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ENERGY DISSIPATION PLATFORMS BASED ON WIRE ROPE ISOLATORS FOR THE SEISMIC PROTECTION OF EQUIPMENT

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Abstract

This paper summarizes the developments of experimental studies to assess the seismic performance of energy dissipation platforms based on wire rope isolators for the mitigation of the seismic effects on equipment located in different floors of different buildings. Two types of platforms supporting simulated equipment were tested: (1) platforms consisted of steel plates sandwiched by wire rope isolators in different configurations, and (2) a platform consisted of two steel plates sandwiched by a set of wire rope isolators and a set of rolling balls. Simulated equipment comprised non-slender rigid blocks and slender frames. Platform-simulated equipment settings were subjected to earthquake shaking of different intensities from measured accelerations records on multistory instrumented buildings, from past experimental testing, and from numerical simulations. These studies are aimed: (1) to experimentally evaluate the three-dimensional seismic performance of several platforms based on different configurations of wire rope isolators; (2) to assess the seismic energy-absorbing capacity of the platforms and their effects on the seismic response of slender frames holding equipment; (3) to characterize the seismic performance of new configurations of wire rope isolators to reduce/eliminate rocking responses; and (4) to study the effectiveness of a hybrid frictional energy dissipation platform based on wire rope isolators and rolling balls.

The experimental responses demonstrated that the energy absorbing capacity of platforms based on wire rope isolators can control deformations of slender rigid frames. This outcome suggests that to secure the effectiveness of the platforms controlling deformations on slender frames, the frames that the platforms support must be relatively rigid. As expected and because of the slenderness of the frames supported by platforms that provide three-directional coupled flexibility, seismic responses of slender frames were controlled by rocking on the platforms based on wire rope isolators configured in shear/roll, and in compression/shear/roll. Proof of concept studies demonstrated that rocking may be controlled when adjusting the distance between the equipment’s center of mass and the center of stiffness of the platform by rotating the isolators. Asymmetrical arrangements of isolators in shear and in roll lead to different effective fundamental periods in the horizontal directions of the platforms. The asymmetric lateral stiffness provided by the wire ropes configuration on the platforms may be favorable when defining the dynamic properties of the platforms to protect equipment at different floors and in buildings with asymmetric plan configurations. The rolling balls increased significantly the effective damping ratio of the hybrid frictional isolation platform. The first mode equivalent damping ratio was up to 29%, and the restoring stiffness of the system is controlled by the effective stiffness of the wire rope isolators on the arrangement.

Keywords: Isolation/energy dissipation; Equipment; Wire rope isolators; Rolling balls; Slender frames

1. Introduction

Seismic isolation and energy dissipation mechanisms are extensively proven for global seismic protection by significantly reducing seismic demands on structures, buildings contents, and attached equipment. Despite the evidence on the effectiveness of isolation interfaces and energy dissipation on the mitigation seismic effects, the majority of existing essential buildings are still conventionally fixed base to their foundations. Fixed base essential facilities are furnished with essential equipment, such as specialized, high-tech equipment, telecommunication, computer technology, and emergency power-generating equipment. To avoid disastrous seismic impacts on these facilities due to loss of functionality of the essential equipment, the engineering of seismic protective mechanisms within the equipment is necessary. However, reliable and validated seismic strategies to locally protect essential equipment in multistory buildings are currently scarce. This scarcity may be due in part to the additional challenges that brings the definition of seismic protection mechanisms for equipment in multistory buildings; particularly, when trying to control absolute accelerations in different floors that are amplified depending on the dynamic response of the building; and to control absolute displacements of equipment at higher floors that may require significant free space to accommodate the movement of the equipment-protective mechanisms. Currently, there are few commercially available isolated floors and platforms for light weight equipment that use complex setups to lengthen the isolation period to achieve mitigation of accelerations at lower floors.

A research effort is underway to evaluate the seismic performance of different isolation/energy dissipation platforms for the local protection of equipment in essential multistory buildings. Specifically, this paper presents experimental findings on the seismic performance of energy dissipation platforms based on wire rope isolators for the mitigation of the seismic effects of equipment located in different floors of buildings. The mitigation of seismic effects on equipment supported by the platforms is envisioned via the implementation of strategic settings with relatively stiff-energy-absorbing interfaces using wire rope isolators and rolling balls to enhance the energy dissipation capacity of the system. Wire rope isolators are mountings conformed of sets of high-tensile strength steel twisted wires between metal retainers. The geometric arrangements of the strands provide three-directional flexibility and energy is dissipated by rubbing and friction between the individual strands. Wire rope isolators are traditionally applied for shock and vibration isolation of industrial machinery. In the early 90's, Demetriades et al. [1] pioneered experimental studies on a set of wire rope isolators for seismic protection of frames to hold computer equipment under seismic shaking. The study reported that frames supported by a set of stiff wire rope isolators performed better under unidirectional-horizontal earthquake shaking than the frames locked at the base; however, these experimental studies also evidenced significant rocking responses of the frames supported by sets of wire rope isolators.

To increase knowledge in strategies using wire rope isolators for the seismic protection of relatively light-weight slender frames holding computer equipment, experimental studies are carried out on the seismic performance platforms based on helical wire rope isolators. This paper summarizes findings of studies aimed: (1) to experimentally evaluate the three-dimensional seismic performance of several platforms based on different configurations of wire rope isolators; (2) to assess the seismic energy-absorbing capacity of the platforms and their effects on the seismic response of slender frames holding equipment; (3) to characterize the seismic performance of new configurations of wire rope isolators to reduce/eliminate the rocking responses; and (4) to study the effectiveness of a hybrid frictional energy dissipation platform based on wire rope isolators and rolling balls. The experimental studies reported herein consisted of earthquake simulation tests of different platforms supporting simulated equipment under three directional shaking. The simulated equipment consisted of non-slender rigid blocks and slender frames. The testing specimens were subjected to earthquake shaking of different intensities from measured accelerations records on multistory instrumented buildings [2], from past experimental testing [3], and from numerical simulations. In an intent to characterize the dynamic behavior of the platforms, testing settings conformed of steel plates placed over the different platforms were subjected to sinusoidal displacements that were input by the earthquake simulator. (Standard testing methodologies for the platforms' characterization were not possible since the only testing option available was the earthquake simulator.) Specific details about these platforms can be found at [4-6].

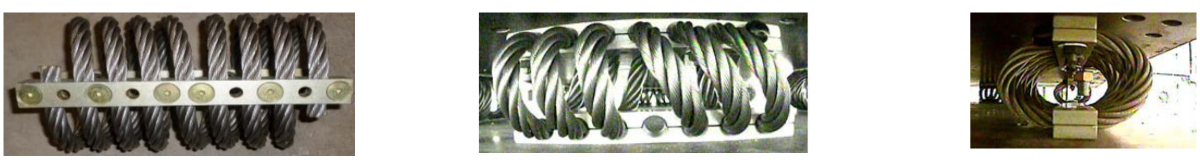
2. Experimental responses of platforms based on wire rope isolators

The experimental studies included several platforms consisting of steel plates sandwiched by wire rope isolators in different configurations, hereafter called platforms. Several platforms with wire rope isolators configured as commonly implemented for vibration isolation are included in the study. The experimental three-dimensional seismic performances of the platforms are evaluated to assess the seismic energy-absorbing capacity of the platforms and their effects on the seismic response of slender frames holding equipment. Also, a configuration of rotated wire rope isolators is explored to demonstrate the possibility of reducing/eliminating rocking responses on the platforms supporting slender equipment. The studies involved these platforms supporting flexible and rigid frames holding different weigh sets to simulate different systems. This section summarizes the main experimental findings on the responses of these platforms.

2.1. Description of the platforms

For vibration isolation purposes, wire rope isolators are mostly configured working in shear and roll. One main design parameter on the definition of the wire rope stiffness for vibration isolation is the weight to be supported by the system, symmetric horizontal stiffness arrangements do not primarily control the system configuration. Fig. 1 presents photographs of a wire rope isolator as traditionally installed in shear and roll. Lateral wire rope isolators are recommended to provide laterally support to slender equipment (height is twice larger than the width [7]) for vibration isolation installations; however, the testing settings herein did not included lateral support to test frames standing alone to be able to study slender critical installation conditions.

Applications of wire rope isolators for vibration isolation also include installation with isolators' 45° oriented to have isolators working in compression/shear/roll, hereafter referred as compression/shear/roll configuration. Fig. 2 presents the plan view of one of the platforms for the testing setup in shear/roll, and the platforms' elevations for the shear/roll setup and the compression/shear/roll setup. The plan view on Fig. 2 illustrates the asymmetric horizontal stiffness of the system having a total of six isolators working in each horizontal direction; in *x* direction, the system has four isolators in roll and two isolators in shear; while in *y* direction, the platform has four isolators in shear, and two in roll. Because of the asymmetric plan distribution of the isolators, the measured effective stiffness of the system in the *y* direction is larger than that in the *x* direction. In this shear/roll testing setup using wire rope isolators CB61400-17 [7], the measured initial horizontal effective stiffness of the system supporting 5.2 kN, under 3 Hz unidirectional sinusoidal excitations, and at maximum displacement of 25 mm, are 431 N/mm, and 510 N/mm in *x* and *y* directions, respectively.



Plan view Shear Roll

Fig. 1 – Wire rope isolator as traditionally installed in shear and roll

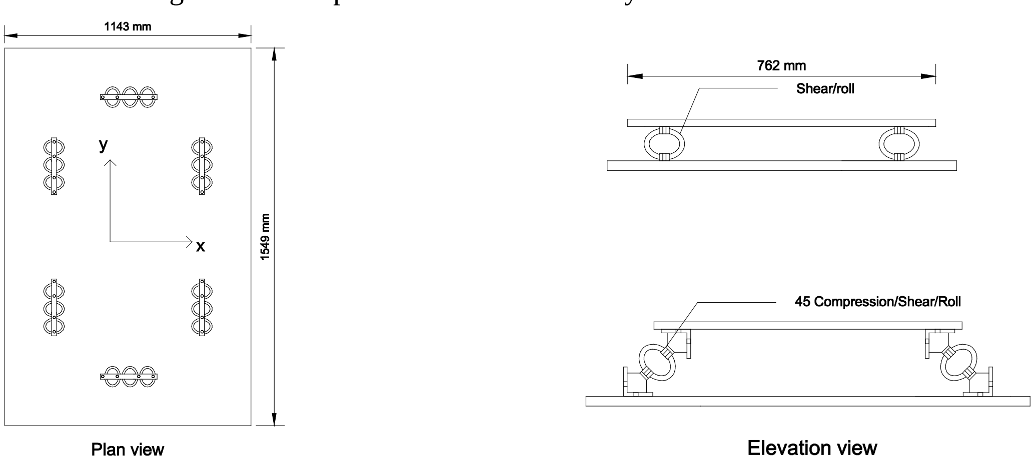
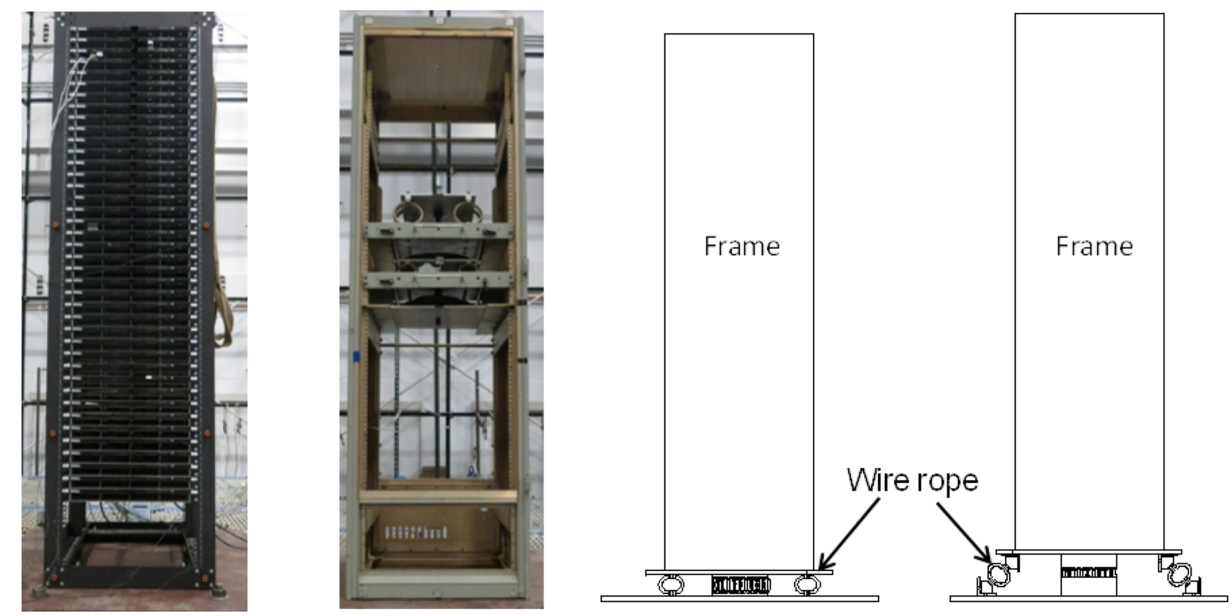


Fig. 2 – Plan and elevation views of platforms configured as commonly implemented for vibration isolation

The platforms were studied separately supporting two different frames and steel plates' settings. Fig. 3 presents details of the two different frames and sketches of the platforms. Further, in an intent to characterize the properties of the platforms, a testing set-up consisting of steel plates with a total weight of 5.2 kN placed over the platforms was subjected to sinusoidal input displacements that were input by the earthquake simulator.

To demonstrate how the flexibility of the slender frames affect the performance of the platforms, the platforms were studied separately supporting a flexible and a rigid frame. Frame 1, a computer server's frame (in Fig. 3), is characterized as a flexible and slender. The dimensions of the frame are 914 mm × 610 mm × 2210 mm. This frame is holding 40 servers resulting in a total weight of 4.45 kN. The estimated fundamental periods of frame 1 in the fixed base condition in the longitudinal and transversal directions are 0.54 s and 0.57 s, respectively. Frame 1 is tested standing alone to create a slender critical installation. It is worth noting that the common installation of this type of frames on data centers do not include standing alone frames as the one included in this testing setting; in daily operations, a line of several frames are installed next to each other forming relatively non-slender blocks. Fig. 4 presents photographs of the flexible frame supported by two platforms, one with wire rope isolators in shear/roll and the other with wire ropes isolators in compression/shear /roll. Frame 2 (Fig. 3) is considered as a relatively rigid frame, its dimensions are 762 mm × 559 mm × 1880 mm. The estimated fundamental periods of frame 2 in the fixed base condition in the longitudinal and transversal directions are 0.22 s and 0.13 s, respectively. The frame 2 holds a total weight of 2.89 kN.



Frame 1: height 2210 mm   Frame 2: height 1880 mm   Shear/roll   45° degree compression/shear/roll

Fig. 3 – Photograph of a flexible and a rigid frame and illustration of frames on platforms

2.2 Platforms controlling deformations on the rigid frame.

This section presents sample peak responses of the deformation of the slender frames holding simulated equipment supported on the two different platforms, shear/roll and compression/shear/roll, and in the fixed base configuration. To demonstrate the deformation control capability of the platforms supporting the rigid frame and amplification of deformations in the flexible frame, Table 1 presents the resultant peak (*x*-*y* plane) deformations on the two frames, flexible and rigid, for selected tests that include input ground and floor accelerations. The input accelerations consisted of a set of recorded ground and floor motions from a 4-story commercial building at Watsonville, California, during 1991 Loma Prieta earthquake (Station CSMIP 47459), and two ground motions recorded during 1994 Northridge (Station CSMIP 24571) and during 2010 Chile (Concepcion station) earthquakes. The supporting platforms mitigated significantly peak deformations on the rigid frame. The comparison of the deformations of the rigid frame on the fixed base setup with those deformations on the frame supported by the platforms, illustrate reductions of deformations ranging from 72% to 90%. Further, the deformations on the rigid frame supported on the platform using the compression/shear/roll configuration were mostly of less magnitude than those of the rigid frame supported by the platform with shear/roll configuration, with differences ranging from -35% (smaller magnitude) to +5% (larger magnitude). The later comparison indicates that the orientation of the isolators has an effect on the platform effectiveness controlling deformations. In contrast to the rigid frame experimental observations, the peak deformations on the flexible frame were significantly amplified by the platform. The deformations on the flexible frame supported by the platforms are 16% to 62% larger than those of the frame in the fixed base condition. This expected response amplification for the flexible frame is due to the dynamic interaction between the platform and the flexible frame. These results demonstrated that to secure the effectiveness of the platforms controlling deformations on the slender frames, the frames that the platforms support must be relatively rigid. Hereafter, the responses of the platforms supporting the flexible frame are omitted.

Shear/roll Compression/shear/roll Wire rope isolator 45° oriented

Fig. 4 – Flexible frame on the two platforms: shear/roll and compression/shear/roll

Table 1 – Peak deformation of frames for different configurations

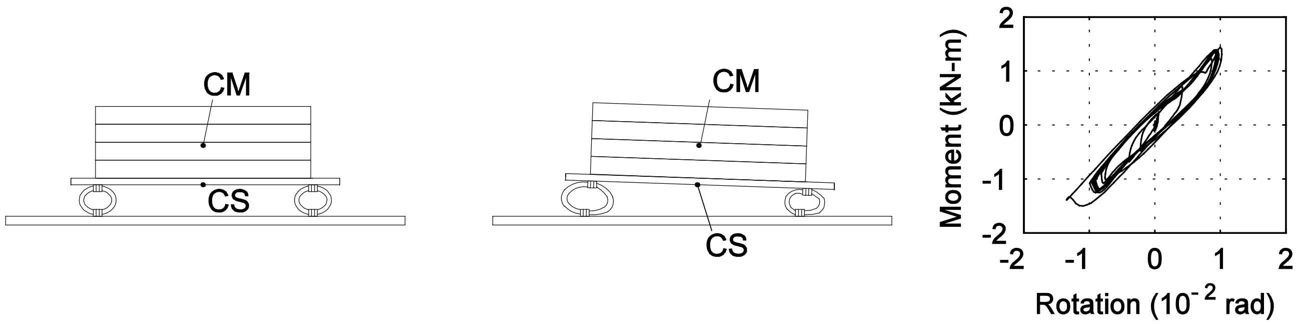
No.	Frame	Input	Station	Intensity (%)	Maximum deformation (mm)		
					S/R[1]	C/S/R[2]	Fixed
1	Rigid	Loma Prieta ground motion	CSMIP47459	50	4.3	3.7	35.6
2	Rigid	Loma Prieta ground motion	CSMIP47459	100	20.7	14.4	75.2
3	Rigid	Loma Prieta 2nd floor motion	CSMIP47459	50	8.1	5.3	40.6
4	Rigid	Northridge ground motion	CSMIP24332	100	4.1	4.3	17.9
5	Rigid	Chile ground motion	CONSP	75	17.8	15.3	66.0
6	Flexible	Northridge ground motion	CSMIP24332	50	30.5	36.8	24.6
7	Flexible	Northridge ground motion	CSMIP24332	100	58.2	63.5	44.7
8	Flexible	Northridge ground motion	CSMIP23634	50	12.2	17.0	10.5
9	Flexible	Loma Prieta ground motion	CSMIP47459	100	19.6	21.1	16.3
10	Flexible	Loma Prieta 2nd floor motion	CSMIP47459	100	48.8	56.1	39.9

[1]Shear/roll

[2]Compression/shear/roll

2.3. Rocking responses of the platforms

Rocking responses on the platforms in shear/roll and compression/shear/roll are expected because of the slenderness of the frames supported by platforms that provides coupled three-directional flexibility. In this section, the rocking responses of the shear/roll platform are described using experimental evidence. A slender frame has the center of mass significantly higher than the center of stiffness of the wire rope platform. The center of stiffness of the platform is defined as the intersection of horizontal reacting forces. The center of stiffness of the platform is located at the connection plane between the platform and the frame. Fig. 5 presents the un-deformed and deformed configurations of the platform. The center of both mass and stiffness of the system are displaced and rotated due to the simultaneous lateral displacement and rotation of the platform, leading to isolators under compression in one side of the platform and isolators under tension in the other side. The isolators in tension and compression have asymmetric behavior; the isolators in compression are softer than those in tension because of the helical shape of the isolators. Resisting moments from the wire rope platform are counteracting the overturning moments of the slender frame that are directly related of the distance between center of mass of the frame and center of stiffness of the platforms. Fig. 5c presents an example of the rocking response (moment rotation relationship) of the wire rope platform supporting 5.2 kN artificial mass under a 3 Hz unidirectional sinusoidal excitation in the *y* direction. The effective rotational stiffness and damping estimated for this case is 120 kN·m/rad, and 19.1 %, respectively. The force-displacement relationship can be found in Fig. 8 on section 2.5. Fig. 6 presents the history of rotations, i.e., rocking responses of platform under 75% Chile Concepcion ground excitations. Fig. 7 presents the moment-rotation relationship under 75% Chile Concepcion ground excitations.



(a) Un-deformed configuration (b) Deformed configuration (c) Sample moment-rotation loop

Fig. 5 – Definition of rocking for original design of the wire rope platform for vibration isolation

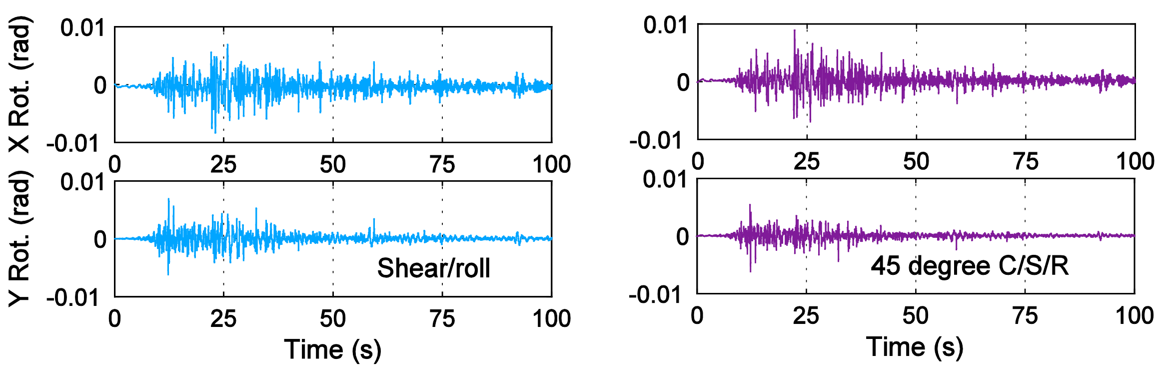


Fig. 6 – Time histories of the rotation of the platform under 75% Chile Concepcion ground excitation

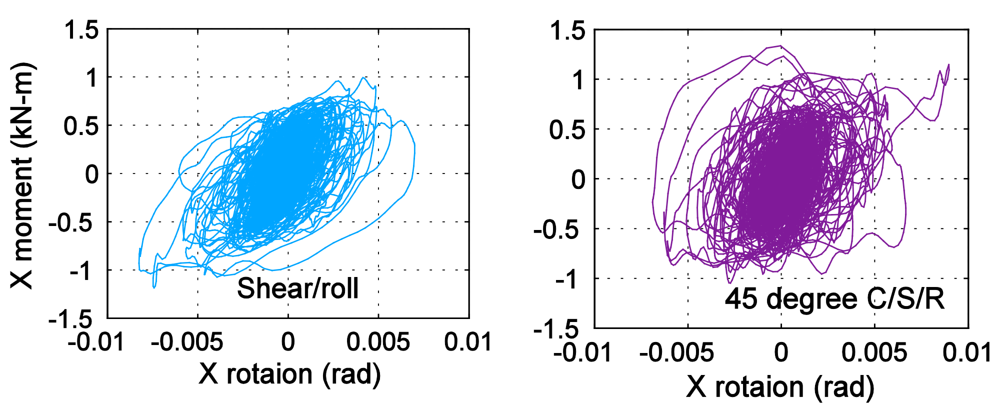


Fig. 7 – Moment-rotation relationship of the platform under 75% Chile Concepcion ground excitation

2.4 Rotational energy dissipation

Table 2 presents the first mode (rocking) equivalent viscous damping ratios experimentally estimated for the rigid frame supported on the shear/roll, and compression/shear/roll platforms for the same selected tests. The equivalent damping ratios of the experimental settings considering the frame supported by the platforms are calculated through the moment-rotation hysteresis loop of the platform. The damping ratios of these two configurations range from 6.2% to 20.1%. The damping ratios of the frame-platforms settings vary with different rotation levels and vertical load fluctuation achieved in the wire rope isolators. These results illustrate the ability of the platforms (in both configurations) to dissipate seismic energy during both ground and floor excitations.

Table 2 – First mode equivalent damping ratio for different configurations supporting the rigid frame.

No.	**Input**	**Floor**	**Station**	**Intensity (%)**	**Damping ratio (%)**		**Maximum rotation (10^{-3} rad)**	
					S/R[1]	C/S/R[2]	S/R[1]	C/S/R[2]
1	Loma Prieta	Ground	CSMIP47459	50	8.8	6.2	2.5	1.9
2	Loma Prieta	Ground	CSMIP47459	100	12.2	19.9	12.3	11.4
3	Loma Prieta	2nd floor	CSMIP47459	50	15.8	12.9	7.6	6.9
4	Northridge	Ground	CSMIP24332	100	7.1	11	2.2	2.66
5	Chile	Ground	CONSP	75	12.6	20.1	7.94	9.55

[1]Shear/roll

[2]Compression/shear/roll

2.5. Effects of asymmetry on the horizontal stiffness of the platforms

The platforms have different the lateral stiffness in *x* and *y* directions because the asymmetric plan distribution of isolators, the measured effective stiffness of the system in the *y* direction is larger than that in the *x* direction. Fig. 8 presents the relationship of total base shear and lateral displacement of the shear/roll platform with wire rope CB61400-17, supporting a total weight of 5.2 kN under 3Hz unidirectional sinusoidal excitation, the excitation was applied independently to both horizontal directions. The estimated lateral effective stiffness in *x* and *y* directions at maximum displacement are 431 N/mm and 510 N/mm, respectively. The lateral stiffness in the *y* direction (four in shear, two in roll) is 18% larger than that in *x* direction (four in roll, two in shear). The isolators' configuration (shear/roll or a rotated configuration that combined shear and roll), i.e., the effective lateral stiffness of the platform, play an important role in the definition of the effective period of the platforms. The effective damping ratios in *x* and *y* directions are 6.7% and 8.1%, respectively. The objective on the selection of the isolation period of the platform is to avoid tuning with the controlling modal periods of the building; the controlling period of the floor accelerations depends on the fundamental periods the buildings (the buildings in this study are assumed to respond within, or close to, the elastic range with minimum inelastic deformations to satisfy operational or immediate occupancy levels [8]). Depending on the building configuration, the fundamental periods in the two horizontal directions of the platform may differ. The asymmetric horizontal stiffness of the platforms may be beneficial when defining the effective dynamic properties of the platforms to protect equipment at different floors and in buildings with asymmetric plan configurations.

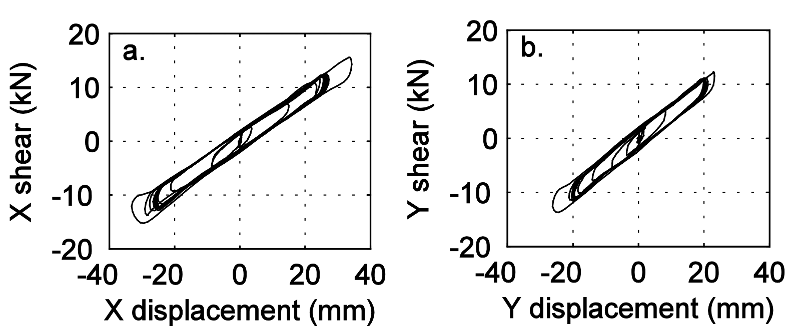
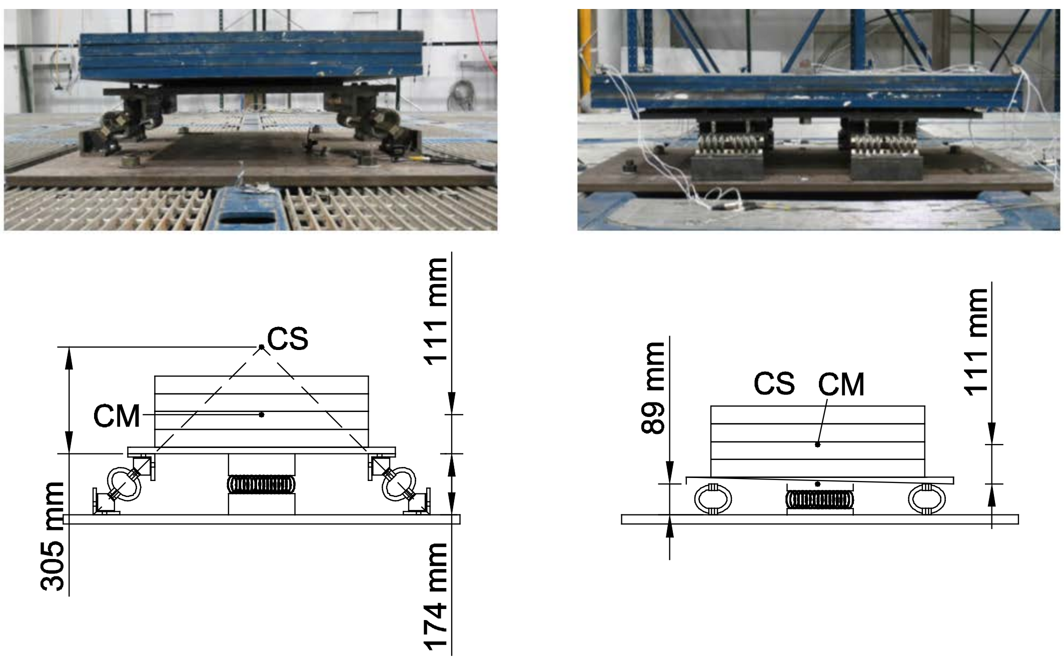


Fig. 8 – Force-displacement relationship of both horizontal directions under unidirectional sinusoidal excitation

2.6 Proof of concept of rocking control platforms

As explained in section 2.3, rocking is mostly proportional to the distance between the center of mass of the slender equipment and the center of stiffness of the isolation platform. A set of experiments were performed to demonstrate that rocking may be controlled when adjusting the distance between the equipment's center of mass and the center of stiffness of the platform by rotating/inclining the isolators. Fig. 9 presents pictures of two testing setting including two platforms with isolators configured in shear/roll and in compression/shear/roll supporting steel plates with a weight of 5.6 kN. In the shear/roll platform, the distance between the plate's center of mass and the center of stiffness of the platform is 31 mm positive (center of mass higher than center of stiffness). In the compression/shear/roll platform, the distance between the plate's center of mass and center of stiffness of the platform is 247 mm negative (center of stiffness higher than center of mass). Fig. 10 includes the horizontal force-displacement and moment-rotation loops of the two platforms under a unidirectional sinusoidal excitation of 3 Hz. The rotational stiffness on the moment-rotation loop for the shear/roll platform indicates positive rooking, while the rotational stiffness on the moment-rotation loop for the compression/shear/roll platform indicates negative rocking. Then, the difference on the rotational stiffness of these two systems indicates that rocking can be counteracted by defining a wire rope orientation that eliminates/minimizes the distance between the plate's center of mass and the center of stiffness of the platform. In other words, rocking can be controlled by configuring the wire rope isolators with a specific angle for which the reacting forces on the isolation system are concurrent to the center of mass of the equipment to protect. Details on the practical implementation of these concurrent isolators and the characterization of the three-directional coupling behavior of the rotated isolators require further studies.



(a) 45°degree compression/shear/roll (b) shear/roll

Fig. 9 – Configurations of wire rope platforms (CS=center of stiffness, CM=center of mass)

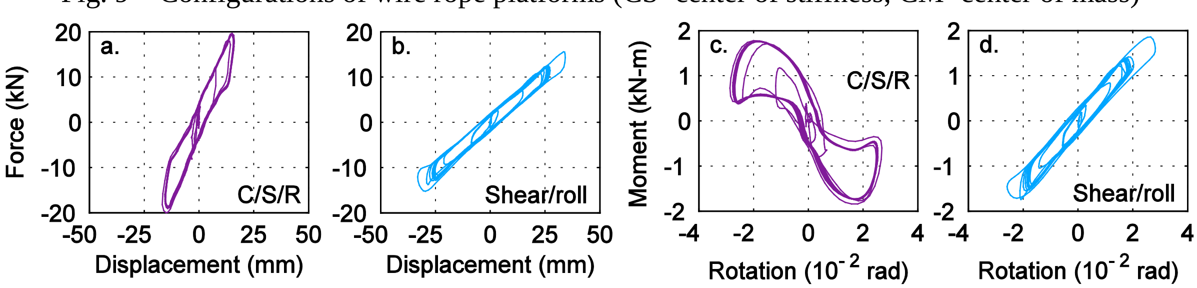


Fig. 10 – Force-Displacement and moment-rotation relationship of wire rope platforms

3. Studies on a frictional energy dissipation platform

This section includes the proof concept of a wire rope isolator platform with supplemental frictional damping for the mitigation of seismic responses on pieces of equipment. The experimental studies were directed to characterize the behavior of a hybrid energy dissipation platform using the earthquake simulator. Then, using the effective dynamic properties of the platform, the floor spectra analysis is used to represent the horizontal seismic spectral demands of the isolation platforms and to demonstrate the effectiveness of the platform mitigating seismic effects.

3.1. Description of the platform

The hybrid platform consists of two steel plates sandwiched by a set of wire rope isolators and a set of rolling balls. The wire rope isolators provide lateral restoring stiffness, while the rolling balls provide both supplemental frictional energy dissipation and vertical support. Fig. 11 presents a photograph and an illustration of the elevation view of the hybrid energy dissipation platform that consists of two steel plates sandwiched by two wire rope isolators (CB61400-17, shear effective stiffness 127 N/mm, roll effective stiffness 88 N/mm at lateral displacement of 20 mm) and four commercially available (for industrial applications) rolling balls' strips of nine balls (36 balls in total, 25.4 mm ball's diameter, and ball's surface chrome-plated finish). The total weight supported by the platform is 5.8 kN. Fig. 12 presents the plan view illustration of the platform. Fig. 13 presents a large view of the balls' strips bolted-up in contact with a not finished surface steel plate.

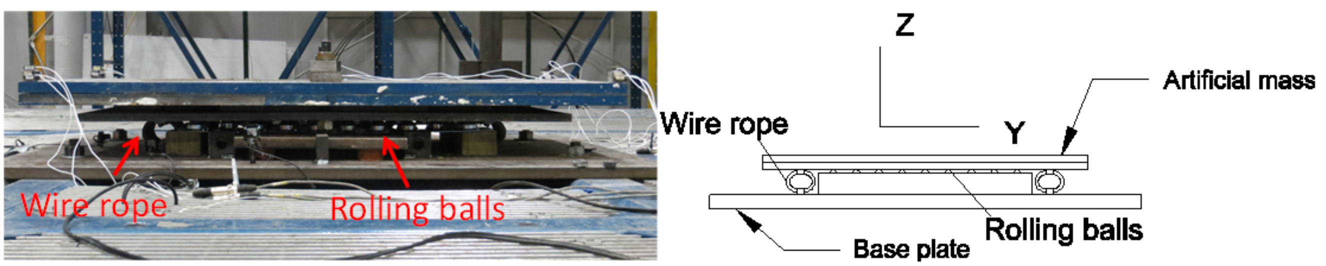


Fig. 11 – Hybrid energy dissipation platform: two wire rope isolators and rolling ball strips arrays

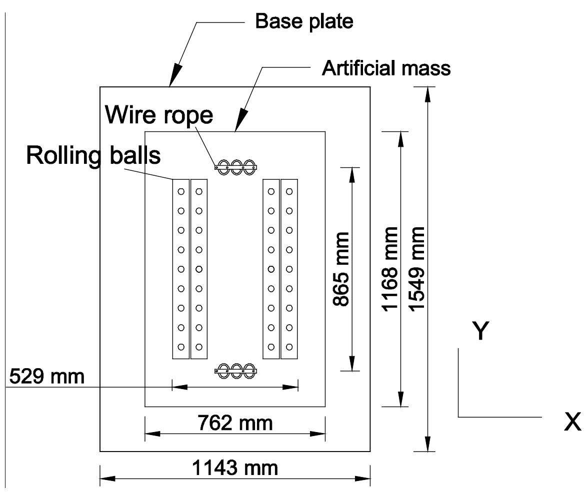


Fig. 12 – Plan view of the hybrid energy dissipation platform

Fig. 13 – Balls' strips bolted-up in contact with a steel plate array and balls' strips.

3.2. Effective dynamic properties of the platform

Table 3 presents the dynamic properties of the frictional energy dissipation platform obtained from 1 Hz unidirectional sinusoidal tests. The input motions applied by the shake table onto the platform were displacement controlled, i.e. 12.7 mm and 25.4 mm. The measured coefficient of friction of the systems in the two directions is 15%. Lateral stiffness, damping ratios and calculated fundamental periods are listed in Table 3. The lateral stiffness ranges from 309 N/mm to 492 N/mm. The calculated fundamental periods of the platform range from 0.21 s to 0.26 s. The first mode equivalent damping ratios of the platform range from 20.1% to 28.6%. As expected, and due to large effective stiffness of the wire rope isolators at small displacements, the test using the sinusoidal input with smaller amplitude provided higher effective both lateral stiffness (smaller fundamental period) and damping ratio than those for the large amplitude input. Fig. 14 presents the total base shear and lateral displacement relationship of tests 3 and 4 from Table 3. The secondary stiffness on these shear-displacements loops are defined by the effective stiffness of the wire rope isolators. The system effective lateral stiffness in *x* (shear) direction is 1.17 times of that in *y* (roll) direction, since the shear effective stiffness of the wire rope isolators is 1.4 times of the roll effective stiffness.

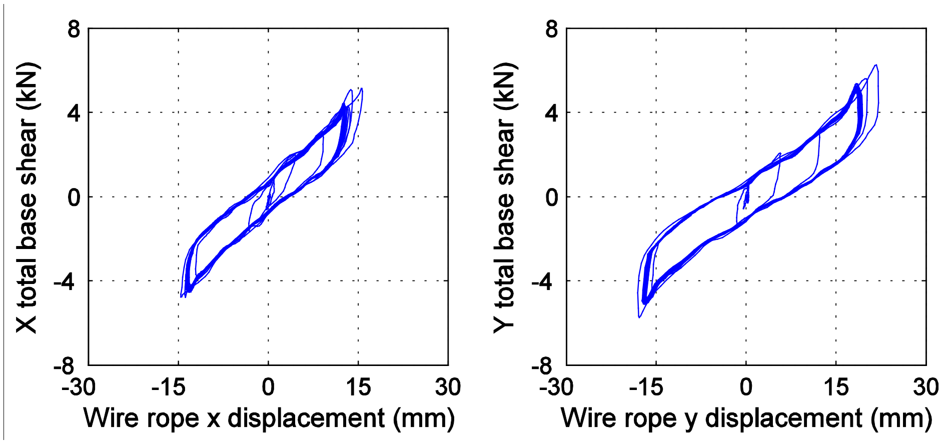


Fig. 14 – Total base shear-lateral displacement loop under uniaxial sinusoidal excitation

Table 3 – Effective properties of the frictional energy dissipation platform from sinusoidal input tests.

No.	Input displacement (mm)	Maximum displacement (mm)	Direction	Stiffness (N/mm)	Damping ratio (%)	Fundamental period (s)
1	12.7	5.1	X	492	23.2	0.21
2	12.7	5.1	Y	426	28.6	0.22
3	25.4	15.1	X	360	20.1	0.24
4	25.4	19.1	Y	309	21.9	0.26

3.3. Sample spectral analysis the demonstrate the effectiveness of the of the platform

Using the effective dynamic properties of the platform, the floor spectra analysis is used to represent the horizontal seismic spectral demands of the isolation platforms and to identify the effectiveness of the platform mitigating seismic effects.

Fig. 15 presents the acceleration spectra normalized by peak floor accelerations (PFA) for ground and floor motions of Virginia 2011 earthquake. The ground accelerations are the record from station NMSN CVVA. The floor accelerations are derived from the response of numerical analysis of a 4-story concrete frame building model [9]. The acceleration spectra for the ground motion illustrates that the tested frictional energy dissipation platform can achieve acceleration reduction for the ground acceleration with an approximated fundamental period of 0.25s and 20% damping ratio. To achieve the acceleration reduction at higher floors, e.g. 2nd floor and roof, the fundamental periods of the platform with approximate 20% damping ratio need to be higher than 0.47 s in the *x* direction and 0.52 s in the *y* direction. This spectra analysis illustrates that the effective dynamic properties of the platforms (period and damping) to protect equipment at different floors can vary with the placement of the platform–equipment setting within the building.

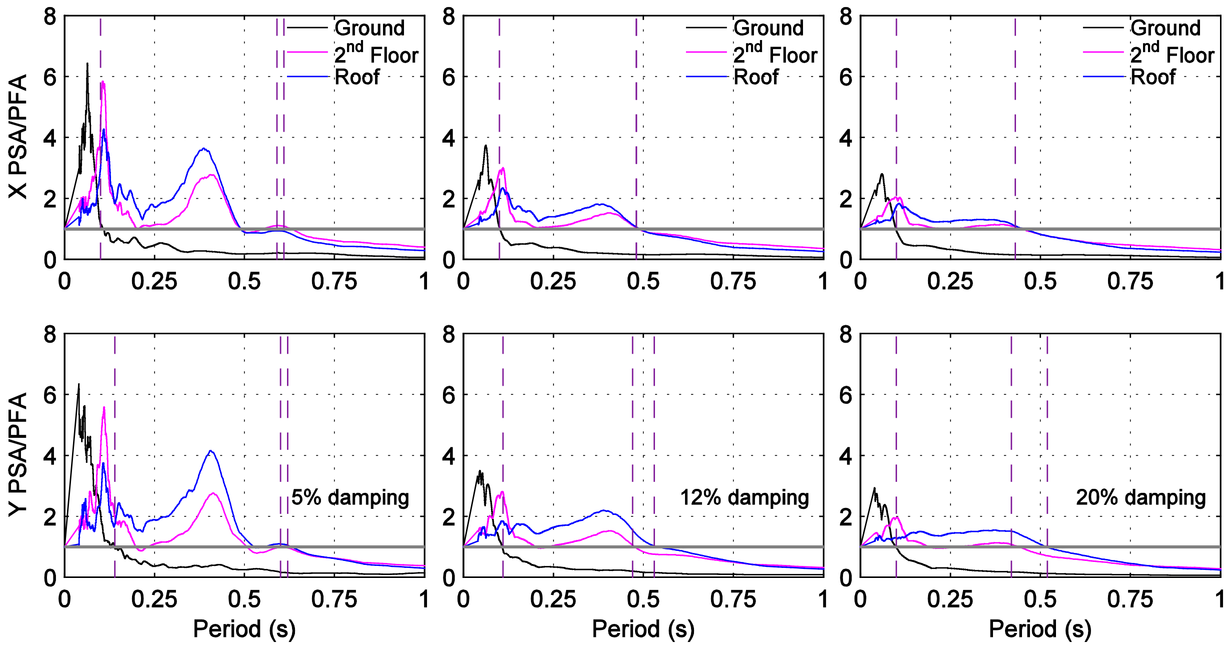


Fig. 15 – Ground and floor acceleration spectra normalized by peak floor acceleration

4. Summary and conclusions

This paper reports on the experimental performance of energy dissipation platforms based on wire rope isolators for the mitigation of the seismic effects of equipment located in different floors of different buildings. Two types of platforms supporting simulated equipment were tested: (1) platforms consisted of steel plates sandwiched by wire rope isolators in different configurations, and (2) a platform consisted of two steel plates sandwiched by a set of wire rope isolators and a set of rolling balls. Simulated equipment consisted of non-slender rigid blocks and slender flexible and rigid frames. The testing specimens (platform-simulated equipment) were subjected to earthquake shaking of varying intensities that were taken from measured accelerations records on multistory instrumented buildings, from past experimental testing, and from numerical simulations. The experimental three-dimensional seismic performances of the platforms are evaluated to assess the seismic energy-absorbing capacity of the platforms and their effects on the seismic response of slender frames holding equipment. Also, a configuration of rotated wire rope isolators is explored for reducing/eliminating rocking responses on the platforms supporting slender equipment. The main findings of the study are listed below.

The experimental responses demonstrated that the energy absorbing capacity of platforms based on wire rope isolators can control the deformation responses of slender rigid frames. The experimental studies involving platforms supporting flexible and rigid frames demonstrated the deformation control capability of the platforms supporting the rigid frame and amplification of deformations in the flexible frame. The platforms reduced significantly deformations on the rigid frame ranging from 72% to 90% if compared to those on the frame on the fixed base configuration. The results demonstrated that to secure the effectiveness of the platforms controlling deformations on slender frames, the frames/equipment that the platforms support must be relatively rigid.

As expected and because of the slenderness of the frames supported by platforms that provides three-directional flexibility, seismic responses were controlled by rocking on the platforms based on wire ropes isolators configured in shear/roll, and in compression/shear/roll. A set of experiments demonstrated that rocking may be controlled when adjusting the distance between the equipment's center of mass and the center of stiffness of the platform by rotating the isolators with a specific angle for which the reacting forces on the isolation system are concurrent to the center of mass of the equipment. Details for the practical implementation of these concurrent wire rope isolators require further studies.

Asymmetrical arrangements of isolators in shear and in roll lead to different effective fundamental periods in the horizontal directions of the platforms. The asymmetric horizontal stiffness of the platforms may be beneficial when defining the effective dynamic properties of the platforms to protect equipment at different floors and in buildings with asymmetric plan configurations.

The rolling balls increased significantly the effective damping ratio of the hybrid frictional isolation platform. The platform that consisted of two steel plates sandwiched by a set of two wire rope isolators and rolling balls arrays was subjected to unidirectional sinusoidal excitations. The first mode equivalent damping ratios of the platform range from 20.1% to 28.6%. The secondary stiffness (restoring stiffness of the system) on the shear-displacements loops are defined by the effective stiffness of the wire rope isolators. Using the effective dynamic properties of the platform, the floor spectra analysis demonstrated that the effective dynamic properties of the platforms (period and damping) to protect equipment at different floors vary with the placement of the platform–equipment setting within the building.

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