful common procedure in the world for evaluations, rehabilitation, and design stages;
- Buildings which not consider seismic requirements in codes at the design stage, have low performance and have more vulnerability against earthquakes, it may run between "near collapse" and "collapse prevention" to "collapse" performance level category.
- Buildings that consider seismic requirements in codes at the design stage have high performance, have less vulnerability against earthquakes, and may run between "operational" to "life safe" performance level category.
- There is a gap between architectural design and the requirement of earthquake engineering design in buildings in Yemen. However, structural decisions are -commonly- considered the architectural purposes against the seismic requirement.

For future work, the performance-based seismic design can be modeled for other systems such as steel structures. Also, the technics that increase the performance of the structures can be studied.

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