Desempeño sísmico de un pórtico con disipadores de energía pasivos de placas ranuradas de acero

Seismic performance of frames with passive energy dissipation steel slit plates

Juan Pimiento*, Andrés Salas*, Daniel Ruiz¹*

* Pontificia Universidad Javeriana. COLOMBIA

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Resumen

En este artículo se evalúan dos tipos de disipadores de energía pasivos histeréticos metálicos (placas ranuradas de acero). Estos dispositivos son de bajo costo y de fácil construcción e instalación. Con ensayos en mesa vibratoria se estudió el desempeño sísmico de tres modelos estructurales: un pórtico sin disipadores de energía y dos pórticos con dos tipos de placas ranuradas de acero. Los modelos fueron instrumentados con acelerómetros, galgas extensométricas y deformímetros; y fueron sometidos a dos tipos de señales sísmicas: un sismo regional y un sismo de campo cercano. Los resultados de los ensayos de laboratorio sugieren que los pórticos con las placas ranuradas de acero tienen hasta un 90% menos de distorsión de entrepiso que el pórtico sin rehabilitación. Esto se debe a que las placas ranuradas de acero disipan una gran parte de la energía suministrada por los sismos y los daños sobre la estructura de soporte se minimizan.

Palabras claves: Disipación pasiva de energía, dispositivos de fluencia, placas ranuradas de acero, ensayos de mesa vibratoria, rehabilitación sísmica

Abstract

This paper evaluates two types of hysteretic passive energy dissipation devices (steel slit plates). These devices are low-cost and easy to build and install. The seismic performance of three structural models were studied with shake table tests: a frame without energy dissipation device and two frames with two types of steel slit plates. The models were instrumented with accelerometers, strain gages and LVDTs, and were subjected to two types of earthquakes signals: a regional earthquake and a near-field ground motion. The results of laboratory tests suggest that the frame with steel slit plates have up to 90% less seismic drift than the frame without rehabilitation. This is because steel slit plates dissipated a large portion of the input energy supplied by earthquakes and the damage to the parent structure was minimized.

Keywords: Passive energy dissipation, yielding devices, steel slit plates, shake table tests, seismic retrofitting

1. Introduction and justification

When ground motions act on a structure, they can seriously affect the structural elements, since they absorb the earthquake's input energy. This kind of damage entail complicated retrofit processes and many times the use or occupation of the structure has to be restricted (Karavasilis, et al., 2012).

Therefore, it is necessary to develop structural retrofitting techniques or methods for existing buildings, which in Colombia have become increasingly relevant in the last three decades. This need is justified in two aspects: most Colombian cities are located in areas with seismic risk of high and medium intensity; on the other hand, many existing buildings were not designed to resist seismic loads (Oviedo and Duque 2009).

Although in the last years some seismic retrofitting techniques have been introduced for existing buildings, concerning increased energy dissipation capacity, they differ from the traditional rehabilitation premise that has predominated in Colombia; that is, increasing the buildings' stiffness and strength mainly by reinforcing with concrete structural walls.

¹ Autor de correspondencia / Corresponding author:

Departamento de Ingeniería Civil. Pontificia Universidad Javeriana Colombia
E-mail: daniel.ruiz@javeriana.edu.co

Considering the above, Colombia saw the need to innovate by adapting a low-cost energy dissipation device that is easy to build, with the aim of using it in seismic retrofitting of existing concrete frames, as illustrated in the references of Hossain et al. (2011) and Marín and Ruiz (2005).

Specifically, they are dissipation devices based on steel slit plates, which, when strategically placed in the building, concentrate the damage and energy dissipation (by hysteresis) in the same devices, thereby reducing the damage in the structural elements.

2. Dissipation of the energy induced by an earthquake

In a structure subjected to ground motions, the law of conservation of energy transforms the input energy into elastic energy and dissipated energy (Medeot 2000), as shown in Equation 1:

$$E_I = E_P + E_K + E_\beta + E_H \quad (1)$$

Where:

E_I : Input energy.

E_P : Potential energy.

E_K : Kinetic energy.

E_β : Energy by equivalent viscous damping.

E_H : Energy by hysteretic deformation.

Figure 1 shows an analysis of the energy balance obtained for an inelastic system with a single degree of freedom subjected to an earthquake, with a structural period of 0.3 seconds and a yield strength of 20% its weight. Damping in relation to the critical point is 3%.

Figura 1. Balance energético de un oscilador simple inelástico sometido a una señal sísmica
Figure 1. Energy balance of a simple inelastic oscillator subjected to a seismic signal

In Figure 1 it can be seen how, at the beginning, all the energy is transformed into Elastic Energy (E_E), either in kinetic energy or (non-permanent) elastic deformations. But when the input energy increases, approximately 70% of the energy is dissipated by hysteresis (E_H) and the remaining one is dissipated by intrinsic damping of the structure (E_b).

In a frame, E_H appears when the stresses generated by the earthquake in the structural elements exceed the elastic region of the materials and, therefore, the structure resorts to the inelastic region. From then on, part of the energy induced by the earthquake produces inelastic deformations and damage. This is evident in phenomena like cracking, yielding and the appearance of plastic hinges.

The objective of the proposed energy dissipation technology is to maintain this large energy dissipation percentage by hysteresis, but reducing the damage in the structural elements. Therefore, we propose a system that canalizes the energy and the damage towards devices that benefit from the hysteresis of steel slit plates with a great ductility capacity to strain.

3. Hysteretic passive energy dissipation devices with steel slit plates

Currently there is a large variety of seismic energy dissipating devices in the world, which can be active, passive and/or semi-active. Figure 2 illustrates different energy dissipation techniques, and emphasis is put on metallic hysteretic passive energy dissipation systems, which are precisely the type of devices that are being dealt with in the present document.

Figura 2. Cuadro conceptual de disipación de energía
Figure 2. Energy dissipation conceptual diagram

Unlike other systems, passive dissipation systems do not depend on an energy source in order to operate. These systems entail a more economical mitigation strategy compared with other systems and their implementation has the following advantages (Sadek et al., 2003):

- Passive dissipation systems reduce the structure's response to external loads due to its increased damping and stiffness.
- Dissipation devices absorb great deal of the earthquake acting energy, preventing bigger damages in the building's structural system. Normally, most of these damages are produced in the dissipation devices, which can result in lower retrofit costs, since they can be replaced (Symans et al., 2008).

Passive dissipation by yielding absorb part of the energy generated in the structure through cycles of hysteresis, thus avoiding considerable structural damages. The energy that the devices receive makes them run smoothly and, in the worst of cases, devices fail but not the structural elements of the building. According to Xua et al. (2007), even in critical conditions such as near-field ground motions, dissipation through yielding can simultaneously reduce the displacement, acceleration and the energy that the structural elements must bear.

Hysteretic devices studied in the present work (Steel slit plate dissipation systems) are characterized because energy dissipation is produced by the yielding of steel, due to the relative displacements in the device (Karavasilis et al., 2012). This behavior can be modeled through hysteretic strength-displacement ratios. Their advantages are its stable behavior, good resistance to environmental factors and temperature.

Steel slit plates are located in the same plane of the frame that needs to be retrofitted (Figure 3), therefore, they normally operate by shear forces.

Figura 3. Disipador de energía tipo placa con ranuras sometida a esfuerzos cortantes
Figure 3. Steel slit plate energy dissipation system subjected to shear strain

During the development period of this type of dissipation system, both the possible locations of the plate in the structure and the type of slits in them (round, oval, polygonal) have been studied.

In order to guarantee the performance and avoid strain concentrations on undesired points of the slit plate, researchers like Benavent, Hirishi (1999), Kunisue, Koshika and Kurokawa (2000), Reyes (2001), Wada, Huang and Iwata (2000), Marín and Ruiz (2005), Fuentes, Martínez and Ruiz (2005), Chan and Albermani (2008), Chan, Albermani and Williams (2009), Karavasilis, Dimopoulos and Hale (2012), Chan, Albermani and Kitipornchai (2013), Saffari, Hedayat and Poorsadeghi (2013), Ghabraie et al. (2010), Oh, Kim and Ryuc (2009) have proposed different types of dissipation systems with high levels of equivalent hysteretic damping and very stable cycles of hysteresis.

Hysteretic passive energy dissipation devices with steel slit plates are low-cost given the nature of the material and because it is easy to manufacture them in metalworking workshops. These aspects are very important for developing countries.

4. Physical and mechanical characterization of the studied metallic hysteretic dissipation systems

The design of dissipation systems is similar to those established by Marín and Ruiz (2005) and Fuentes, Martínez and Ruiz (2005), based on the works of Reyes (2001), Hanson and Tsu Soong (2001) and Kunisue, Koshika and Kurokawa (2000).

Marín and Ruiz (2005) and Fuentes, Martínez and Ruiz (2005) worked on dissipation devices at a 1:2 scale; however, for the shake table tests presented in this document, the chosen scale was 1:3; therefore, the dimensions established by the original authors were modified by the scale factor. In both cases, the steel used was A-36. In Marín and Ruiz (2005) a slit plate with 6 columns was proposed and the reference Fuentes, Martínez and Ruiz (2005) proposed a dissipation device with 6 holes. Figure 4 shows the basic scheme for both dissipation devices and their dimensions at the 1:3 scale that will be used in the present study. The steel used to manufacture these slit plates was ASTM-A36. Each dissipation system included six additional holes to connect them to the structure to be rehabilitated. The thickness of these dissipation devices was 3.2 mm.

Figura 4. Dimensiones de disipadores histeréticos con placas ranuradas a) de 6 columnas Marín J. y Ruiz D. (2005) y b) con 6 agujeros circulares Fuentes R., Martínez M. y Ruiz D. (2005)
Figure 4. Dimensions of hysteretic dissipation devices with slit plates a) with 6 columns Marín and Ruiz (2005) and b) 6 holes Fuentes, Martínez and Ruiz (2005)

It should be mentioned that prior to the experimental tests, a numerical model was carried out that allowed determining that plastic hinges of the frame to be rehabilitated were generated in the slit plates of Figure 4 before than in the structural elements.

In order to characterize the material implemented for the manufacture of dissipation devices, stress tests were performed which determined that the yield strength of the material was 254 MPa and the rupture strength was 365 MPa. The material's maximum strain in relation to rupture was 17.5% (mm/mm).

In order to obtain the mechanical properties of the dissipation devices with slit plates of Figure 4, a frame was designed and built through which it was possible to simultaneously test two energy dissipation devices. This test is an adaptation of the reference Reyes (2001). In this experimental test, axial loads of a universal testing machine were transformed in a series of shear forces applied in the plane of the dissipation device, as shown in Figure 3. Strain gages were installed to determine the strength vs. displacement curve.

Each pair of dissipation devices was subjected to loading and unloading cycles without reloading, controlled by deformation (pseudostatic analyses). Based on these measurements, the basic characteristics of the dissipation device's behavior were established, such as yielding loads and deformations, elastic and inelastic stiffness. Figure 5 shows the assembly of the experimental test and the state of the dissipation devices at the end of the test, where it is evident that the slit plates were plasticized.

Figura 5. Montaje del ensayo de caracterización mecánica del disipador con placas ranuradas
Figure 5. Assembly of the mechanical characterization test of the dissipation device with slit plates

Data of the experimental test were adapted to a bilinear model, which is the most recommended for metallic dissipation devices of hysteretic behavior, according to Marín and Ruiz (2005) and Hossain et al. (2011). Figure 6 shows the experimental results with yielding theoretical data, which were determined with finite element analyses (elastoplastic constitutive model).

Figura 6. Curvas experimentales de fuerza cortante vs. desplazamiento en el plano de los disipadores de energía evaluados
Figure 6. Experimental curves of shear force vs. displacement in the plane of the evaluated energy dissipation devices

5. Shake table tests

Tests were carried out in the shake table of the Laboratory of Tests and Trials of the Pontificia Universidad Javeriana (Colombia). The device consists of a table driven by a dynamic actuator with load capacity of 100 kN and total displacement of 250 mm (± 125 mm) in uniaxial direction. The platform of the shake table is a square of 1.5 m each side and the actuator-table assembly can generate accelerations up to 5.0 g in structural models of up to 15 kN in weight.

5.1 Studied steel frame

The steel frame is built on a 1:3 scale, and it is constituted by four columns distributed in three levels. The floor slab height is 0.75 m for a total height of 2.25 meters. The structure's floor plan is a square of 1.30 m side and in each level there is a grid-type structure where the mass of the system is located. The A36 steel sections of the beams and columns are tubular with 30 mm square section and 2.5 mm thickness. The joints of the frame are welded.

Models were implemented with 4 strain gages, 4 seismic accelerometers (one per floor) and 4 electronic LVDTs (one per floor). A data collection system was used which registered 2,000 data per second for each one of the 12 channels. The displacement and the force generated by the dynamic actuator were also registered. With the displacements of each floor, the slab distortion was determined as a percentage of the height (seismic drift), which is the value that in the technical and scientific literature is related to damage levels and the effectiveness of the passive energy dissipation devices.

The frame was tested with and without retrofitting with the two types of dissipation devices shown in Figure 4. These devices were installed in the axis aligned with the direction of the ground motion applied. Two dissipation devices were installed in each level, in such a way that the two flat frames directed towards the motion application had 3 dissipation devices each for a total of 6 dissipation devices in the spatial frame. Figure 7 shows the frame rehabilitated with energy dissipation devices with 6-hole slit plates. As part of the experimental design, non-linear numerical models were developed for the frame with and without dissipation devices in a finite element software. These models proved that the location, size and geometry of the energy dissipation devices were adequate to improve the frame's seismic behavior.

Figura 7. Imagen de pórtico rehabilitado con placas ranuradas con 6 agujeros circulares
Figure 7. Image of the frame retrofitted with slit plates with 6 holes

According to the design conditions for hysteretic passive energy dissipation devices with steel slit plates, the assembly requires braces to provide a stiff connection so that the input energy to the system is concentrated on the dissipation devices and not on the bearing elements. The installation of each dissipation device to the frame was made with two braces. Each brace was formed by 2 angle profiles with wings of 50 mm each side and 6.35 mm thick for a total of 4 angle profiles per dissipation device.

5.2 Earthquakes Used

Seismic signals were used in accordance with the seismic threat of Bogota, capital city of Colombia. Two of the seismic signals of the reference Marín and Ruiz (2005) were used. One of the signals corresponds to an earthquake near the city of Bogota, with epicenter of less than 5 km (Figure 8a). The other signal corresponds to a regional signal, with epicenter at 40 km (Figure 8b).

Figura 8. Señal de aceleración vs. tiempo para registro de a) sismo cercano y b) sismo Regional
Figure 8. Acceleration signal vs. registration time of a) near-field earthquake and b) regional earthquake

The signals above were modified according to Harris and Sabnis (1999) in relation to the scale models (similitude laws), so that the seismic signal that generated motions in the steel frame holding the instruments had a lower signal duration but a higher acceleration level.

5.3 Experimental estimate of period values for analyzed models

With the purpose of calculating the experimental period of the three types of models tested on the shake table (without dissipation devices, with dissipation device with 6-column slit plates, and with dissipation device with 6-hole slit plates), free vibration measurements were taken. This period was used to calibrate the numerical models elaborated in the software SAP 2000 CSI (2012). Table 1 shows the comparisons of the structural periods.

Tabla 1. Resumen de resultados de los periodos fundamentales de la estructura
Table 1. Summary of the results of the structure's main periods

Estructura Tipo/ Structure Type	Periodo estimado con SAP2000 (s)/ Estimated Period with SAP2000 (s)	Periodo determinado experimentalmente (s)/ Period determined experimentally (s)
Sin Disipadores de energía/ Without Energy Dissipation Devices	0.210	0.225
Con Disipadores de energía de placas ranuradas con 6 columnas/ With Slit Plate Energy Dissipation Devices with 6 Columns	0.091	0.094
Con Disipadores de energía de placas ranuradas con 6 columnas/ With Slit Plate Energy Dissipation Devices with 6 Columns	0.043	0.047

In Table 1 it is evident that the presence of the slit plate dissipation device stiffens the frame, which is reflected in the decrease of its natural vibration period. Likewise, slit plate dissipation devices with 6 holes are stiffer than those with 6 metallic columns, as shown in Figure 6.

5.4 Floor slab distortion (seismic drift) and behavior of the models with ground motion signals on the base

Figures 9 and 10 show the experimental results for the more critical slabs distortions (seismic drifts) during the tests performed on the shake table. The critical drift is presented for the two analyzed earthquakes and each model with slit plate energy dissipation devices. Floor slab distortions are calculated as the higher floor displacement less the lower floor displacement divided by the floor height (in %). Each chart shows the drift of the structure with and without retrofitting with dissipation devices.

Figura 9. Deriva sísmica máxima en el pórtico de acero rehabilitado con placas ranuradas de 6 columnas
Figure 9. Maximum seismic drift in the steel frame rehabilitated with slit plates with 6 columns

Figura 10. Deriva sísmica máxima en el pórtico de acero rehabilitado con placas ranuradas con 6 agujeros redondos
Figure 10. Maximum seismic drift in the steel frame rehabilitated with slit plates with 6 holes

Table 2 presents a summary of the maximum drift values for each experimental model.

Tabla 2. Resumen de resultados de los periodos fundamentales de la estructura
Table 2. Summary of maximum drifts results for models tested in the shake table

	Niveles/Levels	Sismo Cercano/Near-field Earthquake	Sismo Regional/ Regional Earthquake
Sin disipadores/ Without dissipation devices	3 a 2	0.47 %	0.60 %
	2 a 1	0.64 %	0.89 %
	1 a cimentación/1 to foundations	0.74 %	1.34 %
Con disipadores ranurados de 6 columnas/ With Slit Plate Energy Dissipation Devices with 6 Columns	3 a 2/ 3 to 2	0.10 %	0.15 %
	2 a 1/ 2 to 1	0.18 %	0.25 %
	1 a cimentación/1 to foundations	0.30 %	0.35 %
Con disipadores ranurados con 6 agujeros redondos/ With Slit Plate Energy Dissipation Devices with 6 Holes	3 a 2/3 to 2	0.07 %	0.07 %
	2 a 1/3 to 2	0.10 %	0.13 %
	1 a cimentación/ 1 to foundation	0.09 %	0.11 %

According to the above results, a relevant drift reduction is observed when retrofitting the frame with hysteretic energy dissipation devices with steel slit plates. The frame without dissipation devices had a maximum drift of 1.34%, the retrofitted frame with 6-column slit plates had a maximum drift of 0.35%, and the frame retrofitted with 6-hole slit plates had a maximum drift of 0.13%. These results imply a 74% and 90% reduction in the maximum drifts, which is consistent with the references of Marín and Ruiz (2005), and Fuentes et al. (2005). These reductions are directly reflected in lower stress levels for beam-column joints and the automatic damage reduction in non-structural elements. According to the above results, even if both devices generate a considerable improvement in the frame's mechanical behavior, the dissipation device based on slit plates with holes has a greater and better effect on the structural system, although it is clear that this device is stiffer and stronger.

In order to verify that the dissipation devices were contributing with stiffness, strength and ductility to the retrofitted frame (with 6-column steel slit plates), a frequency scanning with controlled displacement of the shake table was carried out. Therefore, and for 2 mm displacement of the shake table (with a sinusoidal function), the motion frequency was increased from 1 Hz to 10 Hz.

Total displacements in the frame's deck were simultaneously registered. It should be noted that the resonant frequency of the frame was 10.6 Hz (0.094 s). Figure 11a shows this displacement record of the deck. It is evident that when achieving at 97 seconds a total displacement of 8 mm (relative displacement of 6 mm) at the frame's resonant frequency, loading and unloading cycles were induced on the dissipation devices that originated a fatigue failure in them, as shows Figure 11b.

Figura 11. a) Desplazamiento total en la cubierta para diferentes frecuencias y una misma amplitud de desplazamiento de la mesa vibratoria. b) Falla de los disipadores por fatiga

Figure 11. a) Total displacement in the deck for different frequencies and the same displacement amplitude of the shake table. b) Fatigue failure of the dissipation devices

In order to get the indicated result, it was necessary to apply 630 loading and unloading cycles to the hysteretic dissipation devices, which is not very likely to occur during a real seismic event, when they would be subjected to 10 loading and unloading cycles at most, with strengths similar to yield strengths. This suggests that this type of energy dissipation devices have stable hysteretic cycles, with an adequate level of energy dissipation and reduced damage in the structural and non-structural elements as a consequence of lower seismic drift levels.

6. Conclusions

- *The hysteretic passive dissipation devices with steel slit plates installed in the analyzed frame modified its dynamic characteristics. Therefore, the frame's fundamental period decreased from 0.22 seconds to 0.094 seconds and 0.047 seconds for the structure with slit plate dissipation devices with columns and holes, respectively.*

- Dissipation devices were able to absorb most of the input energy of the shake table's ground motions. Due to the energy dissipation capacity of the slit plates in these devices, they were able to reduce the strengths acting directly on the frame's structural elements. Thus, the seismic vulnerability of the frame was reduced.
- According to the experimental results, a significant reduction was obtained in the slab floor distortion for the analyzed earthquakes in all levels of the frame. Dissipation devices with slit plates with holes reduced the maximum drift by 90%, while dissipation devices with slit plates with metallic columns reduced the drift by 74%.
- The good performance of rehabilitation depends on the design of the dissipation devices to be implemented. The present work was developed based on a specific frame, with inherent dynamic characteristics, which was analyzed under previously defined seismic effects. Therefore, in order to retrofit a structure with this type of slit plate dissipation device it is necessary to carry out a prior dynamic analysis of the structure considering the seismic risk of the building.

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