World Academy of Science, Engineering and Technology
International Journal of Computer and Systems Engineering
Vol:10, No:11, 2016

Dissipation Capacity of Steel Building with Fiction Pendulum Base-Isolation System

A. Ras, I. Nait Zerrad, N. Benmouna, N. Boumechra

Abstract**—**Use of base isolators in the seismic design of structures has attracted considerable attention in recent years. The major concern in the design of these structures is to have enough lateral stability to resist wind and seismic forces. There are different systems providing such isolation, among them there are friction-pendulum base isolation systems (FPS) which are rather widely applied nowadays involving to both affordable cost and high fundamental periods. These devices are characterised by a stiff resistance against wind loads and to be flexible to the seismic tremors, which make them suitable for different situations. In this paper, a 3D numerical investigation is done considering the seismic response of a twelve-storey steel building retrofitted with a FPS. Fast nonlinear time history analysis (FNA) of Boumerdes earthquake (Algeria, May 2003) is considered for analysis and carried out using SAP2000 software. Comparisons between fixed base, bearing base isolated and braced structures are shown in a tabulated and graphical format. The results of the various alternatives studies to compare the structural response without and with this device of dissipation energy thus obtained were discussed and the conclusions showed the interesting potential of the FPS isolator. This system may to improve the dissipative capacities of the structure without increasing its rigidity in a significant way which contributes to optimize the quantity of steel necessary for its general stability.

Keywords**—**Steel structure, energy dissipation, friction-pendulum system, nonlinear analysis.

I. INTRODUCTION

EACH year, thousands of earthquakes occur everywhere in the world. Some of them are so weak that they are not felt. However, others are so strong that they can destroy completely a city which involves large damages in infrastructures with the loss of thousands of human's lives. There are different ways to limit damages caused by these natural hazards, among these ways; there is the passive dissipation of the input energy by the use of base-isolation devices. One of these bearing devices which became a challenging subject for researchers from previous years is the friction pendulum system. It was developed in its modern form in USA in 1987 [1], however it appeared for the first time in San Francisco in 1870 [2]. This is an innovative seismic isolation device capable to improve the structure resistance, the durability and the flexibility with chipper cost compared to other systems. It is combining both a sliding and a geometry restoring system. These characteristics allowed it to be used in seismic isolation of the great Mosque of Algiers [3].

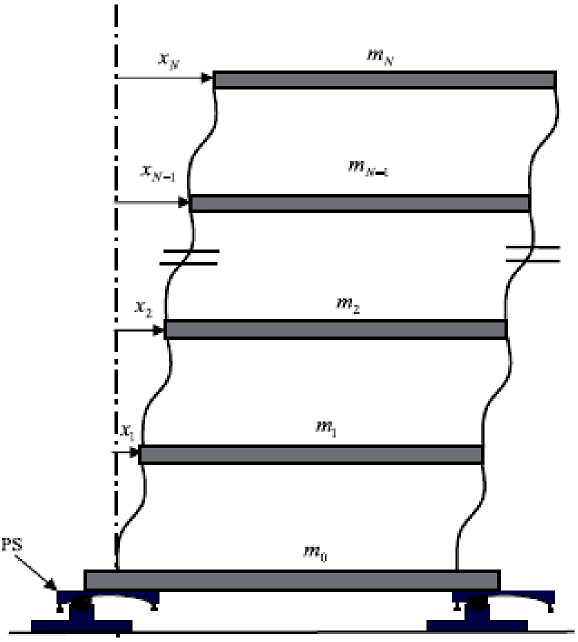

Fig. 1 Bearing base isolation system

Friction pendulum system consists of a concave surface with spherical form, covered with a polished stainless steel plate, on which slides a hinged element in Teflon composite material providing a low frictional resistance to keep it uniformly in contact with the concave surface during motion. In the FPS system, the lateral flexibility is obtained by means of the sliding interface, which may be lubricated with silicone grease. In the case of the pendulum friction device, the fact that the interface is placed on a spherical surface causes the mass to move laterally, and it must move also vertically upwards, allowing greater side stiffness compared to a sliding device to flat surfaces. Several studies have focused on the analysis of performance of these systems to withstand the dynamic action of different types of seismic signals [4]-[6]. All the results showed good potential of these devices to increase safety in buildings that are equipped with. In other works, mathematical models capable to simulate with accuracy the hysteretic loop of the friction pendulum isolator behaviour have been developed [7], [8]. Comparisons between the analytical and experimental results concluded that the proposed models represent sufficiently well the relationship force-displacement of the device.

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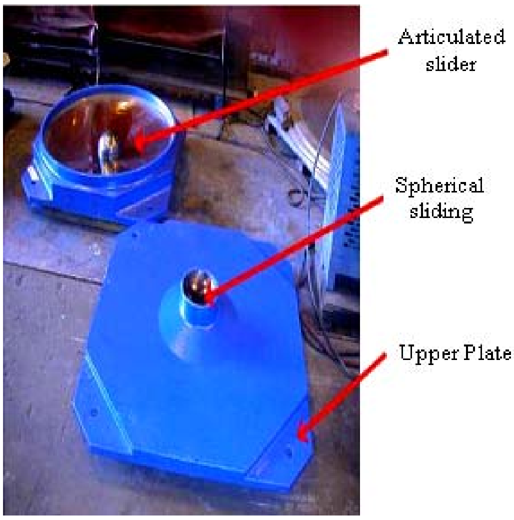

Fig. 2 FPS base isolation system

II. Friction Pendulum System

A. Characteristics of Friction Pendulum System

The Friction pendulum system is used to reduce the base relative displacement and provide an additional mean of energy dissipation. FPS works on the principle that during an earthquake the articulated slider moves along the concave surface generating a displacement of the structure with small harmonic motions increasing the period of the response and at the same time the friction generated by moving the slider generate the damping of the motion. In this case, the response of a building based on this type of device depends on the coefficient of friction and the total mass of the structure, also the intensity of horizontal dynamic forces transmitted to the structure is inversely proportional the value of the available friction.

The vibration period is extended proportionally based on the radius of curvature, which reduces the movements of vibration and protect the building and its contents during violent earthquakes.

The mechanical behaviour of this device is equivalent to a frictional damper. The schematic model of the FPS base-isolation system is shown in Fig. 3. The restoring mechanism is obtained by returning the slider to an equilibrium position (the lowest of the concave surface point) after unloading.

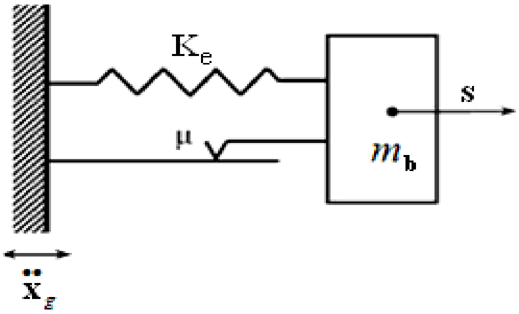

Fig. 3 FPS model

B. Modeling of System with Friction Pundulum System

The lateral force developed IN the FPS device is given as:

$$F = \frac{W}{R}.s + \mu.W.sign\left(s^{\bullet}\right) \qquad (1)$$

with s: Relative displacement between the isolator and the ground, R: curvature radius of the spherical surface, W: Structure weight, μ: Fiction coefficient of the slide surface

The equation of motion is given as:

$$M.\left(\ddot{s} + \ddot{x}_g\right) + F + M.\sum \gamma_i.x_i = 0 \qquad (2)$$

Substituting (1) into (2), the equation governing the base displacement becomes:

$$M.\ddot{s} + \left(\frac{W}{R}\right).s + \mu.W.sign\left(s^{\bullet}\right) + M.\sum \gamma_i.x_i = -M.\ddot{x}_g \qquad (3)$$

Note that stiffness of the system is $K_p = \frac{W}{R}$ (Fig. 4). Equation (3) becomes as [9]:

$$\ddot{s} + \omega_s^2.s + \mu.g.sign\left(s^{\bullet}\right) + \sum \gamma_i.x_i = -\ddot{x}_g \qquad (4)$$

with: $\omega_s^2 = g/R$ and $T = 2.\pi\sqrt{R/g}$

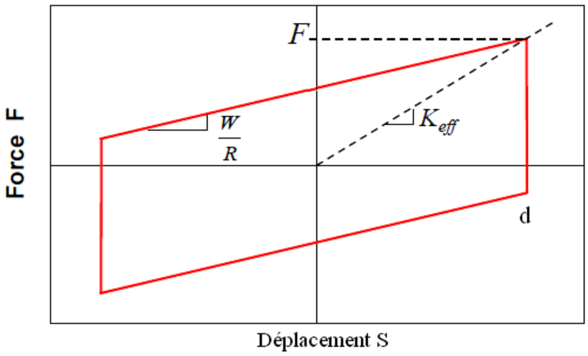

Fig. 4 Hysteretic loop of FPS

The condition of transition from none sliding to sliding phase is verified when:

$$\ddot{x}_g + \sum \gamma_i.x_i \le \mu.g \qquad (5)$$

The direction of the base motion is determined when the velocity is nil. The equation is given as:

$$sign(0) = -\frac{\ddot{x}_g + \sum \gamma_i . x_i}{\mu . g} \tag{6}$$

For $sign(0) = 1$ the direction is positive as well for (-1) the direction is negative.

III. Case Study

A.Structure Characteristics

A twelve-storey steel building modelled as 3D moment resisting frame is analyzed with and without viscous dampers using SAP2000 [10]. The profiles of the various frame elements are shown in Fig. 5. The properties of the building and related information are given in Table I.

The seismic isolators in the system are defined as link components placed between the fixed base and the columns. The parameters selected to define the utilized isolators in the SAP2000 program are as follows. Nonlinear Link Type: Friction isolator, U1 and R3 Linear Effective Stiffness: 24727500 KN/m, U2 and U3 Linear Effective Stiffness: 152.39 KN/m, U2 and U3 Nonlinear initial Stiffness: 229100 KN/m, U2 and U3 Friction coefficient slow and fast respectively: 0.03 and 0.05.

To maximize the performance of the isolators, upstream optimization study on the input values of Rate parameter and radius of sliding surface were carried out.

TABLE I
Geometric Properties of Building

Total length	23.70 m
Total Width	22.92 m
Total Height	45.82 m
Height of 3rd floor	3.40 m
Height of other floors	4.42 m
Modulus of Elasticity	200 GPa
Steel weight per unit volume	7698 KN/m^3
Poisson ratio	0..3

Rate parameter: 40 sec/m and radius of sliding surface: 2m.

The lateral dynamic load applied to the structure was simulated by nonlinear time history (FNA) of the Boumerdes earthquake (Algeria May 2003) with a magnitude of 6.69 on the Richter scale. The time history data of the aforementioned ground motion is illustrated in Fig. 6. The use of Nonlinear time history (NLTH) analysis is mandated for most passively damped structures because the earthquake vibration of most civil engineering structure will induce deformation in one or more structural element beyond their yield limit. Therefore, the isolator will respond with a nonlinear relationship between force and deformation.

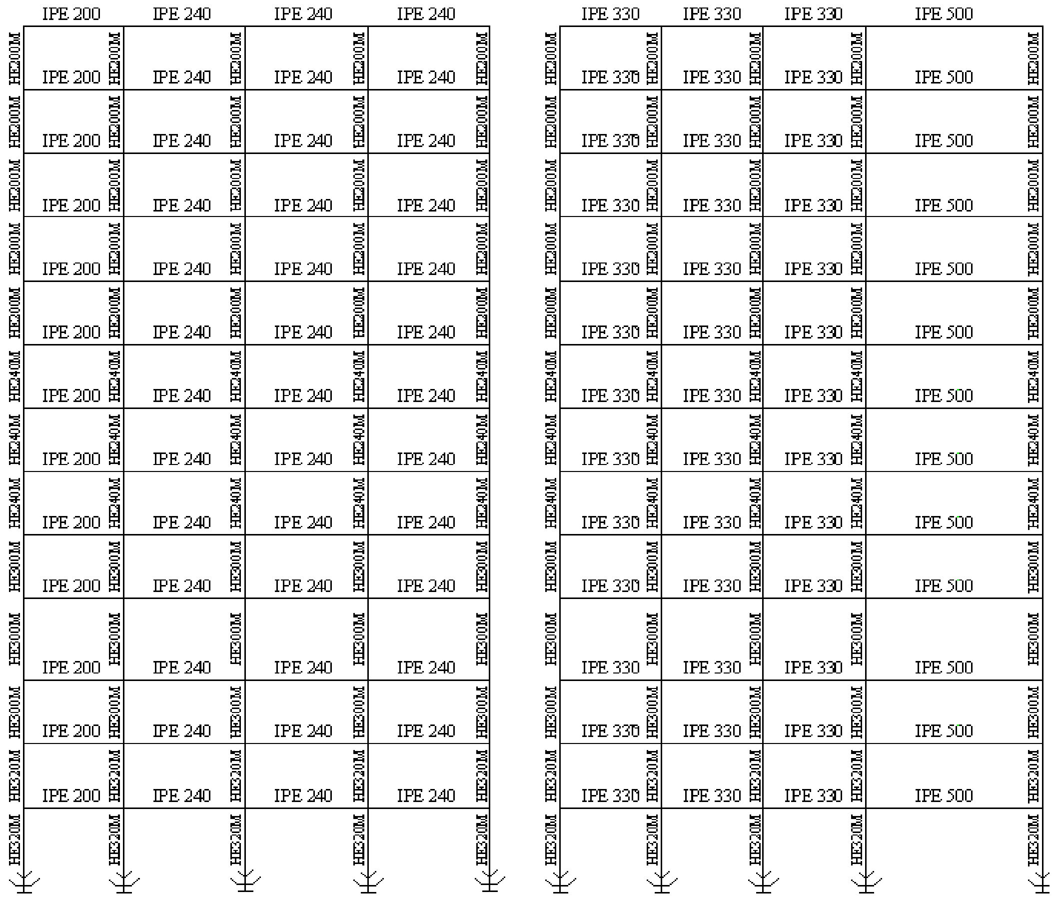

Fig. 5 Modelling of twelve-storey building

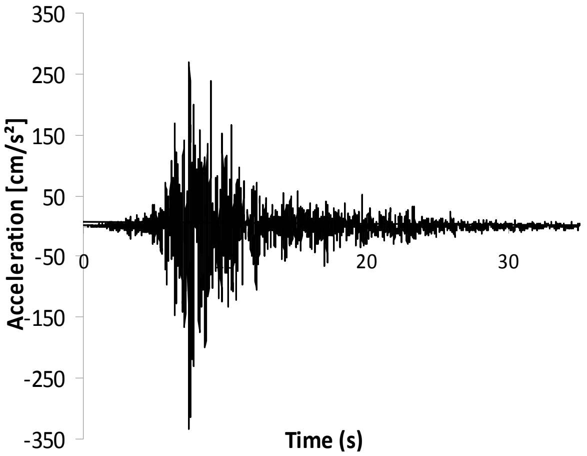

Fig. 6 Boumerdes Ground Acceleration (North-west)

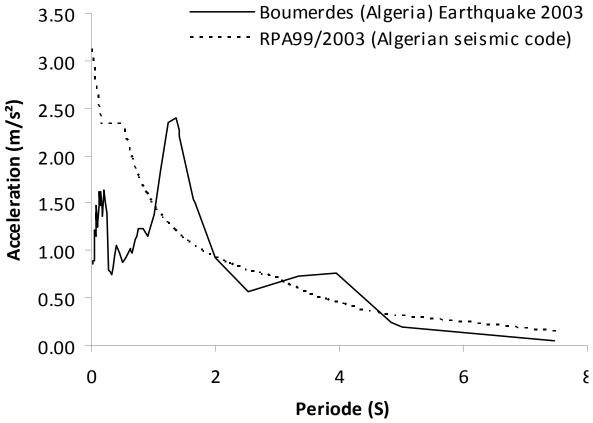

Fig. 7 Comparison of damped acceleration response spectra for selected time histories with design spectra from the RPA99/2003

Fig. 7 shows the response spectra of the time histories of the frame with $\xi_{eff} = 5\%$ (fixed base) in comparison to the Design Earthquake Spectra from the building from the /2003 (Algerian seismic code) [11].

TABLE II
RESULTS COMPARISON OF THE THREE MODELS

Unbraced structure		Braced structure (cross)		Base isolated structure (FPS)	
Period (s)	M .P. (%)	Period (s)	M .P. (%)	Period (s)	M .P. (%)
$T_1 = 7.47$	76.36	$T_1 = 2.02$	73.13	$T_1 = 11.12$	93.98
$T_2 = 4.84$	75.50	$T_2 = 1.87$	76.21	$T_2 = 8.32$	98.82
$T_3 = 3.95$	76.13	$T_3 = 1.33$	77.77	$T_3 = 8.05$	97.41
$T_4 = 2.52$	86.19	$T_4 = 0.63$	88.67	$T_4 = 3.37$	99.04

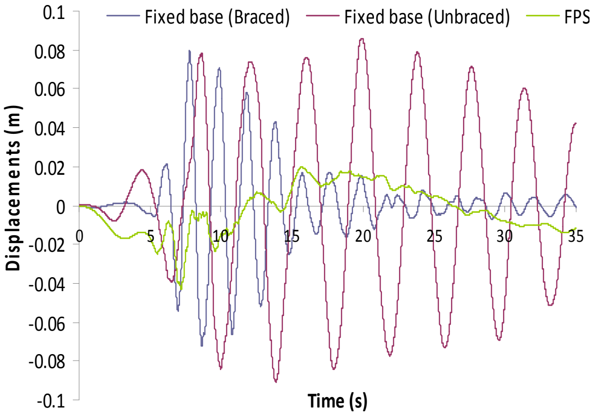

Fig. 8 Time history displacement response

B. Results and Interpretation

Table II summarize the comparison between resulting periods and modal participating ratio of the fixed base of unbraced structure (original frame), braced structure (cross brace with L120x13 profile) and FPS bearing isolated models.

Note that the condition of 90% of mass participation (M.P.) required by RPA99/2003 (Algerian seismic code) [11], have been satisfied in the case of the braced and isolated alternatives respectively at the mode N°8 and N°1.

All friction pendulum isolators added to the base of structure have been chosen with equal mechanical characteristics. As expected, the fundamental vibration period of the braced structure decreases. It is due to the increasing in stiffness involved by the added cross braces. However in the damped model (FPS isolated base), the period increases by 50% compared to the original frame (Unbraced). It is due to the low shear stiffness provided by the isolators to the base of structure. Consequently, the building becomes more flexible.

The time history analysis of top displacement and acceleration response of the structure in the three models is presented in curves of Figs. 8 and 9, respectively.

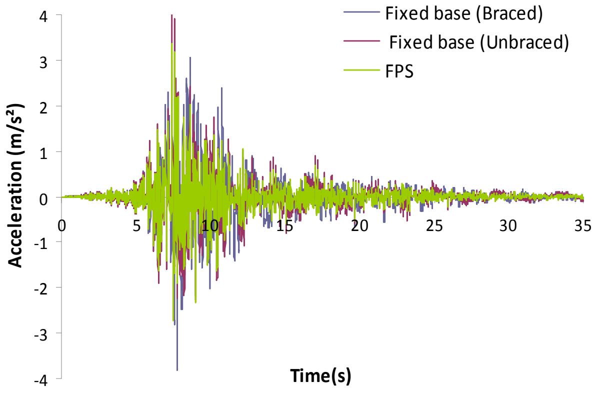

Fig. 9 Time history acceleration response (Cross braced, unbraced and structure with FPS)

Fig. 8 shows a significant response decrease of the structure equipped with FPS, when compared to the unbraced (original

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frame) design. When the top displacement value of the unbraced structure reach maximum, the corresponding one of the damped structure (with FPS) decreases by 45%. In other hand, the results show that the maximum displacements for the fixed base designs (cross braced and unbraced) are close within even so a relative diminution estimated at 12% for the cross reinforced model. However, the aforementioned structure response decreases quickly over the time when it is compared to the unbraced fixed base design. This improvement in displacements response is achieved through a decreasing of the inter-storey drifts which reduce differences between top and bottom storeys displacements such as it will be seen later in the paper. It also can be observed in curves of Fig. 9 that the acceleration response between the two cases, self-supporting and braced is almost the same unlike the case with friction pendulum system device which diminishes at the peak by 18%. This can lead to decreases the base shear forces for the isolated base structure but can allow also the reduce of the unpleasant effects of acceleration for occupants of these buildings and provide more safety against the damage of the non-structural parts as pipes, ceilings, etc.

Fig. 10 gives a particularly and interesting idea on the ability and the performance of FPS isolation device to reduce the base shear force. One can observe clearly that it becomes very important in the cross braced case. It is due to the decrease of the fundamental period (T=2.02 sec) which involve greater acceleration but this forces decrease rapidly over time due to the stiffness of the system. Unlike to the unbraced model where, the base shear force is not very important (T = 7.47 sec) but remains constant throughout the duration of the signal. In the isolated base model (T = 11.11sec), forces are very low representing almost a nought value which involve 99% of diminution compared to unbraced response values. This is due to the capacity of FPS to produce a passive control system by dissipating quickly the input energy forces into heat energy by friction involving the damping of the system.

The verification of structural member’s stability is checked in combinations including earthquake (RPA99-2003 section 5.2), however a time history analysis of the top axial (N), shear (V) forces and moment (M) resulting of the seismic loading has been carried out (Fig. 11). The results showed a net decrease values for FPS model compared to the two others models. The rate of response diminution is estimated at 80% for shear force (Fig. 11 (b)) and 82% for moments (Fig. 11 (c)). This decrease is due to the low shear stiffness provided by the isolation devices at the base of structure where the motion was decoupled from ground motion one. Nevertheless it is also due to the increase of damping ratio for the friction pendulum bearing model. It is also important to note that in the braced structure, the cross diagonals transmit a very significant axial force (Fig. 11 (a)), valued at 185 times the ones of the damped model.

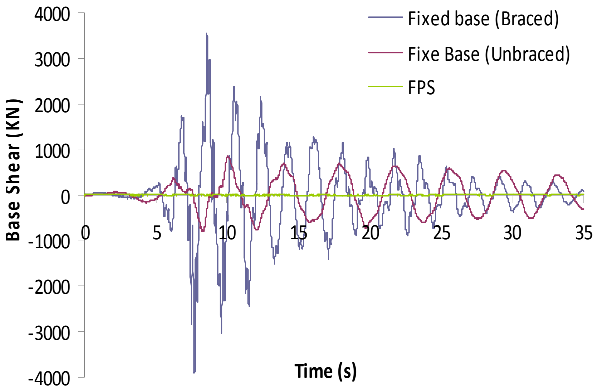

Fig. 10 Time history variation of base shear force

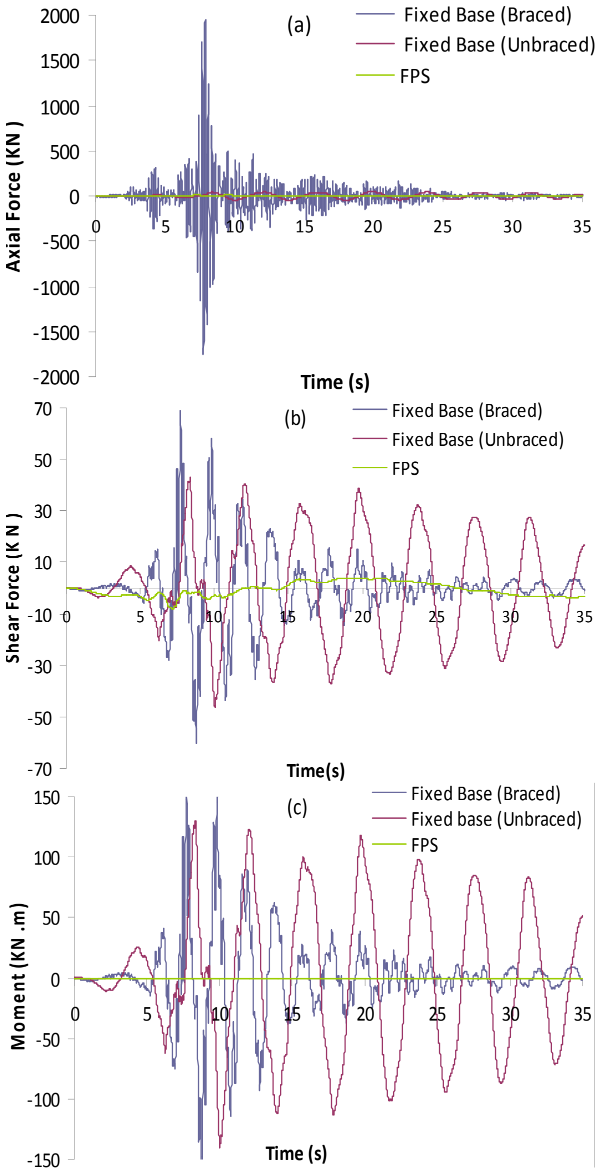

Fig. 11 Time history variation of N (a), T (b) and M (c) in the most loaded column

An analysis of inter-storey drift according on the height of building carried out for the three models is shown in Fig. 12.

One can see that the curve representing isolated structure with FPS looks like a vertical line whose values are almost constant. Hence, the displacements between successive stories show no significant variation which enables the building to behave as a single block.

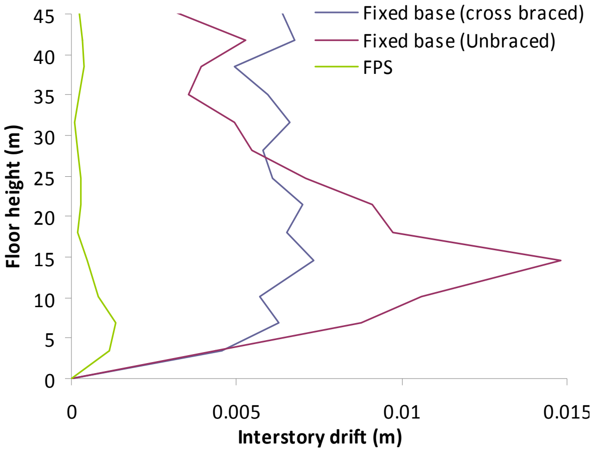

Fig. 12 Inter-storey drifts according to building height

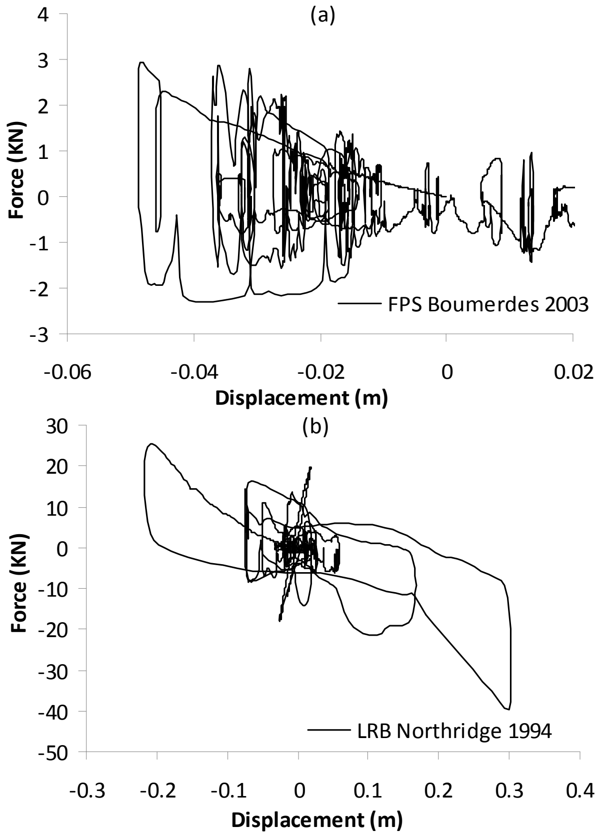

Fig. 13 Hysteric loops of damper resistance force versus displacement under (a) Boumerdes 2003, (b) Northridge 1994

The force-displacement curves for FPS device are presented in Fig. 13 in case of Boumerdes and Northridge ground accelerations, respectively. It is seen that the bi-linear behaviour assumption made in the design stage according to presented model is appropriate. The curve's shapes are similar to the concept presented schematically in the Fig. 4. Hence, it may be considered that these results justify the overall proof of the analysis concept presented in this work. The plots represent variation of base shear force versus displacement. As results, this force allows to the isolated system greater capacity to dissipate the dynamic loading energies.

IV. CONCLUSIONS

This study permitted to analyse the difference in steel structure behaviour, with and without friction pendulum bearing for a seismic load. Numerical calculation with SAP2000 software was used for the analysis of a 12-storey building. The results show that the use of the passive control device FPS in buildings generates a very significant reduction of the structural response compared to the unbraced ones. However, in the case of a 12-storey building, the main conclusions are summarized below.

The fundamental period increases by 50% compared to the unbraced structure. The maximum displacements decreases by 45% compared to the unbraced structure.

Reduction of the maximum acceleration is 18%, which reduces base shear values and its time loading. The N, T and M efforts were reduced by more than 80% in the most loaded members. The inter-storey drift become, almost zero, which generates block's behaviour of the structure and decreases the effects of shear forces.

The benefits of FPS were clearly demonstrated by the comparison data and improving performance of the structure during an earthquake has been proven. These devices are generally inexpensive and effective reinforcement of buildings subjected to dynamic loads.

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