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SEISMIC PERFORMANCE EVALUATION OF AN IRREGULAR AND SLENDER SKYSCRAPER UTILISING STIFF DAMPERS

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Abstract: *In the last decade, there has been a growing trend in the popularity of skyscrapers characterised by their slender and irregular designs. This trend has introduced fresh challenges with regards to their seismic performance and safety considerations. This paper presents a comprehensive examination of the seismic design complexity and performance assessment for an irregular and slender skyscraper incorporating stiff dampers. The building consists of different separated blocks interconnected by a steel truss. Located in the high seismic activity region of Guadalajara, Mexico, the building meets the requirements of the ASCE 7-22 and Mexican design codes. The stiff dissipating devices (SLB) have been implemented to ensure protection against earthquake events. A set of 11 Non-Linear Time History Analyses were used to determine the performance of the structure with and without SLB devices. The results showed that the use of SLBs allowed reducing up to 15% the fundamental period of the structure, a considerable reduction in the number of elements forming plastic hinges and over 50% reduction of the inter-story drift ratio for some of the signals studied. Finally, the effectiveness of the SLB devices in reducing the impact of earthquakes on slender and irregular-shaped skyscrapers located in areas of high seismic activity is discussed.*

1. Introduction

In the context of climate change where environmental conditions are becoming increasingly extreme, earthquakes have emerged as the leading cause of mortality within natural disasters, accounting for 58% of the total fatalities. Additionally, they rank third in terms of economic losses, contributing to 21% of the overall financial burdens, and they constitute 8% of the total occurrence of natural disasters (CRED, 2020)

The classic earthquake-resistant design involves high levels of structural redundancy to ensure achieving the required ductility. This not only results in a significant increase on the cost of the construction and materials but also inherently implies structural plastification (damage) into the design in order to dissipate the energy of a seismic event and protect the structure against earthquakes. In the 1980s, seismic protection devices began to emerge, departing from the classic design and altering strength hierarchy of structural elements, as the seismic protection would attract most of the lateral loads induced by an earthquake, thereby protecting the rest of the building.

Seismic protection systems represent an advancement in seismic-resistant design for multiple reasons. Firstly, due to their specific design to withstand seismic loads, incorporating them into a structure allows us to depart from the inefficient conventional seismic design, which requires significant increases in redundancy and hyperstaticity. This is because the seismic load is directed specifically towards the protective elements and not the other structural components. In this way, the elements working with the seismic load are designed explicitly to meet those demands and, therefore, inherently provide a superior structural response compared to the conventional design based on redundancy. These elements are precisely located within the structure, making their inspection or even replacement after a seismic event straightforward. This is associated with significantly lower costs compared to inspecting or repairing a conventional structure after an earthquake where the damage is widespread along all elements and can be difficult to identify and repair.

In this sense, this paper presents a case study of a high-rise building with significant structural complexity, including two blocks, one leaning on the other, substantial elevation irregularities, and cantilevers exceeding 7 metres, among other factors. This is a real project located in Guadalajara, Mexico, and it is currently under construction. Given the seismic risk in the area, the use of seismic protection has been assessed, particularly on the use of SLB energy dissipators. SLB dissipators are a highly stiff seismic protection system compared to other metal plasticization alternatives such as ADAS or TADAS dampers or Honey-Comb devices (Bergman et al., 1987; Kobori et. al., 1992; Tsai et al., 1993). SLB devices have a metal profile geometry and are manufactured through metal milling, thus avoiding the residual stress concentrations induced by welding, consequently enhancing their deformation capacity under cyclic loads (Franchioni, 2001).

To assess the advantage of incorporating SLB devices on the seismic performance of the structure, 3D non-linear models were generated in the ETABS software (CSI, 2016). The Models consider the elastoplastic behaviour of the structural elements following FEMA guidelines (ASCE/SEI 41-17, 2017). The seismic demand was considered using a set of 11 pairs of real seismic records acting simultaneously in the principal directions of the structure. Each of the considered seismic records is spectrally compatible with the site specific seismic hazard following the ASCE standards (ASCE7-16, 2017) and the current requirements of the Mexican Complementary Technical Standards for Seismic Design (NTC-C, 2020).

The non-linear time history analysis is a dynamic analysis that computes the behaviour of the structure at each instant during the application of seismic signals. This type of analysis has a great computational cost as it integrates all the movement equations of the structure step-by-step, obtaining, for each moment of the analysis, all the plastic deformations and internal forces in the system. In particular, for this case study we used the interstory drift, the story shears and plastic deformations in order to compare both the building with and without seismic protection behaviours under seismic loads.

2. Case Study

The case study is a 34-level project, which is located in the highly seismic region of Guadalajara, Mexico. It has a height of 117.8 meters, large spans of up to 10 meters, cantilevers of up to 7 meters and is divided into connected blocks by a metal truss (see figure 2). The particular characteristics and complexity of the structure are factors that increase the seismic risk and complicate compliance with regulations. For this reason, it was deemed appropriate to use SLB energy dissipators. These devices can be considered as plastic hinges that designer can place according to his inventiveness and knowledge. (Bozzo L, et al., 2019).

SLB devices dissipated most of the total input seismic energy so the structural elements remained in the linear-elastic range without damage. SLB devices dissipated most of the total input seismic energy so the structural elements remained in the linear-elastic range without damage. (M. Pantoja, et al., 2020).

There are different ways to incorporate the dissipators, for this case, uncoupled walls were used. The combination of reinforced concrete frames and uncoupled walls with dissipators increases stiffness and ductility, but most importantly, allows the walls not to be aligned vertically, even in their full height or in the full beam length resulting in important architectural advantages. (M. Pantoja, et al., 2020).

Figure 1. Render view of the building locating in Mexico(right) 3D ETABS model of the building (left)

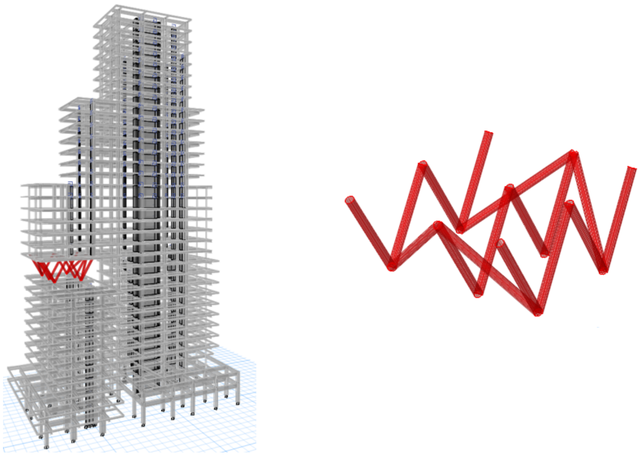


Figure 2. 3D view of the ETABS model (left) and 3D view of the connecting steel truss (right).

The selection and scaling of the acceleration records used in this study were performed in accordance with ASCE standards (ASCE-7-16, 2017) considering the seismicity of the site. Therefore, the average demands of 11 earthquake records adjusted to the site spectrum were evaluated. For the seismic assessment of the different proposals, 11 three-dimensional nonlinear time-history analyses were carried out for each case study, totalling 44 step-by-step nonlinear analyses. Each record was labelled as ACCi, with i representing their record number, ranging from record 1 to 11. Both horizontal components of the seismic events were considered to act simultaneously in the main directions of the structures. The nonlinearity of the structural elements was considered in accordance with the ASCE-41-17 (2017) standards. All seismic records have been defined for a return period of 2475 years.

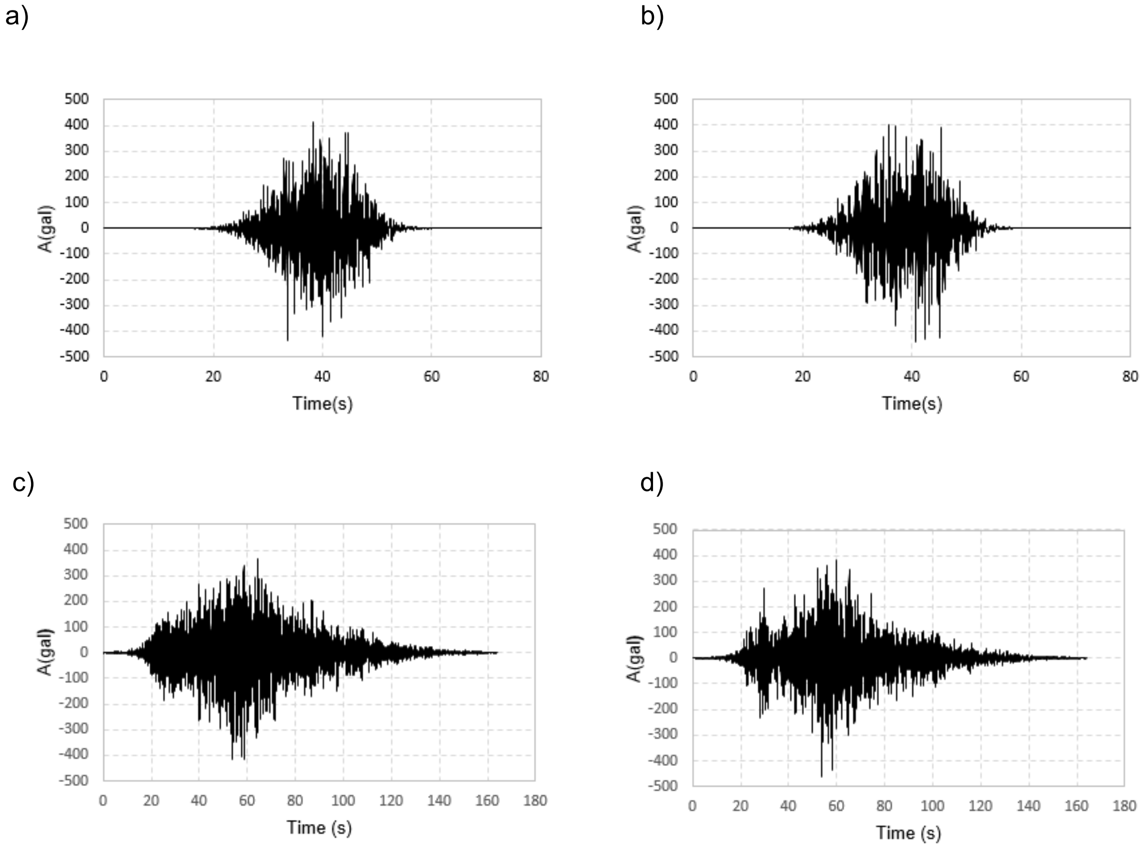


Figure 3. Example of seismic records used for nonlinear dynamic analysis for a return period of 2475 years a) seismic record for ACC1 EW component, b) seismic record for ACC1 NS component, c) seismic record for ACC11 EW component and d) seismic record for the ACC11 NS component.

The seismic records have been scaled in accordance with ASCE (ASCE-7-16, 2017). In such a way that all the response spectra obtained from each accelerogram must meet 90% of the ordinate of the target spectrum for the fundamental period of the structure.

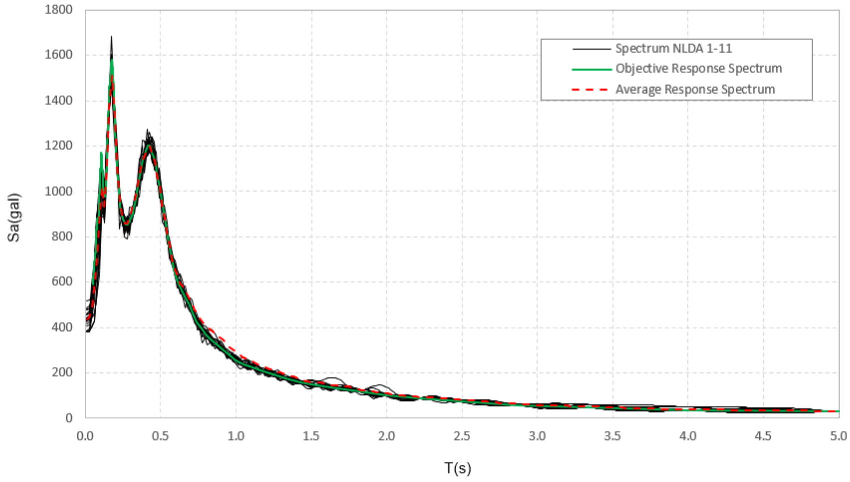


Figure 4. Objective design spectrum compared to the average of the spectrum of the 11 records used for the study.

The inclusion of dampers has led to a reduction in the periods in both directions, decreasing by 23.6% in the X direction and 22.3% in the Y direction. This means that the structure has become more rigid, resulting in smaller displacements, which implies a reduction of damage in a potential seismic event.

Table 1. Modal Participating Mass Ratios for the building without SLB devices

Mode	**Period (s)**	**Ux (%)**	**Uy (%)**	**Rz (%)**
1	6.319	**0.6458**	0.0396	0.0418
2	6.017	0.0587	**0.5486**	0.0533
3	4.307	0.0063	0.0713	**0.5111**

Table 2. Modal Participating Mass Ratios for the building with SLB devices

Mode	**Period (s)**	**Ux (%)**	**Uy (%)**	**Rz (%)**
1	4.827	**0.599**	0.0223	0.0692
2	4.676	0.0327	**0.5833**	0.0051
3	3.749	0.039	0.0172	**0.515**

Maximum Inter-story Drift Ratio

Figures 5a, 5b, 5c and 5d display the Maximum Inter-story Drift obtained along the building's height. These values were obtained through a non-linear time history analysis using 11 seismic records. Figures 5a and 5b illustrate the Maximum Inter-story Drift for the X direction considering and not considering SLB devices, respectively. Figures 5c and 5d show the Maximum Inter-story Drift for the Y direction considering and not considering SLB devices, respectively.

Figures 5e and 5f display the comparison of the Maximum Inter-story Drift obtained as the average of the 11 seismic records for the buildings with and without SLB devices. It is clear that the Inter-story Drift decreases with the inclusion of SLB devices for both X and Y directions.

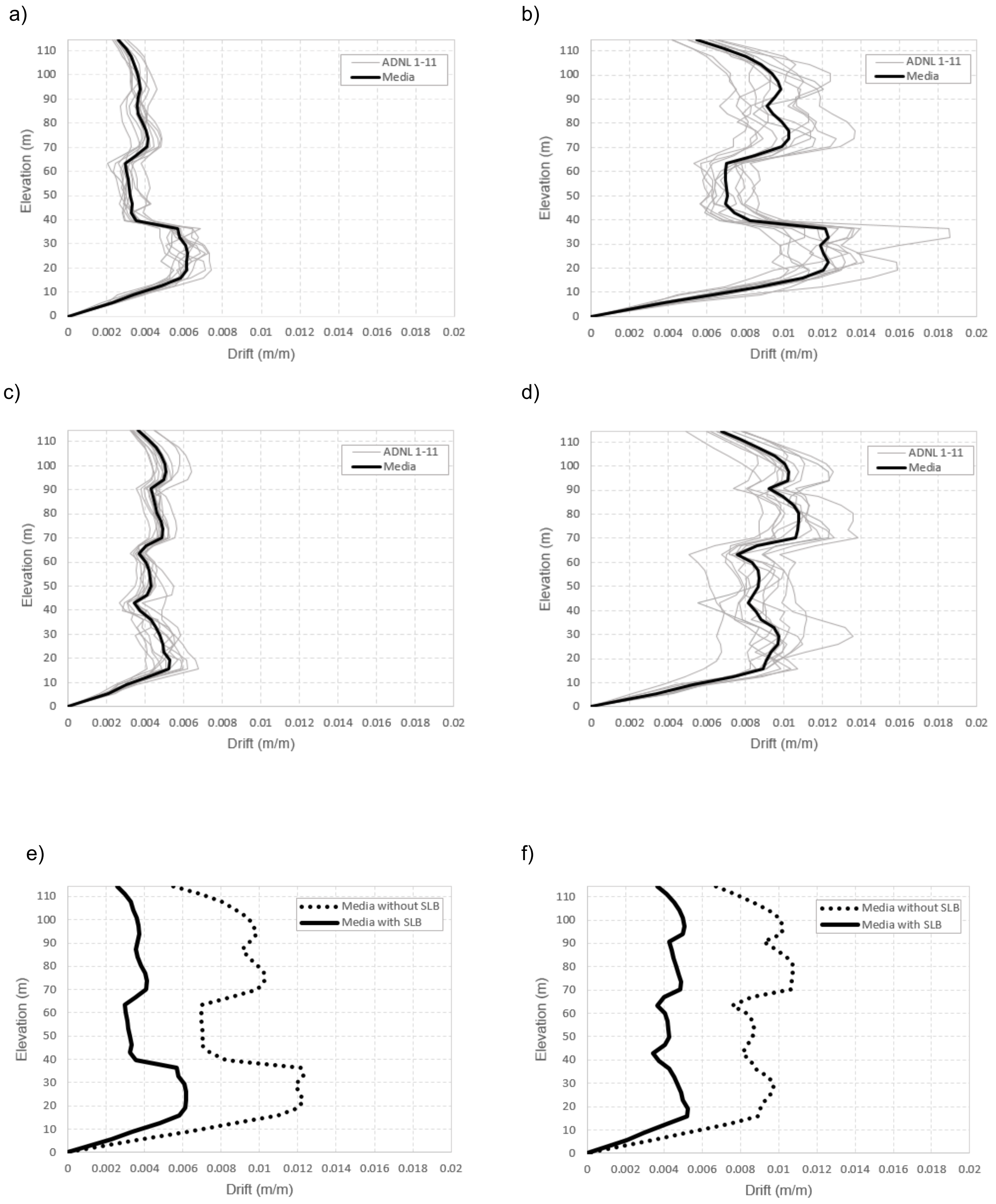


Figure 5. *Maximum drift of the building a) In X direction with SLB, b) In X direction without SLB, c) In Y direction with SLB, d) In Y direction without SLB e) Comparison of the average of the results in X direction with and without SLB and f) Comparison of the average of the results in Y direction with and without SLB.*

Table 1 presents a summary of the maximum inter-story drifts, obtained as the average of the maximum values, from the 11 nonlinear time-history analyses.The inclusion of SLB dampers reduces the drifts in the X direction by 50% and in the Y direction by 49%. Achieving lower maximum drifts means reduced structural damage and, hence, a higher level of safety.

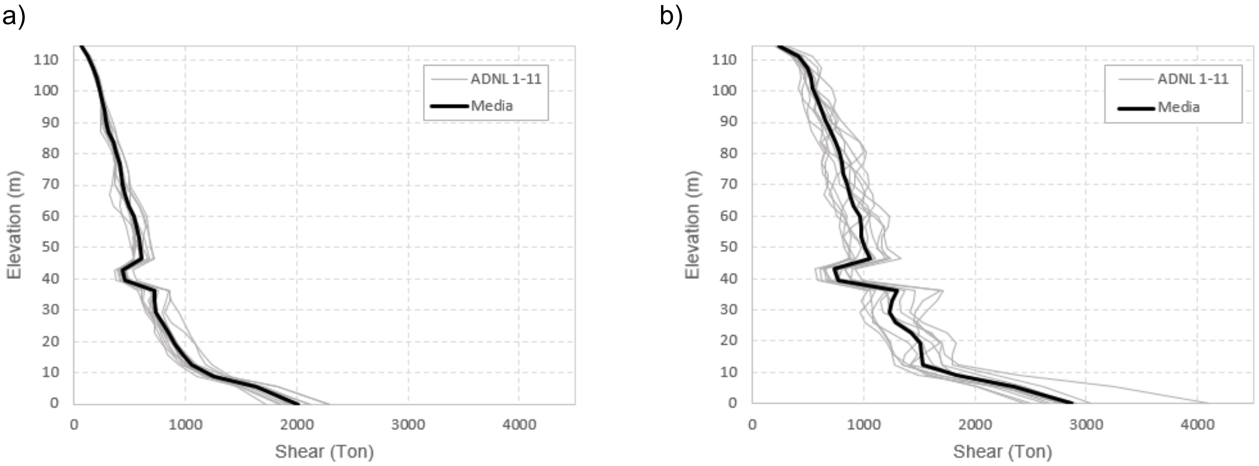
Table 3. Maximum Inter-story Drift Ratio, obtained as maximum of the average values of the 11 non-linear time history analyses.

Building Case	**Drift X direction (mm/mm)**	**Drift Y direction (mm/mm)**
Building with SLB	0.00617	0.00527
Building without SLB	0.01231	0.01076
Reduction (%)	49.88%	51.02%

STORY SHEAR

Figures 6a, 6b, 6c and 6d display the story shear obtained along the building's height. These values were obtained through a non-linear time history analysis using 11 seismic records. Figures 6a and 6b illustrate the story shear for the X direction considering and not considering SLB devices, respectively. Figures 6c and 6d show the story shear for the Y direction considering and not considering SLB devices, respectively.

Figures 6e and 6f display the comparison of the story shears obtained as the average of the 11 seismic records for the buildings with and without SLB devices.



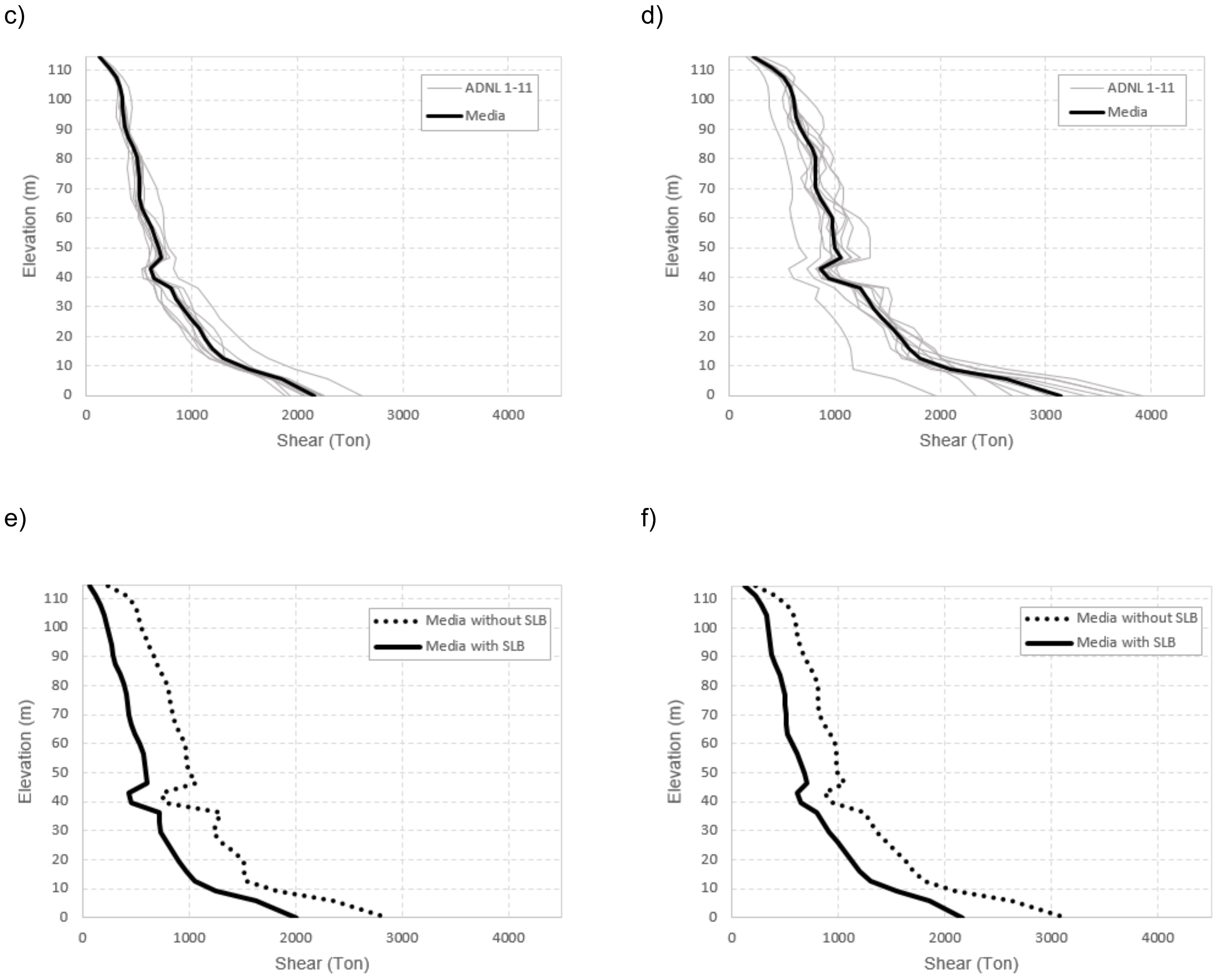


Figure 6. *Story Shear of the building a) In X direction with SLB, b) In X direction without SLB, c) In Y direction with SLB, d) In Y direction without SLB e) Comparison of the average of the results in X direction with and without SLB and f) Comparison of the average of the results in Y direction with and without SLB.*

Table 2 presents a summary of the maximum story shear values, obtained as the average of the maximum values, from the 11 nonlinear time-history analyses.The inclusion of SLB dampers reduces the story shear in the X direction by 30% and in the Y direction by 31%. Achieving lower maximum story shear values means reducing sections in the structure and consequently saving on its final cost.

Table 4. Maximum shear base values , obtained as the average of the maximum values of the 11 non-linear time history analyses.

Building Case	**Shear Base X direction (Ton)**	**Shear Base Y direction (Ton)**
Building with SLB	2009.5	2161.7
Building without SLB	2872.47	3144.1
Reduction (%)	30.04%	31.24%

PLASTIC HINGES OF THE STRUCTURAL ELEMENTS AND DAMPER PLASTIFICATION

The results in the SLB dampers demonstrate that none of the 11 analysed records exceeded the maximum deformation capacity of 50 mm of the SLB devices. (See Figure 7).Figure 7 displays hysteresis cycles of the dampers for the ACC1 and ACC11 records, which exhibited the maximum deformations in the dampers, approximately 15mm.The values of shear 2-2 and deformation U2 shown in figure 7 are shear and deformation values, respectively, of the LINK element that ETABS software (CSI, 2016) used to model hysteretic dampers such as SLB devices.

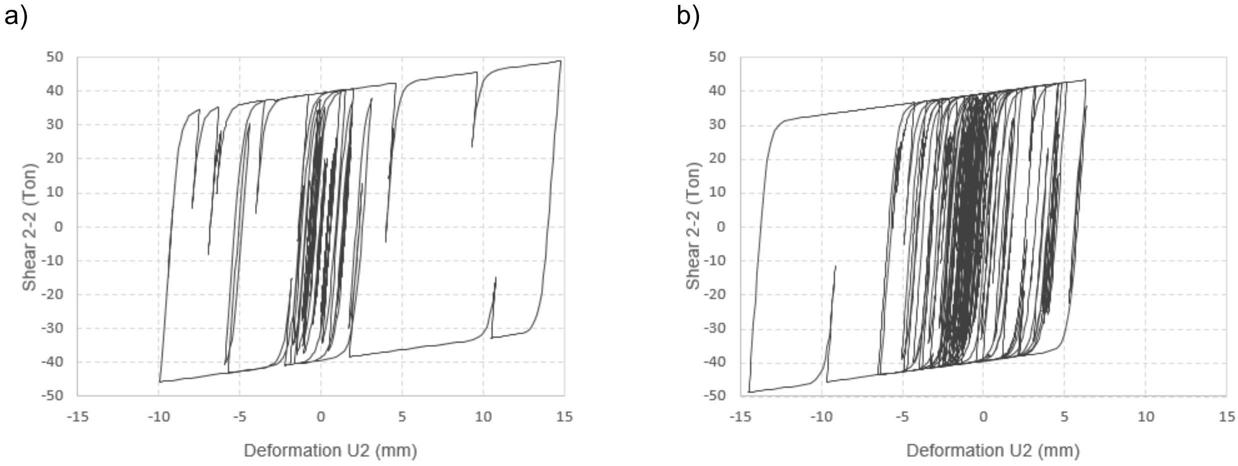


Figure 7. *Link hysteresis cycles of the seismic records ACC1 and ACC11*

Due to the complexity of the building where one structure is supported by another (see Figure 1), and its significant slenderness, safety has been prioritised by oversizing the contribution of SLB dampers. Therefore, the maximum deformation values of 15 mm found in the devices, which are less than their maximum capacity, align with the safety objective described. Figure 8 shows that with the inclusion of SLB dampers, the number of structural elements that reach yielding is reduced, thereby ensuring that the hinges are reached before the immediate occupancy limit.This means into a decrease in repair costs in the event of a seismic event and, consequently, greater resilience of the building.

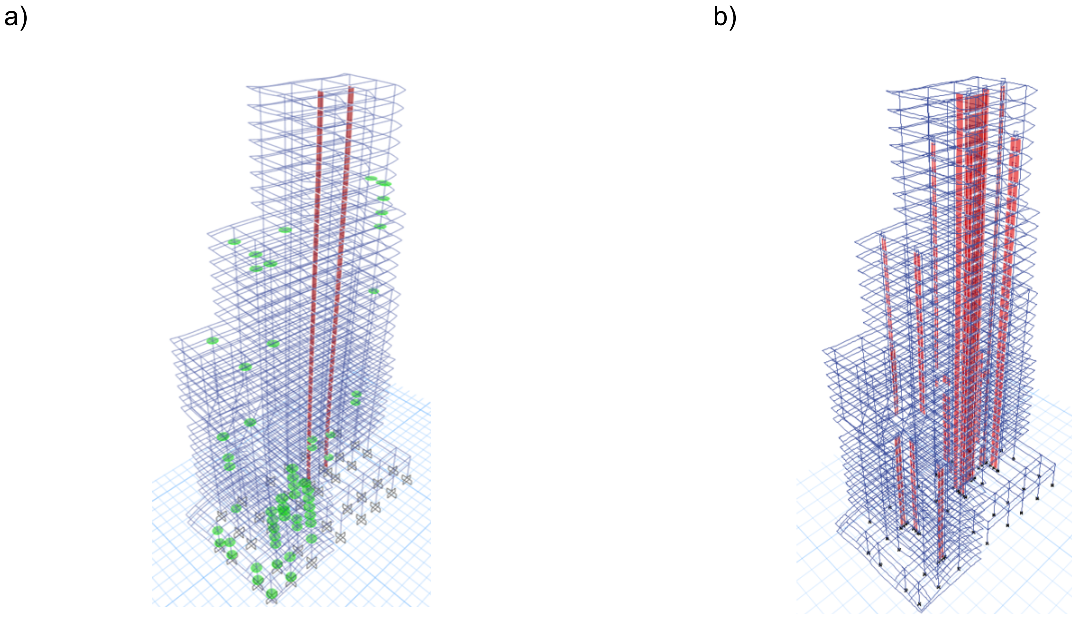


Figure 8. *Example of plastic hinge formation for the ACC1 seismic record of the a) building without SLB, b) building with SLB.*

3. Conclusions and recommendations

The case study presented in the article shows a significant improvement over conventional seismic design, based on structural redundancy, ductility and controlled structural damage. Whether in the form of dampers or dissipators, these devices enable the control and enhancement of structural response, while concentrating the potential damage caused by a seismic event in the eventually replaceable components. Additionally, the ease of inspection and replacement greatly reduces the costs associated with post-seismic event inspection and repairs. Based on the findings in this article, it can be concluded that SLB devices generally exhibit favourable seismic performance. Not only do they reduce drift, which is linked to non-structural damage, but they also impact shear distribution, which is tied to structural damage and the overall cost of the structure. SLB dampers reduced inter-story drift by 49% to 51% compared to cases where they were not implemented. It is worth highlighting that, alongside the reduction in drift, there is a decrease in the base shear of 30% to 31%, respectively, for both case studies.It has been demonstrated that with the inclusion of SLB dampers, the number of structural elements that reach yielding is reduced, thereby ensuring that the hinges are reached before the immediate occupancy limit. This results in a decrease in repair costs in the event of a seismic event and, consequently, greater resilience of the building. Clearly, employing SLB devices in highly flexible, complex frame structures of significant height presents more advantages compared to conventional solutions without the use of energy dissipators. The superior reduction in seismic demand is attributed to the high stiffness and rapid yielding at low displacements (tenths of a millimetre) of SLB devices. Once these devices initiate yielding, they concentrate energy dissipation within themselves, regulating the seismic behaviour of the structure and safeguarding the remaining elements. In this regard, a decrease in seismic demands is observed, even for relatively low yield values in the devices.

4. References

- ASCE/SEI (2017). Seismic evaluation and retrofit of existing buildings. Virginia.
- ASCE 7-16 (2016). Minimum design loads and associated criteria for buildings and other structures. Virginia
- Bergman, D. M. y Goel, S. C. (1987) Evaluation of cyclic testing of steel plate devices for added damping and stiffness. Report no. UMCE87-10, Ann Arbor (MI, USA): The University of Michigan
- Bozzo L, et al. (2019). Modeling, Analysis and Seismic Design of Structures Using Energy Dissipators SLB, *Journal TECNIA Vol.29 N°2 July-December 2019*, Lima, Peru.
- CSI (2016). SAP2000. Analysis Reference Manual. CSI: Berkeley (CA, USA): Computers and Structures INC
- CRED (2020). UN Office for Disaster Risk Reduction. 'Human cost of disasters. An overview of the last 20 years 2000-2019'
- Franchioni G. (2001). Experimental investigations on semi-active and passive systems for seismic risk mitigation. ISMES
- Kobori, T. et al. (1992)«Development and application of hysteresis steel dampers, en Proceedings of the 10th World conference on earthquake engineering, pp. 2341-2346
- M. Pantoja, et al. (2020). Experimental vs Numerical Correlation for a shaking table test of a concrete precast model structure equipped with SLB devices, *17th World Conference on Earthquake Engineering*, Sendai, Japan.
- M. Pantoja, et al. (2020). Numerical analysis and experimental correlation of uncoupled concrete walls incorporating SLB devices, *17th World Conference on Earthquake Engineering*, Sendai, Japan.
- NTC-C-2020, Normas Técnicas Complementarias para el Diseño y Construcción de Estructuras de Concreto. Gaceta Oficial de la Ciudad de México, 2020.
- Tsai, K. et al. (1993) «Design of Steel Triangular Plate Energy Absorbers for Seismic-Resistant», Earthquake Spectra, Vol. 9, No. 3, pp. 505-528