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Two complex high rise buildings case studies equipped with SLB seismic devices.

Recommended Session: EAEE - Special Session 02: Performance-based seismic design of buildings and bridges using seismic protection devices: Seismic isolation, tuned mass dampers and energy dissipation systems

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Abstract: Seismic protection devices such as energy dissipators have been used in structures for many years. However, it has not been until the last years that computers allowed assessingthe full advantages of these devicesinlarge structures by means of nonlinear dynamic analysis. Previous analysis/design techniques for these devices were based on simplified linear approaches such as considering an equivalent increment to theglobal damping. In this paperwe evaluate the performance of theShear Link Bozzo (SLB) seismic dissipatorsof two real high-risebuildings, located in a seismic prone area. In the first casestudy we compare the performance of the bare structureto a similar protection but using Buckle Restrained Braces and the bare structure. In the second case study,we show that apotential rebar optimization can be achieved using SLBdevices without compromising the structural performanceand satisfying the code requirements in high-rise buildings. The use of SLB devices showednot only economic advantages but alsoachieve a better performance compared to the bare structure and the equipped with BRBs.

Keywords: Seismic dissipators, Shear Link Bozzo (SLB), non linear time –history analysis, building performance

1. Introduction

Since the 1980s, various energy dissipation or additional damping systems have been proposed both for seismic structural rehabilitation of buildings and for new structures (Bozzo&Barbat, 1999). Manyof these systems are relatively flexible (e.g. ADAS) or are expensive and complex to calculate (e.g. BRBs). The development of the BRB devices started in Japan (Watanabe, et al., 1988) and these devices consistof three elements: a steel core, a steel tube that confines it, and an interface between the two that can be made of concrete or mortar. The designof these devices is complex given their own configuration and interface, requiring full-scaletests to determine their design properties.

Shear Link Bozzo (SLB) energy dissipators began to be developed in the early 2000s and are a type of dissipator in the form of a vertical metal profile generated by milling. Since SLB's present very large in-plane rigidity, the devices start to yieldwith very low lateral displacements (tenths of a millimeter). In thistype of devices, there are no welds in the yielding zone, thus avoiding the generation of residual stresses and reducing the cyclic performance of the device (Franchioni G., 2001).

SLB devices have a large number of applications as they have shown to provide great versatility at a low cost. Currently, they are being used both in new buildingsand in rehabilitations. In this paper we assess the useof the SLB devices in two new high-rise buildings and theseismic performance in an earthquake prone areais evaluated. In addition, for the second case study, the behavior of the building achieved using SLB is also compared to the behavior of the same structure equipped with BRB devices.

2. SLB Dissipators

In order to characterize the properties of the SLB devices, full scale specimen tests were performed at the University of Cantabria, Spain in November 2020 (LADICIM, 2020). The results showed a stable hysteretic behavior, with convex area and no bottleneck, as can be seen in the hysteretic curve of one specimen in Figure 1. This figure also compares the hysteretic behavior of the specimen with the results of the finite element model used in the design process of the SLB devices showing a good agreement. In the numerical models the Von Mises isotropic hardening model (Chai, 2020) and the Nadai approximation for the behavior of the material (Nadai, 1937), was taken into account.

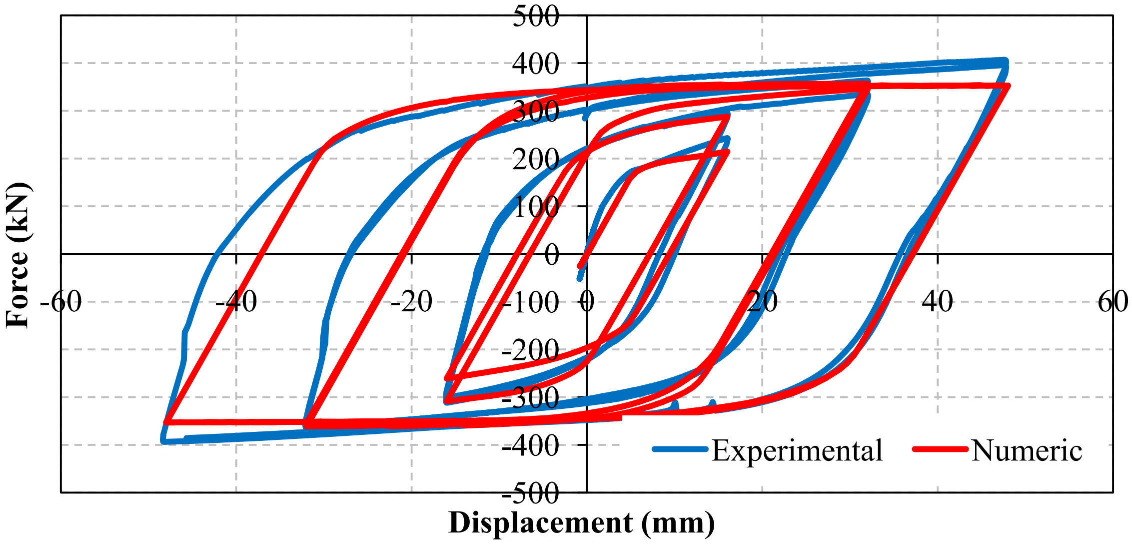

Fig. 1 – Force vs Displacement curve for SLB device (Bozzo, 2021)

Asthe area enclosed in the hysteretic curve is proportional to the energy dissipated, the SLB devices are presented as a good candidate not only for displacement control but also for extra energy dissipation in structures. More importantly, the devices reached displacements of +-50mm following the AISC-16 loading protocol (AISC, 2016) which implies an inelastic rotation of 0.18 and a length ratio of 1.1, a remarkably good behavior with a very high inelastic rotation for their length ratio.Comparing the SLB devices with eccentric braces, it can be seen, as shown in Figure 2, that the plastic rotation capacity is significantly higher than other reported eccentric braces (Ji et. al., 2016).

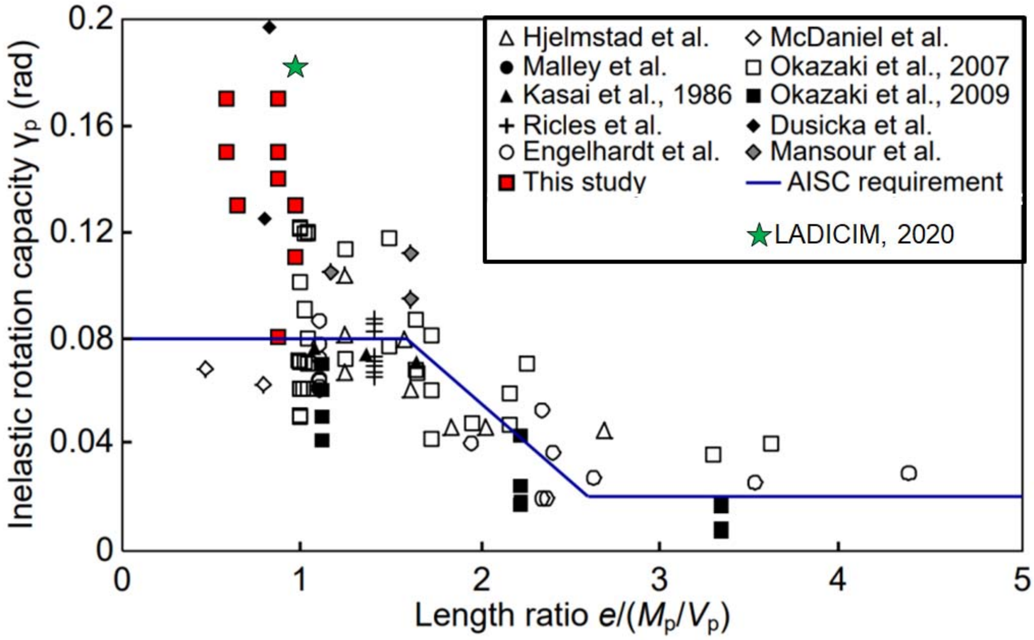

Fig. 2 – Inelastic rotation vs length ratio for different short shear links (Adapted Ji, et. al., 2016). The star presents the results of the SLB devices test (LADICIM, 2020)

The finite element models of the SLB (such as the one showed in Figure 1), although very accurate, are not practical or efficient for nonlinearanalysis of complex real structures with thousands of degrees of freedom. For this reason, simplified hysteretic models are required, such as the Wen model (Wen, 1976), which is commonly used for this type of devices. In this model nonlinear links are defined based on 4 parameters: $\boldsymbol{K1}$, $\boldsymbol{K1/K2}$, $\boldsymbol{F_y}$ and $\boldsymbol{n}$. $\boldsymbol{K1}$ is its elastic stiffness; $\boldsymbol{K1/K2}$ is the plastic to elastic stiffnessratio; $\boldsymbol{F_y}$ is the elastic limit and $\boldsymbol{n}$ is the plastification exponent that defines the curve between the initial slope and the post-yield slope. Wen's model allows simulating various elastoplastic, bilinear or linear responses, but not all its parameters have a clear interpretationwhich is why some authors have adapted some terms from their original model. Bozzo et al. (1996) defined the hysteretic behavior of the dissipator with the parameter$\boldsymbol{n} = 1$ or $\boldsymbol{n} = 2$giving an optimal smoothness to the hysteretic curve.

3. Case studies

In this document, two real projects under construction that incorporate SLBdevicesare studied. Building A is a 33-story building with a framed structure and building B consists of 38 levels (plus 5 underground parking) with more than 170m height and a total area of 1200m2 which makes it a highly complex building.

We studied theadvantages of the seismic protection systems by comparing the displacement and shear base results from the models of the structures with and without seismic protection. In this sense, we start from a 3D base model including all the loads and seismic actions using real seismic accelerationrecords compatible with the site-specific seismic hazard. Direct integration nonlinear time history analyses (NLTH) have been carried out, by means of 6 seismic recordsfor building A and 11 recordsin building B. All the records are accordant the ASCE standards (ASCE-7-16, 2016). Both structures were modeled using the finite elements software ETABS (CSI, 2016).

3.1. Case study A

The first case study, Building A, consist of an L shaped high-rise building shown in Figure 3. In the original project, two seismic protection alternatives were suggested for the building, one using BRB devices and the other using SLB devices.

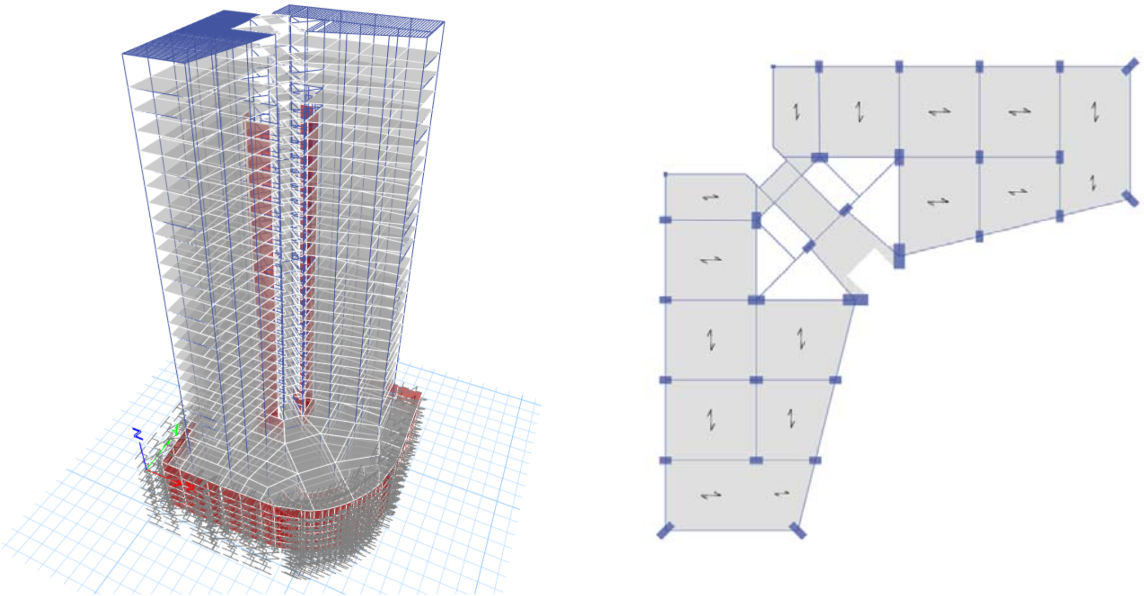

Fig. 3 – Case of study A. Isometric view of the building (left); plan view of the building (right)

As we can see in Figure 4, both systems substantially improve the behavior of the unprotected structure. The results in Table 1 show the average demand obtained from the NLTH analyses. The results show an important reduction of the inter-story drift ratio (MIDR) demand in both the building equipped with SLBs and the building BRBs. However, it can be observed a greater reduction of MIDR demand at the top levels (up to 13%) in the case of the structure with SLB devices compare to the one with BRS. In Table 1, the SLB dissipators present a higher MIDR demand reduction in most part of the structureexcept for the first four stories. We can observe that as the building increases in height, the improvement of the SLB with respect to the BRB also increases, showing a better overall performance of the SLB devices in this type of structures.

Table 1.Drfit Comparison between SLB vs BRB for each story in Building A

Underground – First floor	Story 2 to 5	Story 6 to 13	Story 14 to 22	Story 23 to Rooftop
From 10 to 14%	From 0 to7%	From 1 to 4%	From 5 to 12%	13%

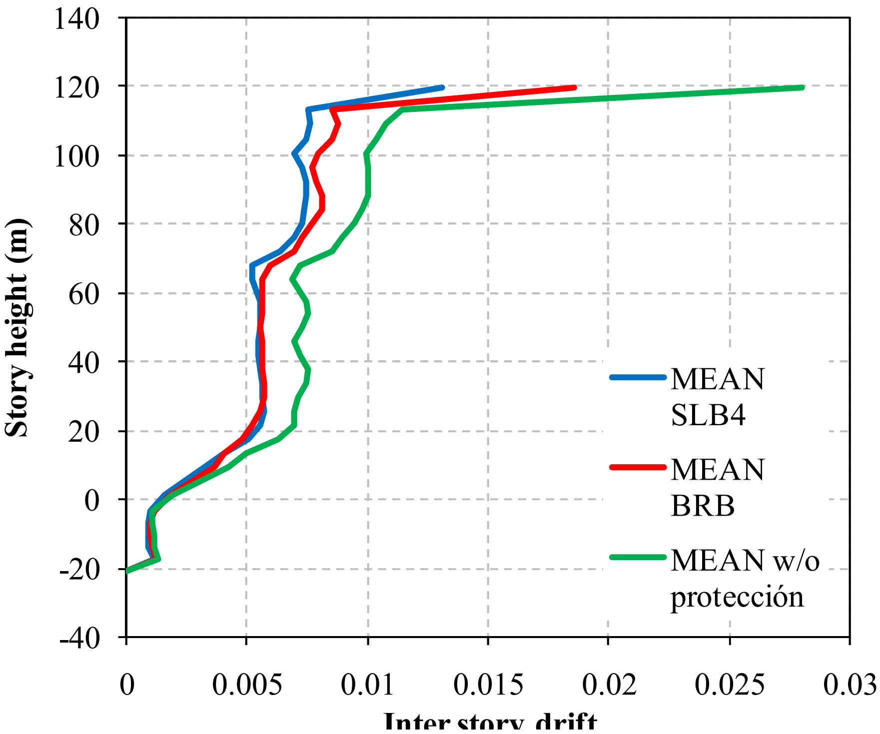

Fig. 4 – Average inter-story drift results from 6 different seismic records for the model: 1. With SLB; 2. With BRB; 3. Without protection

Table 2 shows the maximum base shearof the structure equipped with a SLB solution and a BRBs solution. The base shear is reduced, on average by 15% when employing SLB devices compared to the structure equipped with BRBs. It is important to mention that the cost of implementing SLB devices in this structure was about 10 times cheaper than the total cost of the BRBs system so a clear decision was taken by the owner.

Table 2.Average total base shear for each model

	BRB	SLB	%Reduction
Average base shear (kN)	78698.35	66846.48	15

3.2. Case study B

Case study B is a squared plan high-rise building with high complexity. Not only because it is over 170m tall but it also has large spans of up to 11 meters, double-height columns and significant variations in mass between floors, among other factors. In projects of these characteristics located in seismic prone areas, it is of paramount importance to ensure an efficient structurewithout compromising the seismic performance.

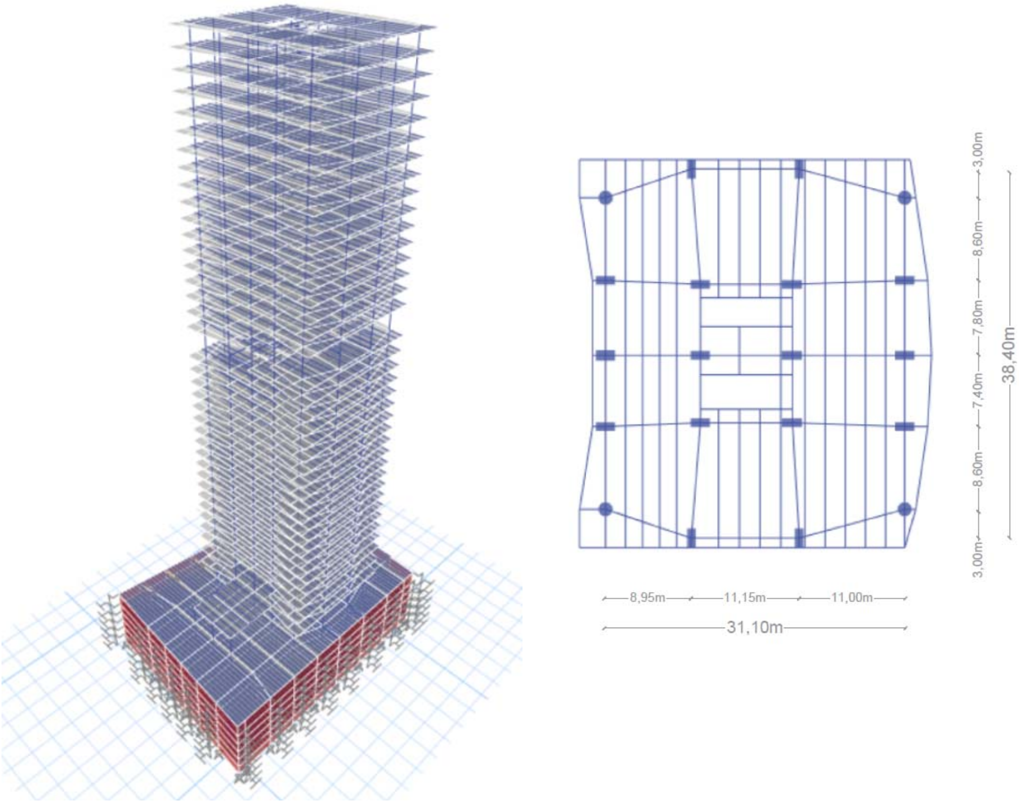

Fig. 5 – Case of study B. Isometric view of the building (left); plan view of the building (right)

Project B has no structural walls so it is a flexible frame structure. The fundamental period of the structure without seismic protection is 8.74seconds, and by usingthe SLB a reduction of the fundamental period to 7.9s is achieved (around 10% reduction). Also, it can be observed in Figure 6 that the structure without protection exceeds theinter-story driftlimit of the code. In order to reduce the lateral displacements,it is possible to increase the beams and columns sections but the architectural restrictions and the cost increment led to consider the use of seismic protection devices (SLB) to control the lateral displacements.

Compared to the structure without SLBs, the behavior of the structure equipped with SLBs improves notoriously by reducing 40% the inter-story dirft and allowing the structure to meet the code requirements. The amount of SLB installed is 242 units at different levels but not in all levels. One of the SLB characteristics is that they do not transfer axial load at their connections which allows them to be installed at the specify areas where they are required for stiffness.

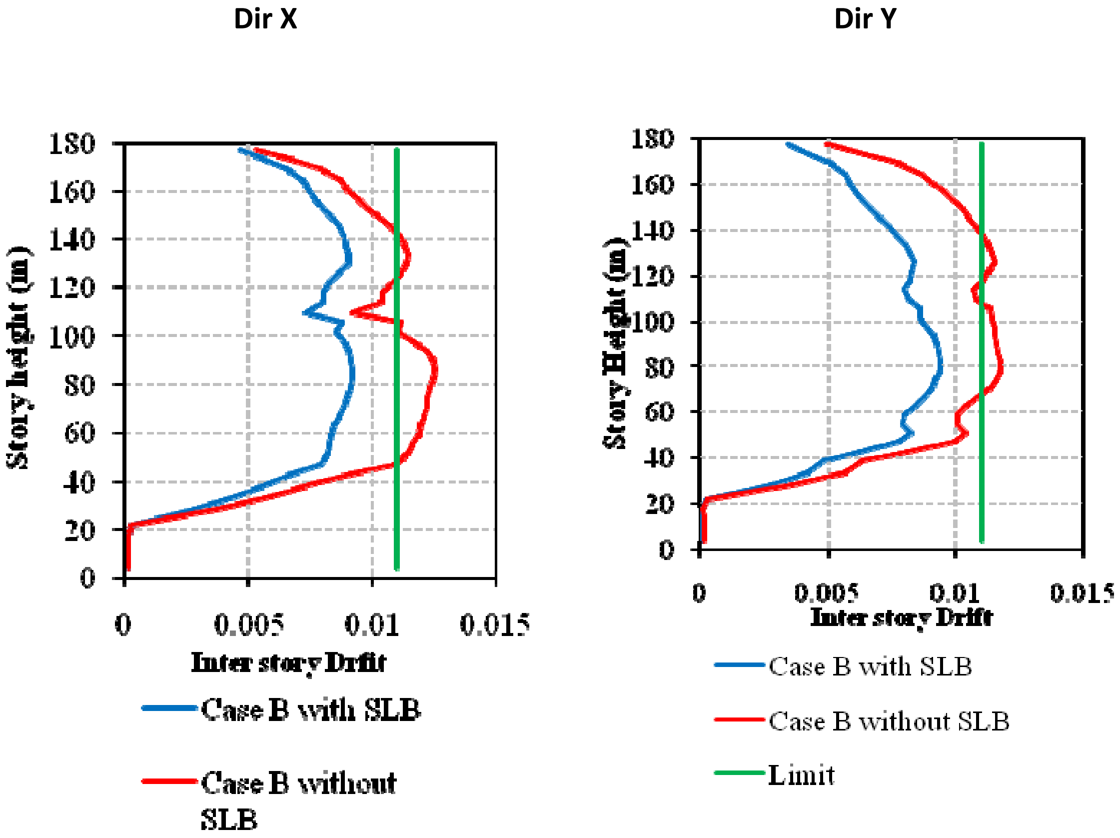

Fig. 6 – Average inter-story drift results from 11 different seismic registers with and without SLBs for direction X and Y

Table 3 shows the average maximum base shear force for the 11 signals of both the structure equipped with the SLB solution and without protection (bare frame). The base shear is reduced, in average, 11% for the option with SLB devices. Consequently, using these devices both the drift and the base shear are reduced.

Table 3.Average total base shear for each model

	Model without protection	Model with SLB	%Reduction
Average base shear (kN)	6716.14	5948.01	11

3.2.1. Complete nonlinear dynamic analysis

For the results obtained in chapter 3.2 we assumed non-linearity only for the SLB devices. A more complete and precise analysis of the structure considering also nonlinear plastic hinges in all elements was carried out. This analysis would be a more accurate representation of how the structure would behave during an earthquake and it would allow showing were the non linear hinges would be expected to appear. As this type of analysis has a large computational cost, for this paper we considered only one signal. As shown in Figure 7 the maximum drift was reduced by 50% using dissipators which is very similar to what we obtained in the previous analysis. Furthermore, the drift distribution is much uniform using SLB devices since for the bare frame and from levels 25 to 35 there is very large drift concentration caused by a large number of plastic hinges appearing at those levels. Consequently, in the bare frame a soft level is generated around the double height area of the tower, this behavior is not present in the structure with the SLB devices.

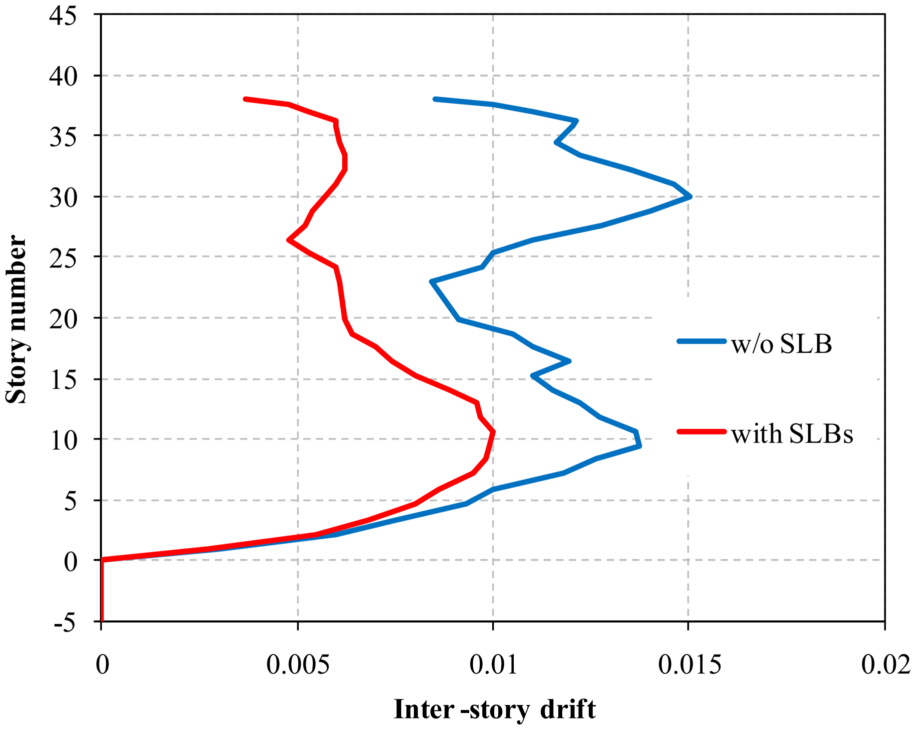

Fig. 7 – Inter-story drift for the models with and without SLBs using a complete nonlinear dynamic analysis

Regarding plastic hinges, we can observe that an important number ofbeams and columns in themodel without SLBs yield generating over 60 plastic hinges whereas in the model with SLBs present only 7 plastic hinges, only in beams, in this sense, protecting the building with SLB dissipators avoided the formation of plastic hinges in columns. This not only shows that the SLBs reduce ten times the apparition of hinges in the structural elements but that they allow the structure to concentrate the energy dissipation in the SLB devices which act like fuses, preventing damage and reducing significantly eventual long term damage reparation costs.

Another relevant aspect not considered in this article is that the use of SLB devices were used to reduce substantially the costsin reinforcement steel. A reduction of 15% the amount of steel reinforcement in beams was achieved with the SLB devices using aperformance-based design. Since each NLTH analysis took about 12hours and a minimum of about 11 signals is required it is clear that, for practical purposes, this type of optimization is time consuming. However, it is clear that actual computational capabilities allow to this type of analysis and result in a significantly overall cost reduction using seismic devices. Furthermore, concentrating plasticity in the SLB devices and not in beams, columns or walls is a more reliable solution that can prevent future repair costs after a seismic event.

4. Conclusions

The Shear Link Bozzo (SLB) devices represents a good solution protecting structures from induced vibrations due to earthquakes or wind. These devices provide a significant contribution reducing the inter-story drift and base shear. They also allow the structure to concentrate the plastic deformations in the devices, preventing the structuralelements from damage. This is a key difference compared to the old design of redundant ductility because this way the damage is concentrated in the devices and they are easy to check and replace if necessary.

The SLB dissipators, although being relatively new devices, have already been installed in more than 40 projects, including the two shown in this paper. For both project A and project B, a great improvement in the resilience of the building and a reduction in the damage suffered in the event of a potential earthquake can be observed. Comparing the results obtained with the BRB and SLB for project A, we observe that the latter solutiongenerates a lower inter-story drift ratio in most of the building, As the inter-story drift ratio is related to the structural and non-structural damage, less or no repairs are expected after seismic event. Due to the better performance and considerably lower cost, SLBs were the solution adopted for this project.

For case study B, we can observe an improvement in the inter-story drift and the story shear because of the original disposition of the supporting elements and the architectural restrictions originated a torsional first mode of vibration. Thanks to the SLBs in plane disposition this issue was resolved, leading to an overall improvement in the structure behavior. The final results led to a reduction of the amount of steel for the beams up to 15% for each floor resulting in great economic advantages for tall buildings especially.

Finally, it was also shown that for the full nonlinear analysis of the structure in Project B the structure without SLBs presented ten times the number of nonlinear hinges compared to the structure with SLBs. More importantly the second mode effects in the bare frame causes a soft story around level 25 which is fully avoided using the devices. This result is significant since it opens the door to structural steel optimization focused on concentrating damage in the SLB devices that are easy to inspect and eventually replace, compared to the damage in beams, columns or walls which in case of damage are expensive and complicated to repair.

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