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Seismic performance of reinforced concrete tall buildings with conventional and non-conventional construction systems

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Abstract. Currently in the city of Lima there is a limited number of high-rise buildings. Therefore, there is not much literature on this type of building in Peru. Peruvian codes focus on medium and low-rise buildings. For this reason, studies are required to analyze and design these tall buildings more appropriately according to the reality of the country. In this article, a pushover modal analysis of 6 types of 35-Story reinforced concrete buildings in the city of Lima will be developed. Three building models with different structural systems and square and rectangular plan are proposed, being the areas of 29m x 29m and 52m x 26m respectively. These structural systems are rigid core and frames with an energy dissipation system (fluid viscous dampers and shear-link-bozzo dissipators SLB) in order to study their behavior against seismic stresses. These buildings were based on the criteria and requirements of the current codes in the country as well as the distribution of the floor plan of buildings commonly used for offices and homes. Natural periods (T) were found to range from 2.6 to 3.3 seconds for rigid core buildings. There is an increase for viscous damping buildings from 4.2 to 5.4 seconds and also for SLB devices to range from 3.7 to 4.6 seconds. In turn, modal static nonlinear analysis was performed to obtain the capacity curves for each type of building, which were compared with the seismic demands according to the design provisions of the Peruvian seismic standard E.030 and an average of design spectra. of acceleration records of severe seismic events in Peru and scaled in a range of 0.2T to 1.5T. The performance points for each building case were determined following the ATC-40 methodologies, finding that tall buildings with a rigid core have approximately twice the stiffness of buildings with SLB dampers, as well as low ductility, unlike buildings with dissipators, that have a high ductility.

1. Introduction.

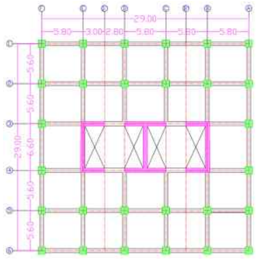
There are currently only a few buildings in Lima taller than 30 stories; some examples are the Westin Lima Hotel & Convention Center (30 stories), the “Banco de la Nación” Tower (30 stories), and, the most current, MET project (37 stories). Current Peruvian design codes are calibrated primarily for medium and low-rise buildings. Because construction of high-rise buildings is already underway, studies should be carried out to determine required updates to the Peruvian design codes to account for the different behavior of these types of buildings [1] [2] [3].

For the correct analysis of the behavior of high-rise buildings, different types of non-linear analysis have been performed, among which are the most well-known non-linear static analysis (Pushover) and incremental dynamic analysis (IDA). That second one is the most accurate analysis, but it requires a large computational load at the time of performing the analysis. Therefore, different variations of static non-linear analyses have been developed that give similar results to dynamic analyses but in a shorter computational time and analysis load [4] [5] [6].

In this study, a pushover modal analysis has been used, since it gives very similar results to the actual behavior of tall buildings. This analysis has been applied to a total of 6 regular buildings of 35 stories being total of 133m height, of which 3 are square plan and 3 are rectangular plan. In addition, each of the buildings on each floor has a different type of construction system: rigid core, viscous fluid dampers and SLB (Shear Link Bozzo) dissipators. Once these analyses were carried out, the capacity curves of each building were obtained. These curves were used to obtain the performance points and quantify their vulnerability.

2. Structure Capacity vs. Seismic Demand

Based on the collected plans, the dimensions of 29x29 m were defined for the square plan and 52x26 m for the rectangular plan, as shown in Figure 1. The dimensions for the structural elements in the first story were 50 cm thick for the structural walls, 80 x 80 cm columns for rigid core buildings, viscous fluid damper and SLB dissipators for the square plan. For the rectangular plan, the columns were 80 x 80 cm for a rigid core and 100 x 100 cm for a viscous fluid damper and SLB dissipators. The beams sections were 45x90 cm and 50x90 cm, they for square and rectangular plan respectively for every structural system at firsts levels. These dimensions decrease throughout the upper levels. Values of f'c vary from 70MPa for first levels to 42Mpa for upper levels.

(a) 

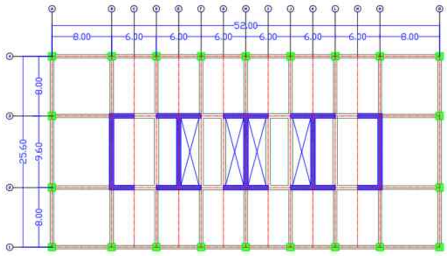
(b) 

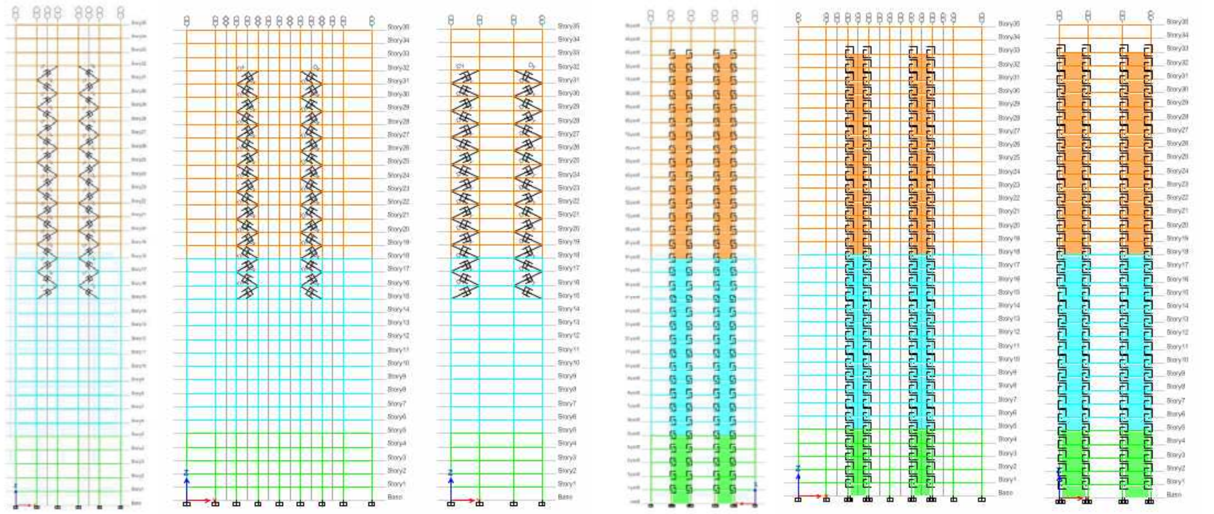
Figure. 1 (a) Square plan detail. (b) Rectangular plan detail

2.1. Seismic analysis and structural design

For Rigid Core Buildings, according to the Peruvian Code E.030 [7], seismic parameters were Z = 0.45, U = 1 common use such as apartments or offices, S = 1 considering that this type of infrastructure has deep foundation based on rock, and reduction value R = 6 for structural walls system. Minimum C / R = 0.11 was used because of large natural periods of the tall buildings. Then, the Seismic Coefficients obtained was 5%, and minimum shear base forces were used to meet E030. The structural design was carried out according to the indications of the Peruvian Code E.060.

For Buildings with viscous fluid dampers, the structural system was changed to a frame system provided with the aforementioned dimensions. Besides it was used 4 pairs of ground motion records from severe earthquakes in Peru: Lima 1966, 1970, 1974 and Pisco 2007. These were scaled based on a spectrum of pseudo accelerations with R = 1 in the SeismoMatch 2016 program in a range of 0.2T to 1.5T according to Peruvian Code E030. Then, a time-history analysis was carried out with each of the earthquakes previously scaled and thus obtain a range of floors where the maximum drifts are observed so that viscous fluid dampers can be placed in them [8], being for both floors 16 to 32. For the calculation and design of these non-linear viscous fluid dampers, an objective drift was determined according to the HAZUS and SEAOC tables [9], and an effective damping was calculated for each axis of each plant that are within a range of 20 to 40% by manufacturer's recommendation [10]. In order to define this type of shock absorbers, the damping C value varies from 200t-s/m to 1200t-s/m, the stiffness of the metal arm the K value from 24470t/m to 33010t/m and coefficient $\alpha = 0.5$. Figure 2 shows the distribution of dampers in buildings.

For SLB dissipators buildings, the same structural frame used for fluid viscous case was used. But, in this case, the structural design of the structural elements of buildings was first carried out using design combinations that only present gravity forces [11]. The SLB devices were located from floors 1 to 33 on both plans as can be seen in Figure 3. Once the dissipators were placed in the buildings, the pseudo-acceleration spectrum for the E.030 code was included to be able to design the devices. The DISSIPA-SLB 2019.2 [12] plugin was used, which serves to define the dissipators as “links” elements, then collect the shear that reaches the device due to the load combinations, including the effects of the earthquake, and finally, to propose a type of SLB dissipators that supports the loads submitted having a demand-capacity factor (D / C) not greater than 1.5. Once the types of devices complying with the aforementioned procedure were obtained, the drift verification was performed and then a nonlinear time-history analysis was carried out to verify the hysterical behavior of the dissipators.



(a) **(b)** **(a)** **(b)**

Figure. 2 Location of viscous fluid dampers - left, and SLB dissipators – right: Square Plan longitudinal and transversal direction (a) Rectangular Plan longitudinal and transversal direction (b)

Maximum drift reached per orthogonal direction of the building were from 0.28% to 0.46% for Rigid Core, 0.42% to 0.53% for Fluid Viscous and 0.26 to 0.45% for SLB structures, being less than the limit required by the Peruvian Code 0.70%. Besides, for core walls it was designed horizontal reinforcement ratio between 0.28% to 0.40% for shear forces, and vertical reinforcement ratio of 0.28% for axial-bending forces, all of them larger than minimum 0.25% ratio as E060 Peru Concrete Design Code [13]. For columns reinforcement, it was found ratios of 1.28% for rigid core buildings, 3.58% for Fluid Viscous and SLB disipators, every case larger ratio of 1% as E060 Code requests.

3. Modal Pushover Analysis – Capacity Curves and determination of Seismic Demand Curves

The buildings were modeled again using a pushover modal analysis to determine the capacity curves of each. Beams and columns were modeled as frame elements in all the buildings; structural walls in buildings with a rigid core were modeled as frame elements having an infinitely rigid beam at the top of these [14]. The nonlinear load cases were defined to have a combination of 1.1 CM + 0.25 CV and standard point loads applied at the center of mass of each floor of the buildings. These load patterns have a modal distribution according to the mode that corresponds to each axis that was evaluated. The reinforcement obtained per each building was used to calculate the moment-curvature diagrams according to predetermined tables for each type of element from ASCE41-16[15]. Plastic hinges (M3) were assigned at a relative distance of 5% and 95% on the beams of all the buildings. Plastic hinges with biaxial behavior (P-M2-M3) at the same relative distance were assigned for the columns, and plastic hinges of uniaxial behavior were assigned for the plates according to the major axis (P-M2 and P-M3) at a relative distance of 50%. Subsequently, the control point was defined in the center of mass of the last story of each building and with a control distance that was iterated until the collapse of each one. Finally, pushover modal analyses were performed for each axis of each building obtaining the capacity curves (basal shear vs. roof displacement). It can be seen that buildings have different types of behavior, evidencing that buildings with a rigid core have greater rigidity in the linear range and that buildings with an energy dissipation system are more ductile and allow greater displacement before failure. Figure 3 shows the Capacity Curve per building case.

Two types of demand curves were considered. First one by the design spectrum according E.030 Peruvian Code, and second one by the average of Sa vs. T spectrum from of 4 pairs scaled ground motion records by SeismoMatch 2016 [16]. The ADRS conversions according to ATC-40 provisions[17] were applied to obtain Sa vs Sd and Shear Base vs Displacement curves

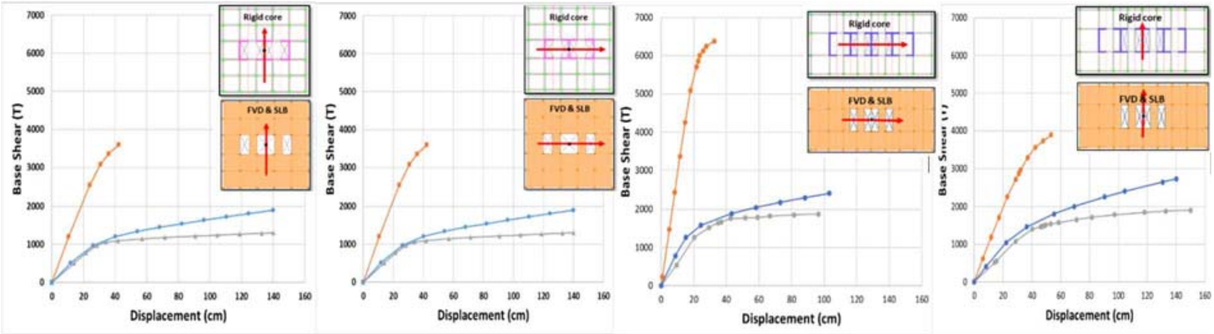


Figure. 3 Pushover Curves per case

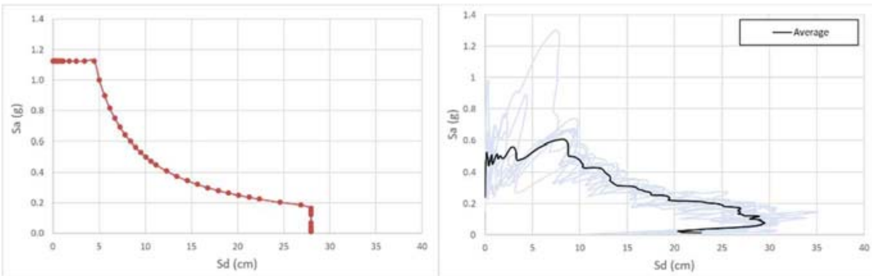


Figure. 4 Demand Spectrum Sd vs Sa of the E.030 code and average of 4 pairs of ground motion records on the Y axis of the square plan

3.1. Determination of the seismic performance point

The performance point is obtained by superimposing and intersecting the capacity curves of the buildings with their respective demand spectrum. Where, the Peruvian Code gives us a spectrum of elastic demand that must be reduced by a factor R = 6 for rigid cores, R=8 for fluid dampers and R=6 for SLB. The displacement would be obtained from the intersection of the capacity curve with the elastic design demand spectra of the E.030 standard (R = 1) and the base shear force (V) by intersecting the capacity curve with a spectrum of inelastic demand divided by a reduction factor R [13]. Results for some comparisons between capacity and demand curves are shown in figures 5 and 6.

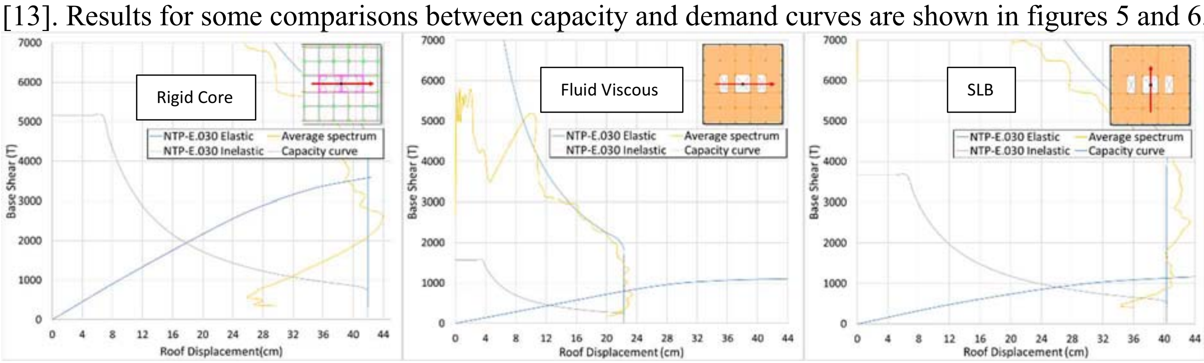


Figure. 5 Performance Points - Square Floor Plan

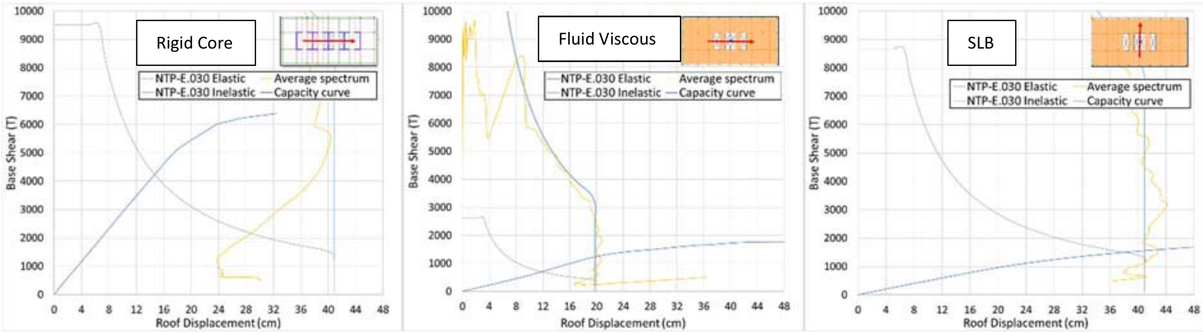


Figure. 6 Performance points – Rectangular Floor Plan

4. Conclusions

In the obtained pushover curves, it can be seen that the buildings with a rigid core have a greater stiffness in the linear range and less ductility in the non-linear range compared to the buildings with dissipation systems.

The collapse mechanism for buildings with a rigid core was caused by a flexural failure of the structural walls in the first floors; therefore, only plastic hinges are formed with flexure rather than shear. The failure that can be seen is fragile in nature. The collapse mechanism in buildings provided with viscous fluid dampers and SLB dissipators is ductile failure with the formation of plastic hinges at the base of the columns.

The seismic performance of rigid core buildings according to the explained methodology was obtained in the linear range of the structure's capacity curve. The performance drifts are within the limit required by the Peruvian Code. However, these buildings would not comply with performance requirements, since they have small drifts in the non-linear range. These small non-linear drives would generate collapse based on a demand curves using the seismic Peruvian code. For the buildings with viscous fluid dampers, the seismic performance was obtained in the limit of the non-linear range. This would lead to the structure forming plastic hinges in the beams based on a seismic design using the Peruvian Code. Finally, in the case of buildings with SLB dissipators, the seismic performance was obtained in the non-linear range, causing the structure to present plastic hinges in the beams in most of the floors, but without collapse.

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