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ASSESSMENT OF A ROLLER SEISMIC ISOLATION BEARING FOR BUILDINGS UNDER BIDIRECTIONAL EXCITATIONS

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Abstract. This work presents the assessment of a base isolation bearing system for seismic protection of buildings under bidirectional excitations. The isolation system consists of roller supports that move on inclined V-shaped surfaces plus an energy dissipation system. The orthogonal arrangement of the roller supports seeks to isolate seismically the building in its main directions, while the dissipation system controls the horizontal displacements of the isolator. Experimental tests of free vibration allowed to identify damping of the isolation system. Besides, accelerations record was found through bidirectional and unidirectional test. By the other hand, numerical responses were obtained with the motion equation solution and these responses were correlated with the experimental accelerations of the system in both directions. According to the experimental and numerical results, it was possible to conclude that the isolation system is viable for analysis in the seismic protection of buildings subjected to real records of earthquakes.

Keywords: : Base isolation, roller seismic isolation, bearings, bidirectional excitation, energy dissipation.

1 Introduction

In the last decades, seismic isolation technology has advanced in an important way in development and implementation of new seismic protection systems. Each one of this systems counts with particular characteristics that converge in a single objective: protecting the integrity of structures subject to severe dynamic loads such as earthquakes.

Incorporating an isolation system in a building allows to partially decouple the building from the ground movement when a seismic excitation occurs [1] [2]. This condition favours the reduction of the basal shear in the building, protecting the building structural system.

By partially decoupling the structure from the ground movement, the damages on the structural system caused by the inertial effects are also significantly mitigated, this is a consequence of the reduction of the displacements, velocities and accelerations on the structures provided with seismic isolation [3]. Besides the aforementioned technical advantages, the use of this devices generates a favourable perception of safety to the inhabitants of the structures that make use of these devices [4].

There are different types of seismic isolators, which can be classified in three groups: elasthomeric, sliding and rolling. From the first group stand out the rubber isolators with lead core and the high damping rubber isolators, LRB and HDRB, respectively. The second group corresponds to the systems that use friction force as the separation mechanism of the structure from the ground movement. A representative of this group used frequently in the seismic protection of structures is the friction pendulum isolator, which are made with one or two sliding structures. Finally, there are the isolators that use the mechanism of friction by rolling, which are characterized by a lower friction coefficient than sliding systems, increasing their performance on seismic isolation. Furthermore, they have restorative capacity (the isolator returns to its initial position after the earthquake happens) and they can also be provided with energy dissipation systems that allow to attenuate the excessive displacement of the isolator.

This research studies the dynamic behaviour of the rolling seismic isolation (RIS) system, constituted mainly by two surfaces and a set of rollers that ease the rolling between the surfaces [5]. This type of devices has been significantly developed during the last two decades with the accomplishment of different research oriented to the design, mechanical characterization and evaluation of its performance in base excitation conditions [6–10]. Research has shown that the implementation of these devices improves the structure response in terms of dynamic effects.

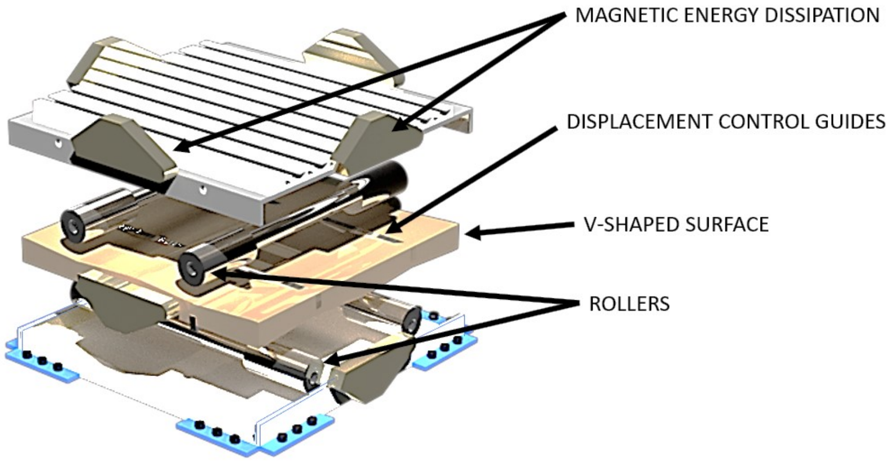


Figure 1. Bidirectional RIS model with magnetic energy dissipation

With respect to the RIS systems with bidirectional isolation, different authors have carried out different investigations [11–15], obtaining good results based on analytical, numerical and experimental comparisons. They found good performance of the isolation system subjected to horizontal excitations in each direction. In addition, this system had a high performance for low and medium height buildings drastically reducing the forces induced by the earthquake; thus, reducing the total acceleration of the isolated system up to ten times compared to the fixed base system. However, this bidirectional isolation systems presents some limitations such the self-centering mechanism and stability in the rolling bearing support.

The objective of this work is to present and characterize a bidirectional base isolation system for the protection of buildings subjected to seismic excitation in order to improve some limitations that have been presented previously in similar devices. Accordingly, the bidirectional isolation system includes the rolling supports, V-shaped tilted surfaces disposed in the two directions and a magnetic energy dissipation system, see Fig. 1 and 2. The orthogonal disposition of the supports seeks to isolate the building on its main directions, while the dissipation system has the purpose of attenuating the horizontal displacements of the isolator and also dissipate the energy caused by seismic stimulation.

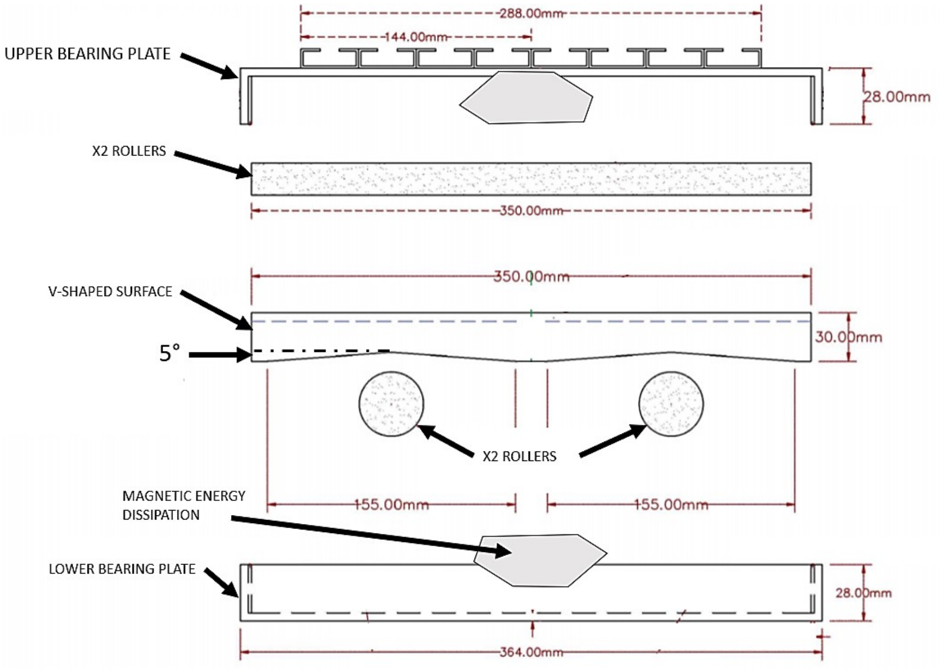


Figure 2. Features and dimensions of model

2 Motion equations of seismic isolation system

To evaluate the dynamic behaviour of the isolation system, the motion equations formulated by Ortiz [6] were used. In this work a unidirectional rolling support system was considered and the equations were obtained from the dynamic equilibrium of the forces acting on the system. A free body diagram of the isolated system is shown in Fig. 3.

Considering the dynamic equilibrium of mass m_1, the motion equation that rules the behaviour of the rolling support system under seismic excitation conditions is given by Eq. (1).

$$m_1\ddot{u} + f_s\text{sign}(u) + f_{Dr}\text{sign}(\dot{u}) + f_{Dm}\text{sign}(\dot{u}) = -m_1\ddot{u}_g. \tag{1}$$

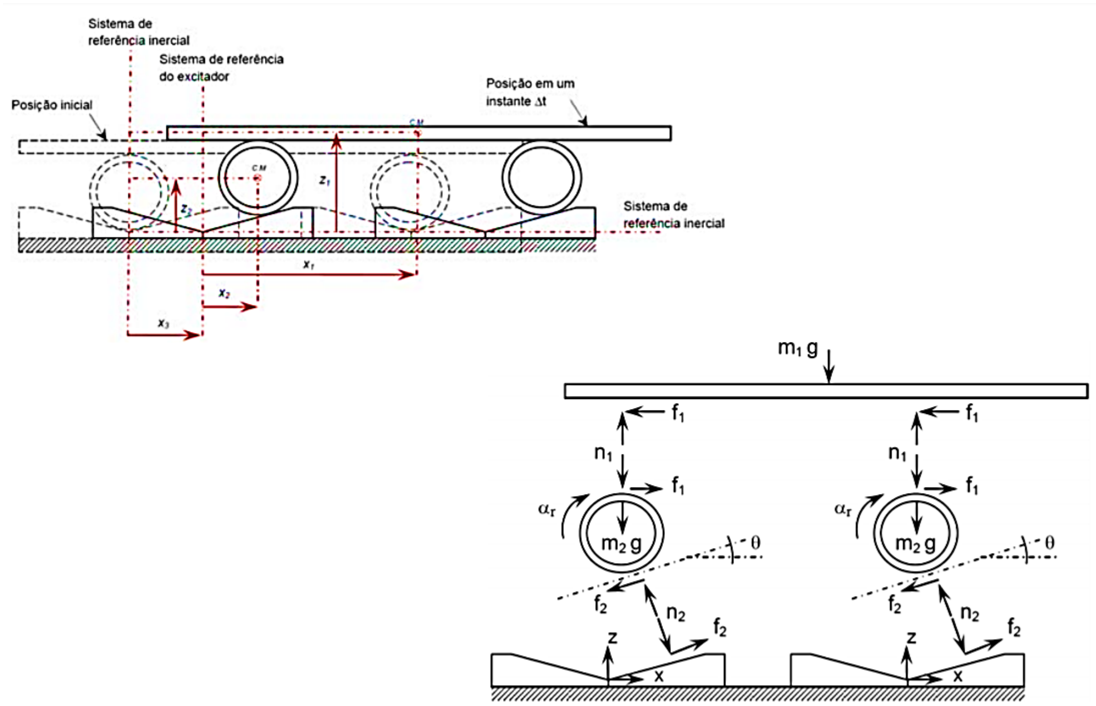


Figure 3. Unidirectional rolling bearing system, Ortiz [6]

Where:
m_1 :mass supported by the rolling support system
u :horizontal displacement of the isolation system
$\dot{u}$:horizontal velocity of the isolation system
$\ddot{u}$:horizontal acceleration of the isolation system
$\ddot{u}_g$:seismic acceleration
f_s :restorative force of the isolation system
f_{Dr} :rolling friction force of the rolling supports
f_{Dm} :force generated by the dissipation system
sign($\bullet$) :signum function

The sign($\bullet$) function presented in Eq. (1), was replaced by the continuous function defined in pieces $f_1(x)$ wich is shown in Eq. (2) adequately representing the behavior of the isolator [6, 7]. In this function d is the yield displacement, k_y is defined as $1/d$ and y is an auxiliary variable associated with the displacement (u) and speed ($\dot{u}$) of the isolator.

$$f_1(x) = \begin{cases} 1 & \text{if } x > d. \\ k_y y & \text{if } -d < x < d. \\ -1 & \text{if } x < -d. \end{cases} \tag{2}$$

On the other hand, assuming compatibility conditions of pure rolling, i.e. without sliding, and admitting that the supported mass m_1 is much bigger than the mass of the rolling supports m_2, it is possible to establish that the restorative force f_s and the force corresponding to the rolling friction force f_{Dr} are given by:

$$f_s = 0.5 m_1 g \sin\alpha. \tag{3}$$

$$f_{Dr} = \mu_r m_1 g. \tag{4}$$

Where, m_1 as defined previously, g is the acceleration of gravity, α is the angle of the V-shaped tilted surfaces, μ_r is the rolling friction coefficient and sign($\bullet$) represents the signum function. Another feature of the isolation systems by rolling supports is the acceleration bound that the system may undergo. This acceleration is denoted as a_{max}, and is given by Eq.(5).

$$a_{max} = 0.5g \sin\alpha. \tag{5}$$

Finally, in the isolation system set up the recommendations given by Wang [5] were considered, he suggests that, for a better rolling of the supports, the system requires the development of a curve surface disposed along the vertex that joins the tilted surfaces with a line length denoted as D. Furthermore, he concluded that the efficiency of the isolation system is highly influenced by the geometric shape of the surface that supports the rollers; thus, a V-shaped tilted surface were used, see Fig. 4. This shape ensure that the system will return to the center (self-centering) after any movement and helps with energy dissipation as well, the curvature on its lower extreme is given by the following Eq.(6).

$$D = 2r \sin\theta. \tag{6}$$

Where:
D :line length on the lower extreme of the V-shaped tilted surface
r :roller radius
θ :tilt angle of the V-shaped surface

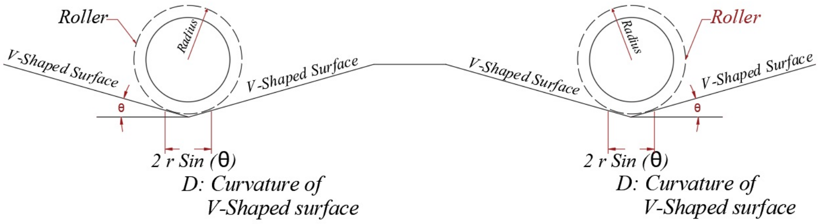


Figure 4. Curvature for V-shaped surfaces

Finally, to obtain a better system performance, Lee [16] studied the dynamic behaviour of the isolation system with the inclusion of frictioning plates as an energy dissipation mechanism, which ease the control of excessive displacement experimented by the isolation system. It is quite important to include an energy dissipation mechanism in the design of seismic isolation structures; the adequate behaviour of the dissipation system must be verified to avoid losing the isolation effects or increasing the accelerations that could result if using a high capacity damping system.

Another issue to take into account in the design of the rolling supports and the tilted surface that make up the isolation system, is the capacity to support structural vertical load. This feature is mainly related to the isolator material and the maximum allowed horizontal displacement defined in the design.

3 Description of the bidirectional roller seismic isolation bearing

For the construction, evaluation and characterization of the seismic isolation system with rolling supports, different proposals found in the technical literature [6, 12, 14, 17] were analyzed. For example, Wang [5] and Lee [16] mentioned stability problems in the rolling supports and also the advantages of using an energy dissipation system which improve the performance of the isolator.

A bidirectional seismic isolation system is proposed made up of three plates: upper, lower and intermediate. The latter, is provided of V-shaped tilted surfaces, which enables the restoration (self-centering) of the system after an earthquake. Furthermore, the surfaces have rails that work as guides, thus keeping the rollers on place. Also, it has four PVC rollers, two in each orthogonal direction, thereby isolating the structure on its main directions, as shown in Fig. 1. Finally, to have more control of the isolator displacements, the system was provided with a magnetic energy dissipation system. All the system components are illustrated in Fig. 5.

To define the tilt angle of the V-shaped surfaces, the recommendations of Lee [16] where considered. He indicated that the surface tilt varies between 2° a 8°, a tilt of 5° was defined for the model with a rolling surface 35 mm in length, 35 mm width and 30 mm height. Furthermore, to ease rolling at the surface vertex, a curved surface was developed with a line length $D = 3.49mm$ given by Eq. (6). $D = 2(20mm)\sin(5^{\circ}) = 3.49mm$.

Finally, the isolation system includes an anchorage system, superior and inferior, allowing its fastening on a shaking table and also the mounting of the structural system. A magnetic energy dissipation mechanism was used to give energy dissipation to the motion and to improve the self-centering of the system, Fig. 5.

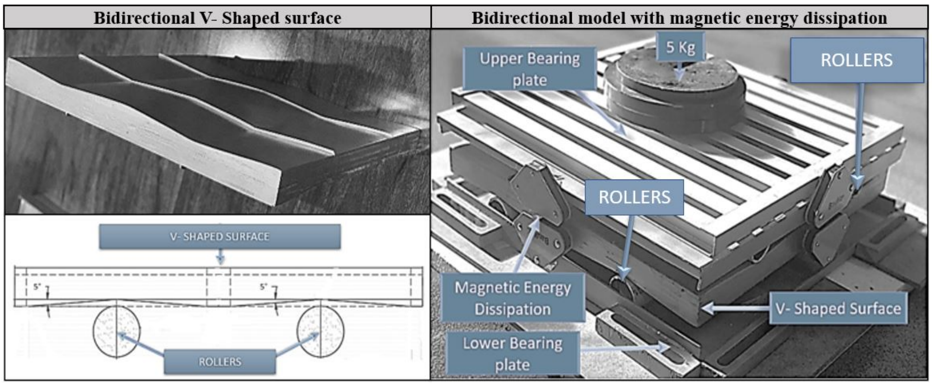


Figure 5. Components of bidirectional model

4 Free vibration test

Free vibration experimental tests were performed to characterize the bidirectional isolation system with rolling supports. The tests consisted of imposing a known displacement simultaneously in each of the x - y directions as shown in Fig. 6. It is important to highlight that the effects of the energy dissipation mechanism were analysed in order to evaluated the isolator dynamic response.

To verify the dynamic response, the accelerations on the perpendicular directions of the system were registered with a conventional cellphone through the *iSismografo 2.0* application. Besides, a 5 kg mass was used to represent an average weight of a physical model of a reduced scaled building. In Fig. 7 is shown the instrumentation and acceleration measured in the vibration test.

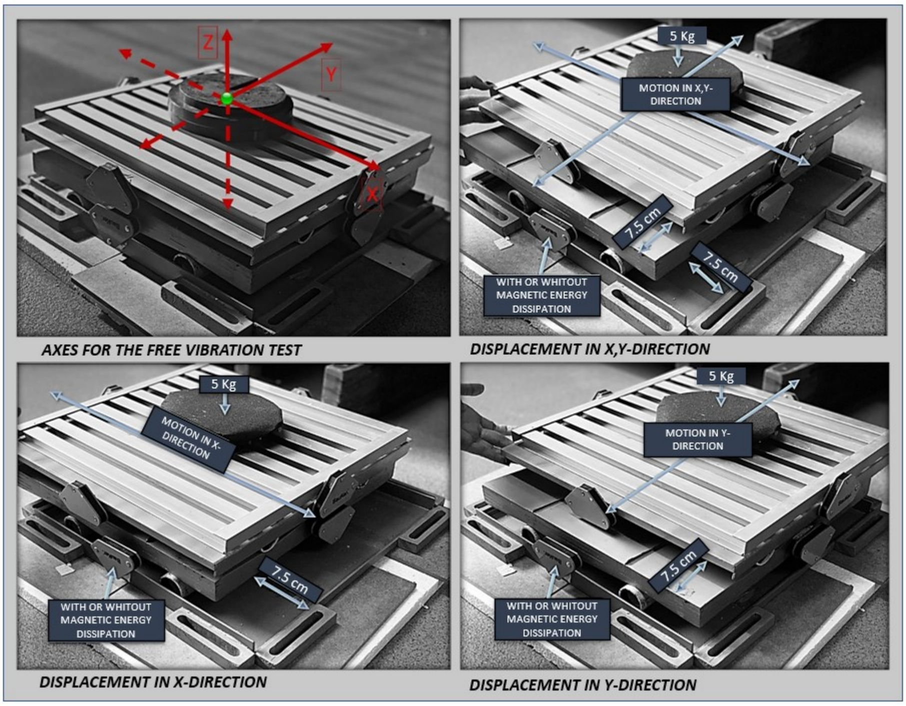


Figure 6. Free vibration test

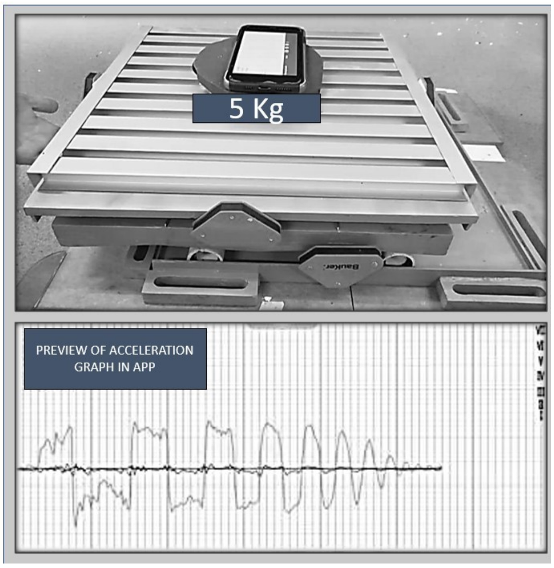
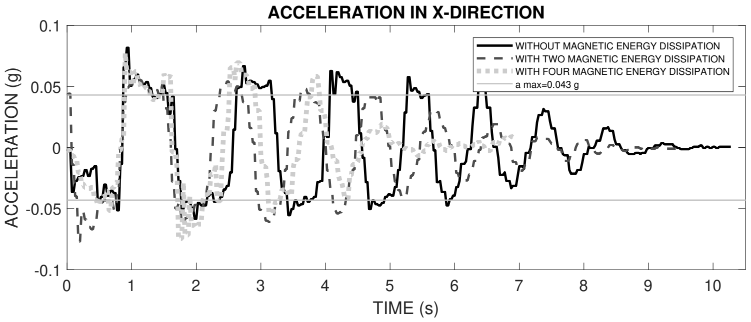


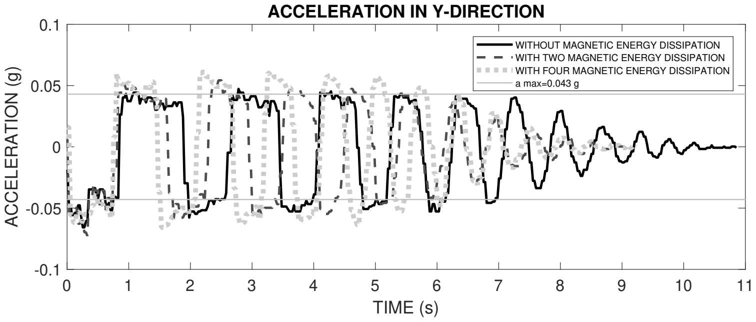
Figure 7. Components using for registration of accelerations in free vibration test

4.1 Acceleration tests in the x and y directions

As previously mentioned, first an initial $75mm$ displacement was imposed in each orthogonal direction of the isolator. Due to the fact that the system starts its oscillation from rest, the initial velocity is equal to zero. Then, the acceleration and displacements in both x - y directions were obtained with and without the energy dissipation system. It is important to point out that two different tests were performed according to the number of magnets installed in the energy dissipation system, two and four magnets; this procedure allowed to verify the damping provided by the isolation system and also the stability on the motion of the rolling supports.



(a) Accelerations registered during the free vibration test in the x-direction



(b) Accelerations registered during the free vibration test in the y-direction

Figure 8. Accelerations registered during the free vibration test (Unidirectional)

The experimental accelerations obtained in the x - y direction are presented in Fig. 8. According to these results, a movement attenuation is verified with the use of the dissipation system passing from 5 (without magnetic energy dissipation) to 3 oscillations when the dissipation system used four magnets, see Fig. 8(a). While in the y direction the registered acceleration did not show a significant reduction on the number of oscillations (Fig. 8(b)); nevertheless, the motion ends prematurely when the magnets are implemented. It is probable that the increase on the number of magnets increases the energy dissipated by the system, given that the magnets could be active during all of the isolator motion, a condition that does not happen on the tests carried in this work.

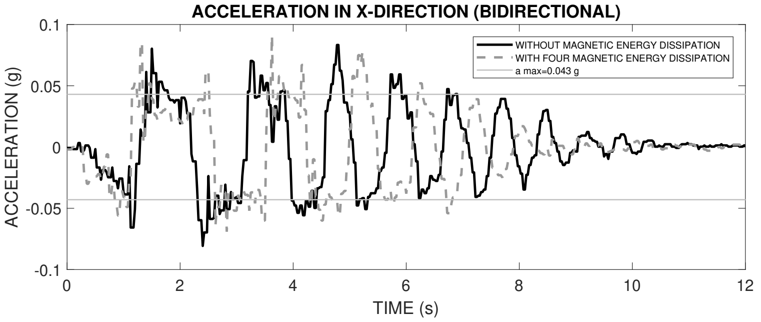
On the other side, it is possible to estimate the maximum theoretical acceleration of the system by applying Eq.(5), obtaining a value of $0.0436g$, which is in agreement with the accelerations registered on the system, see Fig. 8.

The excessive accelerations evident mainly on the direction register could be due to the imperfections on the construction of the isolation system. However, these accelerations are slightly mitigated with the use of the dissipation system. The former results allow to confirm the adequate implementation of the dissipation system for the stabilization and attenuation of the accelerations on the bidirectional isolator.

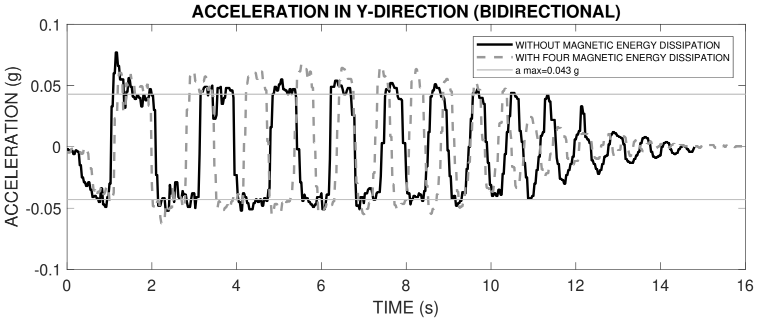
4.2 Bidirectional acceleration tests

The same initial conditions applied in the unidirectional tests were considered for the bidirectional free vibration tests. The imposed initial displacement in each x - y axis of the isolator were simultaneously applied. The registered accelerations in the x and y directions were obtained with and without the implementation of the dissipation system composed by the magnets. Experimental results are shown in Fig. 9.

According to these results the expected order of magnitude for the accelerations is confirmed again. Although it must be highlighted that the system had a better behaviour in the y direction compare to the x direction, which could be associated to the construction conditions of the tilted surfaces and the rolling guides. This result is coherent with the results obtained on the unidirectional free vibration tests.



(a) Accelerations registered during the free vibration test in the x-direction



(b) Accelerations registered during the free vibration test in the y-direction

Figure 9. Accelerations registered during the free vibration test (Bidirectional)

With respect to the accelerations in the x and y directions, there is a greater damping effect in the x direction (lower level of the isolator). This is possibly due to the greater friction force between the rolling supports and the lower isolator plate as a consequence of the higher supported mass produced by the intermediate V-Shape surface.

On the other side, comparing the bidirectional acceleration results with and without magnetic energy dissipation system, it is observed that the use of the magnets reduces the length of the periods while increasing the accelerations mainly in the y direction. In future work the number and placement of the dissipation system that improve the performance of the isolator will be studied.

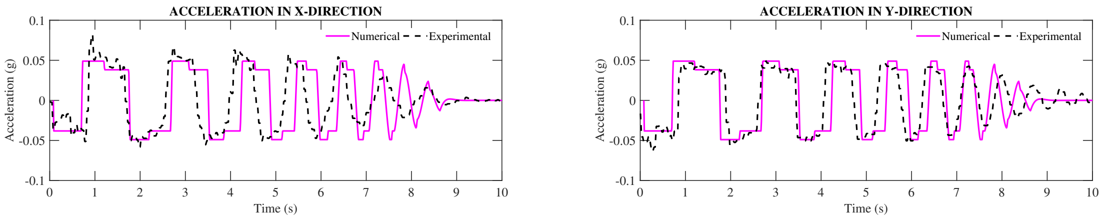
4.3 Numerical-experimental correlation of accelerations

In order to characterize and validate the behaviour of the isolator, a numerical-experimental correlation of the isolation systems accelerations without energy dissipation system was carried out. Accordingly, the differential equation formulated by Ortiz [6] was used to compute the acceleration of the system; this includes the system restorative force, the friction force and the dissipative force as shown in Eq.(1).

The numerical-experimental correlation was obtained using the accelerations of the unidirectional and bidirectional free vibration tests, the motion Eq. (1) was solved using the *Runge-Kutta 4th-order* method (***RK4***), with a constant step-time $h = 0.01$ s.

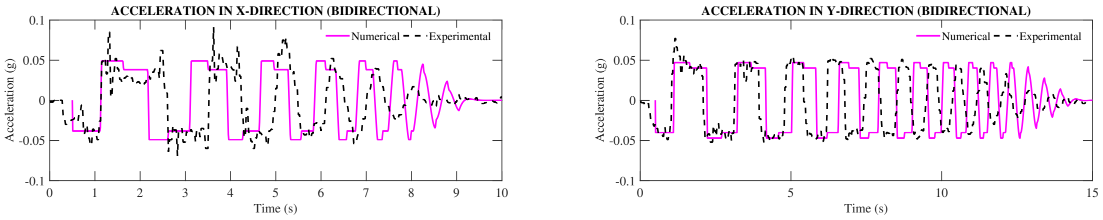
In the numerical simulation the following parameters were considered: $75mm$ initial displacement and zero initial speed, $f_1(x)$ function defined by $d = 3.75mm$, $f_{Dm} = 0$, $m_1 = 5kg$, $\alpha = 5^\circ$ y $\ddot{u}_g = 0$; the μ_r parameter represents the friction coefficient which was adjusted in an iterative process with the aim of obtaining a good correlation between the numerical and experimental results. An adequate numerical-experimental adjustment was obtained with $\mu_r = 0.054$ for the unidirectional and x-bidirectional free vibration tests, while a value of $\mu_r = 0.034$ was the adequate for the y-motion in the bidirectional free vibration condition.

On the other hand, it is important to note that in numerical simulations, using ***RK4*** with the system parameters, there was no problem of convergence or numerical stability.



(a) μ_r=0.054 (b) μ_r=0.054

Figure 10. Numerical and experimental acceleration correlations (Unidirectional)



(a) μ_r=0.054 (b) μ_r=0.034

Figure 11. Numerical and experimental acceleration correlations (Bidirectional)

In Fig. 10 are shown the unidirectional numerical-experimental correlations of the acceleration response of the isolation system in x direction (Fig. 10(a)) and y direction (Fig. 10(b)), while in Fig. 11 are shown the bidirectional correlations of acceleration response in each direction,x direction (Fig. 11(a)) and y direction (Fig.11(b)).

The correspondence between each of the responses confirms the adequate dynamic behaviour of the isolation system presented in this paper. Nevertheless, additional tests should be performed to verify if there is a variation of the friction coefficient in the y direction compare to the x direction in bidirectional conditions.

5 Conclusions

A bidirectional isolation system with rolling supports has been analysed through unidirectional and bidirectional free vibration experimental tests. Besides, to verify its viability and adequate dynamic behaviour, the acceleration results where correlated with the motion equations. Considering the acceleration responses obtained in the present study the following conclusions are given:

1. Using magnetic energy dissipation systems, it is possible to reduce the number of oscillations; thus, increasing the damping of the system. However, there was a slight increase in accelerations. In addition, the use of the magnets allowed to improve the self-centering system and the stability of the isolation system.
2. The dissipation system consisting of magnets is another way to give energy dissipation to the isolation system. However, the use of magnets that are active during the entire movement of the roller bearing isolator is recommended.
3. The agreement between the numerical and the experimental accelerations indicates that the dynamic response of the bidirectional isolation system presented in this research work is consistent with the theory of seismic isolators with rolling supports that move on inclined V-shaped surfaces. The observed differences in the numerical-experimental correlation could be diminished improving the construction quality of the isolation system and improving the magnetic energy dissipation mechanism as well. In future work numerical simulations that include the effects of the dissipation system will be carried out.

4. The isolation system fulfils the function of partially decoupling orthogonal directions without losing the ability to self-centering. In addition, the movement is independent in each direction making the system viable in the analysis of buildings subjected to two-way seismic excitations.
5. A rolling coefficient of friction μ_r of 0.054 for unidirectional free vibration tests in both directions and bidirectional in x direction was found to give the best numerical results in computing the acceleration, while in the bidirectional test μ_r equals to 0.034 gave the best results. Thus, more experimental tests should be carried out to verify the repeatability of the experimental set up.

Acknowledgements

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