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Seismic Vulnerability Due to Construction Defects

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Abstract. In Ecuador, informal construction is a recurrent problem, especially in low-span constructions, as well as in medium-size constructions, in which there is no strict control during their construction and design. This leads to deficient constructions, which diminishes the resilience of the elements, even though they are designed by a professional with experience in structural design, who follows at least all the guidelines of the current standards, and uses the appropriate tools for their conception and design. This generates a false sense of security in the occupants of the building. Failures do not usually occur in the short term, no matter how pitiful the construction method was. In case of anomalies, it is considered something futile, easy to cover up, which only has aesthetic implications. This causes even the most experienced of technicians to trust, making crass mistakes that can lead to the collapse of the structure. Given these problems, the degree of vulnerability due to defects in the building was evaluated.

1. Introduction

The objective of this study is to determine the degree of vulnerability of structures due to construction defects, by means of computational models to determine their capacity and stress increase.

Poor construction practices reduce the resilience of the elements, even if they are designed correctly, generating a false sense of security in the building occupants. Failures do not usually occur in the short term, no matter how pitiful the construction method was. If anomalies do occur, they are easy to cover up. This causes even the most experienced of technicians to become overconfident, making crass mistakes that can lead to the collapse of the structure. Therefore, there is a need to carry out studies to collect information on the loss of capacity of structures, and their consequent lassitude in the event of an earthquake.

The construction and design defects significantly increased the seismic vulnerability of the elements analyzed; the perforations in beams, as well as the location of columns that originate in beams without continuity from the foundation. They have a great impact on these elements, since being vital elements in the special moment resisting frames, their lassitude generates a notorious increase in the seismic vulnerability of the structure.

2. Theoretical framework

2.1. Seismic demand

The serviceability of structural systems during their service life can be significantly affected by the occurrence of extreme events. Despite their low probability, there is the possibility of multiple occurrences of such hazards during the relatively long service life of the systems. [1]

2.2. Performance-Based Seismic Resistant Design

A primary aspect of seismic design is life safety and verification of limit states, which ensure satisfactory behavior within seismic engineering, however there are other impotent metrics such as economic losses [2]. To mitigate the financial detriment, a nonlinear seismic design methodology that controls the damage is required. The most suitable methodology is the combination of nonlinear static analysis (Pushover) and response spectrum. 3] Such as the N2 method, which combines nonlinear analysis and two mathematical models.

The method is based on a manifest performance determination, where monetary losses are established in a probabilistic manner, where uncertainties; seismic, structural response, damage and losses are explicitly considered. 4] Drifts are the main parameter that correlates with structural damage. [5] The expected damage in a building depends on its capacity and fragility. [6]

2.3. Capacity Spectrum

The capacity spectrum method takes a graphical representation of the global force-displacement curve of the structure and compares it to the response spectrum representing the seismic demands. (Freeman, 1998)

It compares the capacity of the structure with the earthquake demand on the ground. A simple approach for the determination of the seismic demand is based on the use of inelastic stress and displacement spectra that can be obtained from a time-history analysis of inelastic systems, or from the elastic spectrum. [7] Using time-history analyses of inelastic response eliminates the errors introduced by the use of equivalent linear approximations. [8]

3. Results and discussion

A computational analysis of two existing structures in the city of Cuenca-Ecuador, which are recurrent in the environment, was carried out. Their analysis is presented below.

3.1. Perforated beam

As can be seen in Figure 1, there is a perforation in a cantilever beam for the passage of a 110 mm diameter pipe. To study the effect of this, a finite element computational analysis was performed on a beam embedded at one end and free at the other, with a distributed live load of 200 kgf/cm^2, applied in the direction of the gravity.
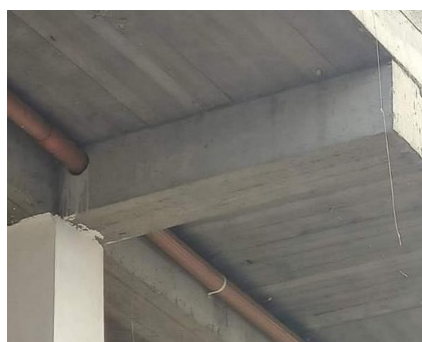

Figure 1. Study element

The idealized beam was developed with a *Shell Thik* element, 2 m long by 0.5 m high, with a thickness of 0.3 m. The Shell element was discretized every 5 cm, Figure 2.
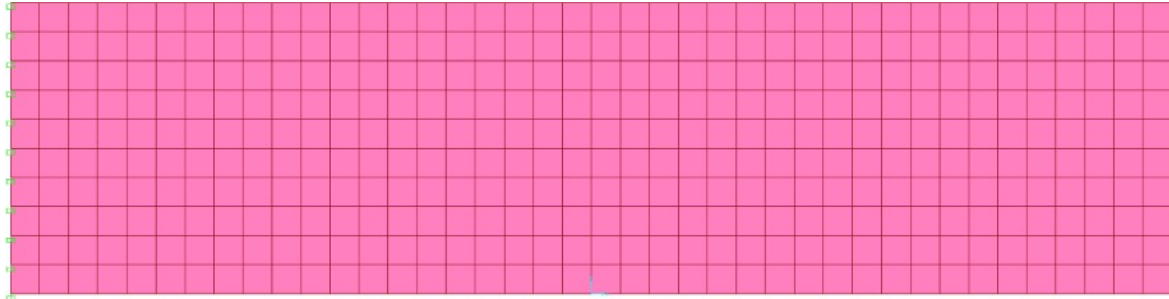

Figure 2. Model beam 2m long, height 50cm, thickness 30cm, discretized every 5cm.

It was considered that the slab over the beam has a minimum thickness of 20 cm, so the drilling was modeled, eliminating the elements below that distance with a square of 15 cm on each side, as shown in Figures 3 and 4.
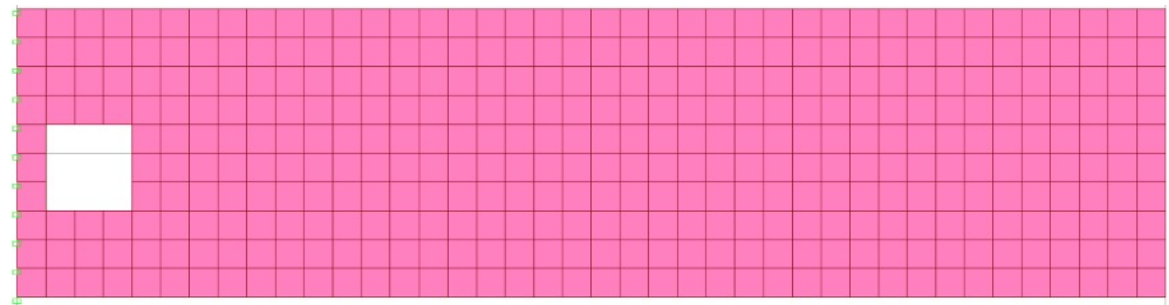

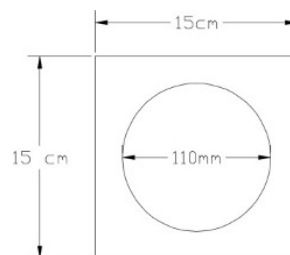**Figure 3.** Model beam with a 15 cm perforation.

Figure 4. Drilling in girder for 110 mm pipe passage

By means of finite element analysis, the distribution of forces in the beam with the drilling was obtained, and the results were analyzed in the same section, without perturbations in its geometry, Figure 5.

Removing the beam section considerably alters the distribution of forces, concentrating them around the removed area.

The difference of forces at the vertices is expressed in percentages relating the forces of the drilled beam to the initial condition, Figure 6.

An increase in forces on the D-C face of 82% and a significantly higher alteration on the A-B face can be observed, leading to a change of sign at the A vertex, changing from tensile to compressive.
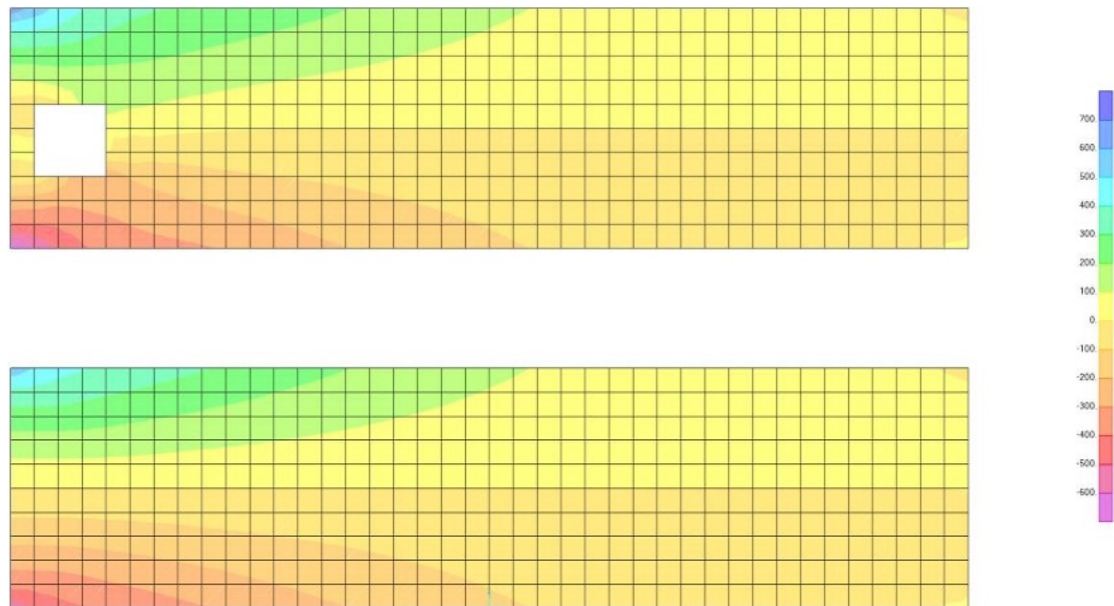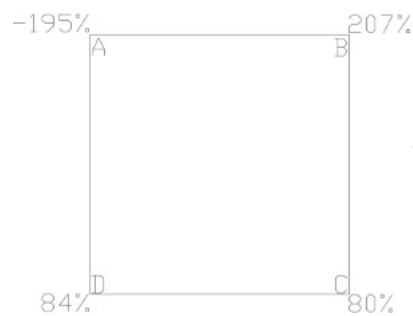
Figure 5. Force distribution kgf-m

Figure 6. Difference of forces, drilled and undrilled girde.

Deformations at the unrestrained end of the beam increase by 2.6%. On the embedded face of the beam there is an average increase of 20% in forces.

3.2. Structure with irregularities in plan

The second case study represents a structure with irregularities in plan and geometry, since the difference between plan dimensions is greater than 30% of the area, as shown in Figure 7.

Figure 7. Building with Irregularities in floor plan

A computational model of the building was made to determine its characteristics and possible vulnerabilities due to the defects it presents. The model consists of 5 stories with a height of 2.7 m between floors, Figures 8 and 9.
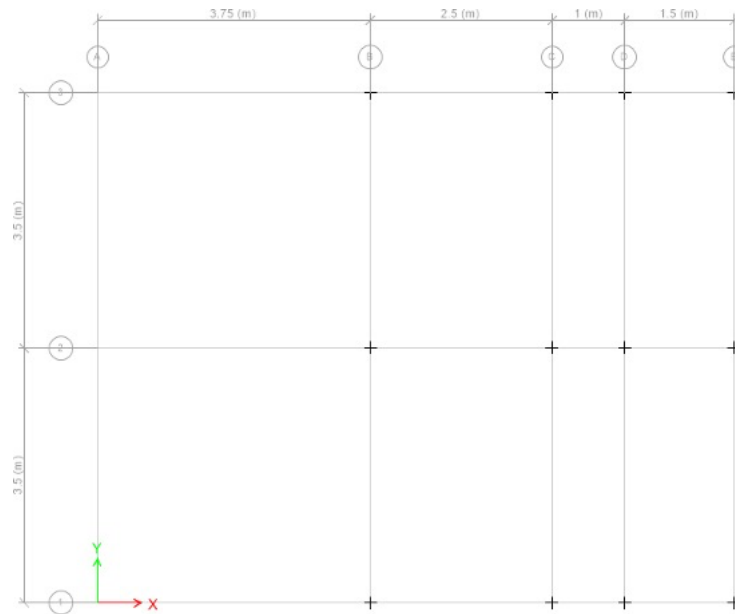

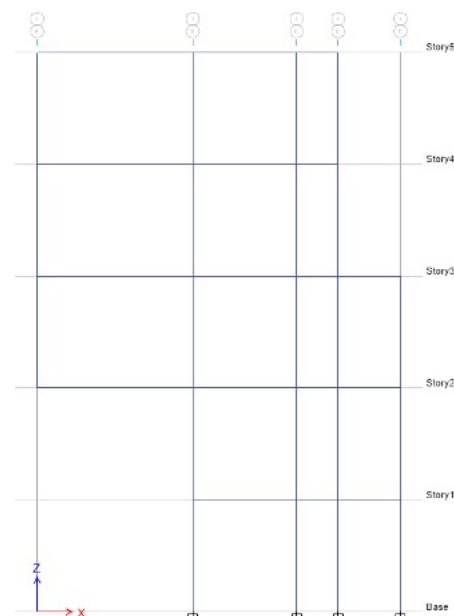
Figure 8. Floor plan, proposed model

Figure 9. Proposed model elevation

Beams of 60 cm by 30 cm and columns of 50 cm by 40 cm were considered, with concrete with a compressive strength of f'c=280 kgf/cm2.

The model included 200 kgf/m2 of live load, a response spectrum for Cuenca using a type B soil and the considerations stipulated in the Ecuadorian Construction Standard [9]. As shown in Figure10.
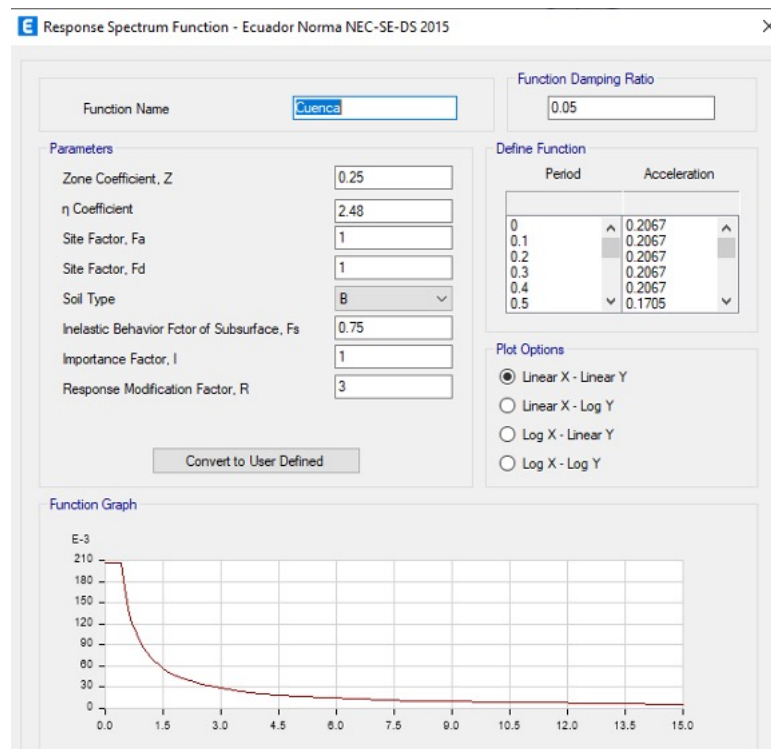
Figure 10. Response spectrum

The AB-2 beam is presented in detail since it is the one with the highest loads.

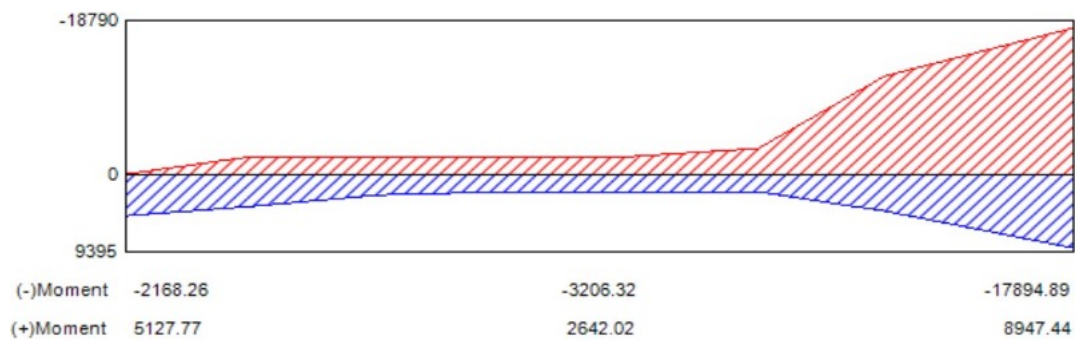|		
(-)Moment	-2168.26	-3206.32	-17894.89
(+)Moment	5127.77	2642.02	8947.44

Figure 11. Moment11Kgf-m, beam AB 2

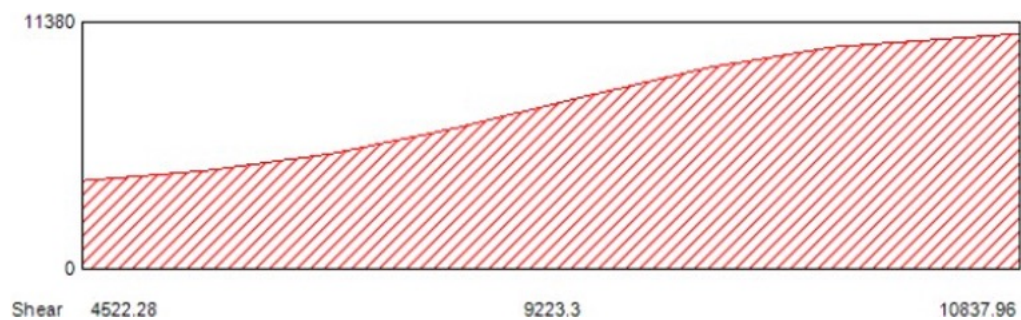|			
Shear	4522.28	9223.3	10837.96

Figure 12. Shear diagram kgf, beam AB 2

Both the shear and moment diagrams show an extremely high value on the face of the beam in contact with the column, with respect to the rest of the element.

The floor drift considering the vertical earthquake, at the second level of the structure, where the beam under study is located, is 0.0286, and has a maximum value of 0.037 located between the 4th and 5th floors.

Floor drift due to vertical earthquake, exceeds with creases what is allowed by the Ecuadorian regulation of 0.02, in reinforced concrete buildings [9].

All elements of the building fail for different reasons, but the general failure is shear failure, Figure 13.
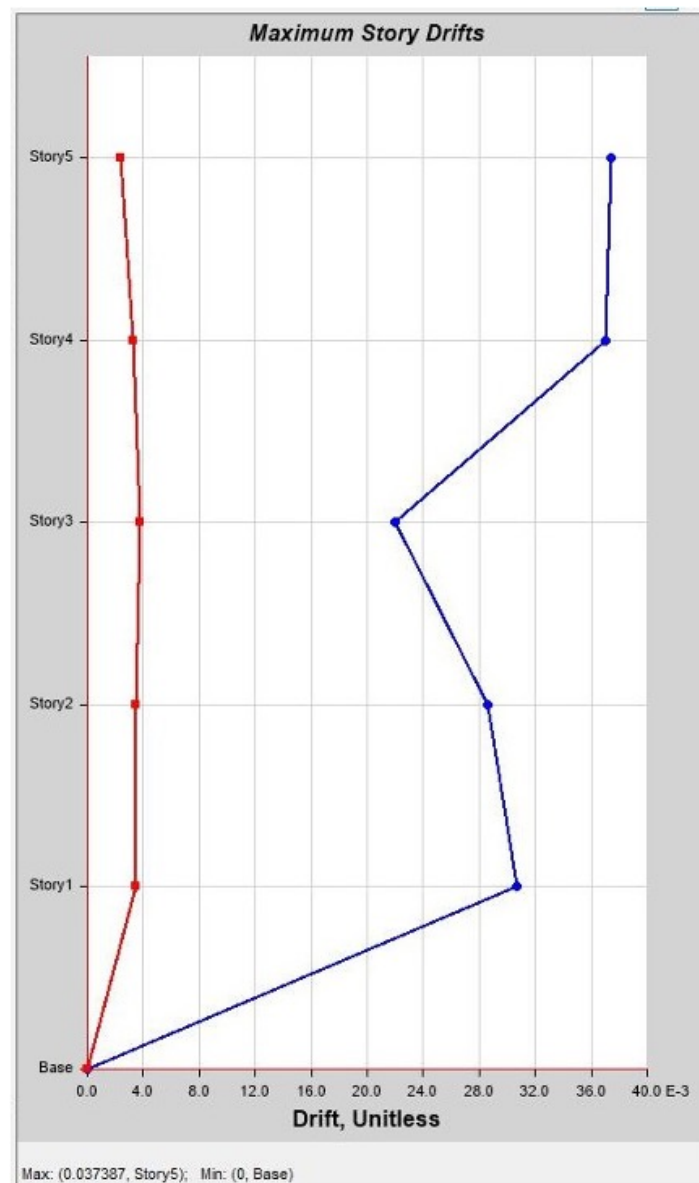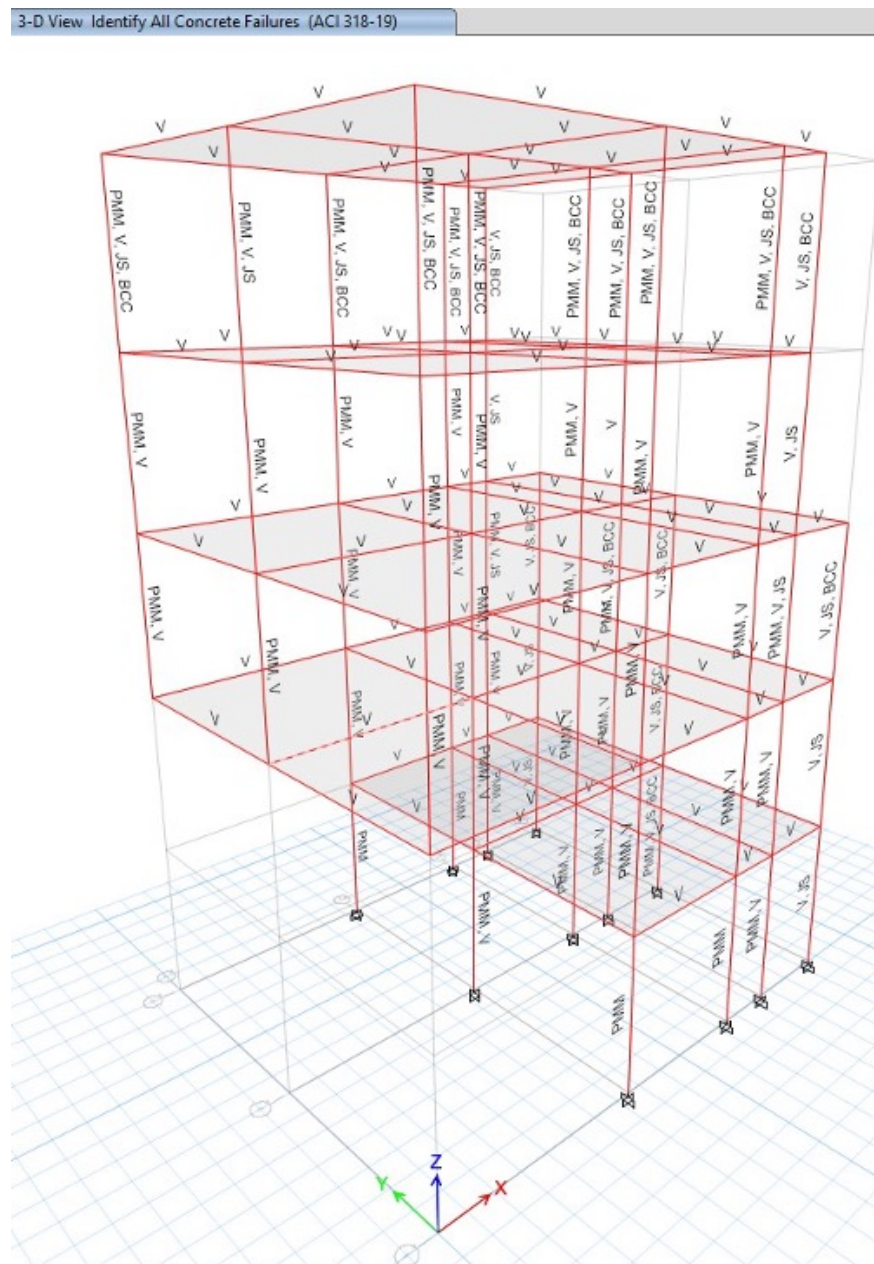

Figure 13. Floor drift

Figure 14. Building shear failure

4. Conclusions

The drilling in the beam was performed near the neutral axis, but in the critical zone, where the formation of the plastic patella is expected, it generated a redistribution of forces, causing them to concentrate in the area surrounding the drilling, and increasing them notoriously when compared to the same zones of the undisturbed beam. The redistribution of forces generated a change in the direction of these forces, introducing compressive stresses on the neutral axis. The stresses in the beam embedment are also increased, as well as its deformation. The percentage increases are of considerable magnitude, which can reduce the resilience of the structure.

When studying the building in case two, multiple construction and design defects can be observed. Emphasis was placed on the condition of the AB-2 cantilever beam, located in the central part of the

second floor of the building, which is loaded with a column that does not have continuity in the lower part of the element, a significant increase in moments and shear on the face of the beam in contact with the column was obtained, as well as a floor drift that exceeds the maximum allowed by current regulations.

Deformations due to seismic loads and drifts in the study beams increased significantly, increasing their seismic vulnerability.

Construction and shape defects in buildings have an important impact on the structural behavior of the elements, since they significantly increase the forces acting on them, even changing the way in which their fibers behave, being able to focus the stresses in areas that were not calculated to perform in this way.

The lack of technical criteria from the idealization to the construction of a building leads to crass mistakes, which can considerably increase the seismic vulnerability of the structures.

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