Effect of vertical component of earthquake on the response of a Friction Pendulum Bearing base isolation system

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Abstract | F*riction Pendulum Bearings (FPB)* are one of the most used base isolation systems worldwide, in which the superstructure is isolated from the foundation through a sliding-based system. Ground motions force structure to slide along the concave surface of the bearing under its own natural frequency. This study aims to evaluate the influence of the vertical component of earthquake on FPB's response. The performance of FPB is numerically tested and analysed for two distinct conditions: (i) one test structure; and (ii) a real structure of a reinforced concrete lab with 3 floors. Seismic responses of isolated structural systems are compared with and without considering the vertical component of earthquake. The results showed that the vertical component of earthquake does not affect FPB's design: the maximum bearing displacement does not change with vertical component of earthquake. Both lateral stiffness and friction resistance have instantaneous and arbitrary variations due to oscillations of the vertical load on the support; however, the envelope of FPB's response is not significantly affected.

Keywords: Seismic Protective Systems, Base Isolation, Friction Pendulum Bearings, Vertical component of earthquake

1. Introduction

Seismic isolation is an effective tool for earthquake resistant design of structures. Friction Pendulum Bearing (FPB) is one type of base isolation system commonly used in practice, i.e. a structural joint installed between the superstructure and its foundation, isolating the superstructure from severe ground motions. It enhances the performance of structures well beyond the standard code requirements with potential for substantial life-cycle cost reduction (e.g. minimizing interruption of the use of the facility, reducing damaging deformation in structural and non-structural components). (Eröz et al, 2008; Kravchuk et al, 2008; Mokha et al, 1996)

Seismic action is described by two horizontal and orthogonal components and one vertical component. Contemporary engineering design professionals usually agree that it is primarily the horizontal ground vibration motions of an earthquake that take damaging to a building. Furthermore, structural details are designed mainly to support vertical loads with safety factors generally considered sufficient to account for vertical seismic loads. (Zayas, 1987) Vertical earthquake motions, despite neglected for earthquake resistant design of structures, could affect the response of some base isolation devices such as FPB.

This paper discusses the main results and conclusions of the research project on "Effect of vertical component of earthquake on the response of a Friction Pendulum Bearing base isolation system" (Amaral, 2013). The research tested, by application in two case studies – a test structure and a real structure of a reinforced concrete 3-storey building-, the effect of vertical component of earthquake on the FPB's response. Nonlinear analysis follows Eurocode 8 requirements applicable to Lisbon area. Despite two different structures were tested, this paper focus on the real structure. The test structure was used to authenticate the results of the real structure.

Next section briefly describes the research problem and introduces FPB. Section 3 presents and discusses the case study. The paper concludes with a list of main conclusions.

2. Friction Pendulum Bearing (FPB)

FPB has become a widely accepted device for seismic isolation of structures since the revolutionary invention of FPS® in 1985 by Victor Zayas, attested by numerous applications in very distinct conditions. Nowadays, the choice of seismic base isolation systems compare the feasibility of a FPB with other well-known bearings (e.g. HDRB and LRB).

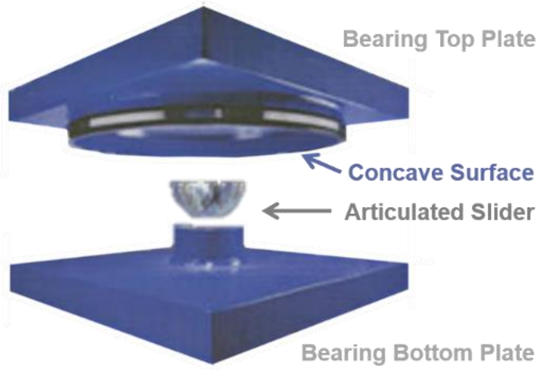

Figure 1 - Components of the FPB

FPB consists of a spherical stainless steel surface and an articulated slider, covered by a low friction material - Figure 1. (Zayas, 1987)

During severe ground motion, the slider moves on the spherical surface lifting the structure and dissipating energy by friction between the spherical surface and the slider – Figure 2. (Hacheem et al, 2010; Kravchuk et al, 2008)

The weight of the building is supported by the articulated slider allowing the superstructure's vertical axis to remain vertical – Figure 3. (Zayas, 1987)

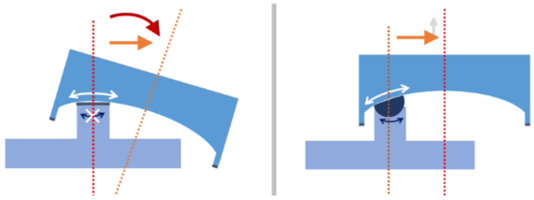

Figure 3 - Articulated slider's importance in isolated structure's motion.

FPB's performance exhibits two stages - a static phase and a dynamic phase -, controlled by friction in the sliding interface mainly to restrain lateral movements under service lateral loads. When lateral forces are below the friction force level, a FPB supported structure responds like a conventionally supported structure, at its non-isolated frequency of vibration, and the system acts as rigid connection transferring the total force to the superstructure. (Chaudhari et al, 2004; Zayas et al, 1990)

When the earthquake forces overcome the static value of friction, the system is activated (the bearing reaches the dynamic stage). (Zayas et al, 1990) FPB's mechanism is based on its concave geometry and surface friction properties. The supported structure moves according to a simple pendulum's motion as the bearing slides along the concave surface and dissipates hysteretic energy via friction. (Hacheem et al, 2010)

The frequency of the FPB is selected simply by choosing the radius of curvature of the concave surface (R). It is independent of the mass of the supported structure (e.g. storage facilities or tanks). In the equation [1], a_V is the vertical absolute acceleration. Unless changes in vertical acceleration occur (induced by structural dynamic motion or ground motions), a_V is considered equal to the acceleration of gravity (g).

$$f = \frac{1}{2\pi}\sqrt{\frac{a_V}{R}} \qquad [1]$$

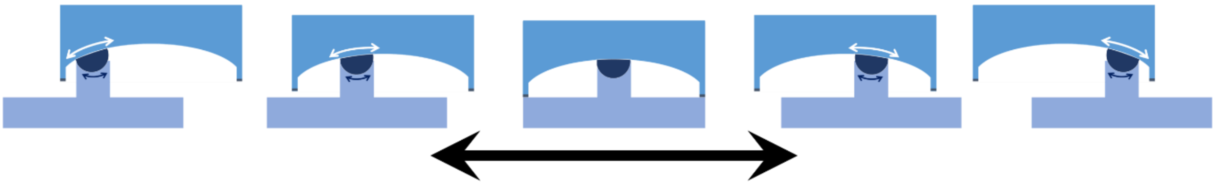

Figure 2 - FPB's characteristic motion.

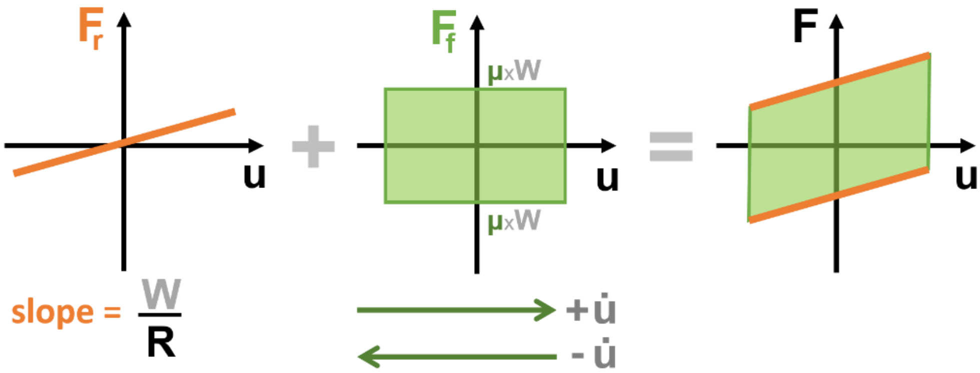

Figure 4 - FPB's hysteresis loop.

The FPS lateral force has two components, (i) a restoring force due to the raising of the building mass along the sliding surface, and (ii) a friction force due to friction at the sliding surface. (Symans, 2013) The horizontal force, $\boldsymbol{F}$, at the horizontal displacement $\boldsymbol{u}$, can be expressed by the following equation:

$$\boldsymbol{F} = \frac{W}{R} \times u + \mu_{dyn} \times W \times sgn(\dot{u}) \qquad [2]$$

restoring + **friction**

where $\boldsymbol{W}$ is the vertical load, $\boldsymbol{\mu_{dyn}}$ is the dynamic friction coefficient of the sliding surface, and $\boldsymbol{sgn(\dot{u})}$ is the sign of the velocity used to define the direction of the friction force. The maximum lateral force transmitted to the superstructure is reached for maximum displacement of the bearing.

The lateral force is proportional to the vertical load, a property which minimizes adverse torsional motions in structures with asymmetric mass distribution. (i.e. lateral stiffness - K=(W/R) - is directly proportional to the weight, therefore the centre of stiffness automatically coincides with the centre of mass of the supported structure.) (Hacheem et al, 2010; Jangid, 2004)

FPB's hysteresis loop can be understood by overlapping the linear operation of a simple pendulum with the friction behaviour of a block acted laterally over a planar surface (Figure 4)

The progression of a FPB isolation system's hysteresis loop for a half cycle of motion is present in Figure 5. Between position 0 and position 1 – before motion –the static value of friction has to be overcome.

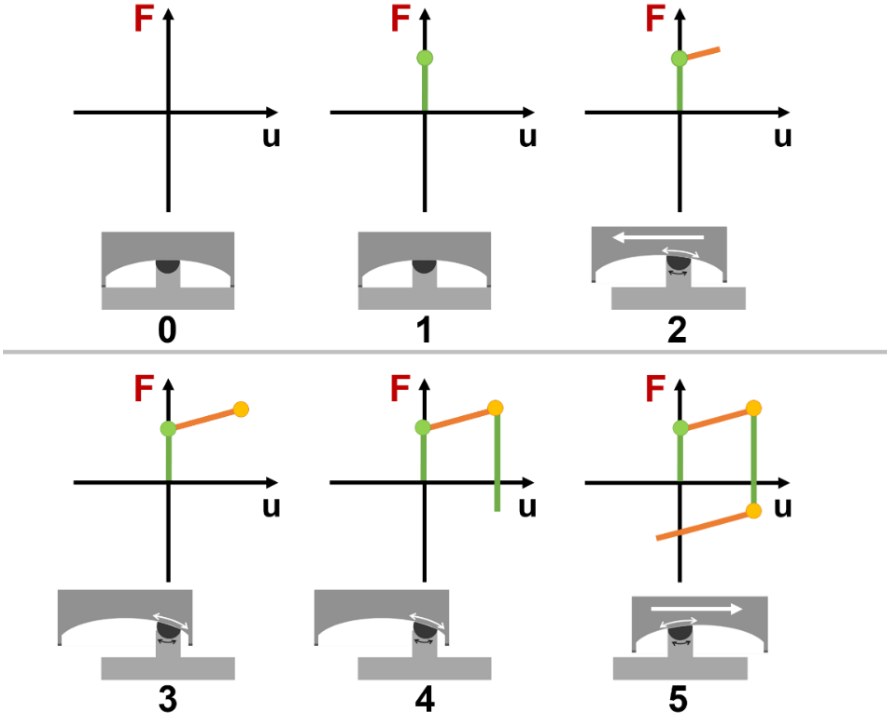

Figure 5 - Progression of the isolation system's hysteresis loop for half cycle of motion. Adapted Symans (2013)

When friction is exceeded, pendulum motion began with the lateral stiffness of a simple pendulum motion (K=(W/R) – position 2. At this point, the restoring force is adverse to the movement. The bearing reaches the maximum deformation when the maximum displacement is reached (in an ideal model) – position 3. FPB's maximum displacement is reached when seismic forces' sign reverses its direction: at this point the bearing has no velocity and stops again. Position 3 corresponds to the maximum lateral force transmitted to the structure being the sum of the constant value of the friction force with the maximum restitution force. Between 3 and 4, seismic lateral force has to overcome the static value of friction (again) to begin the motion in opposite direction. To conclude half cycle of motion, between 4 and 5, the bearing passes by the initial position with maximum velocity - resistance is made just by the friction force. From position 4 to initial position the restitution force is favourable to motion. (Zayas, 1987)

Nowadays, new systems have been patented trying to improve the performance of the original system. Remarkable progress has been observed in the low friction materials fitted to support latest FPB. (Huber et al, 2013; Zayas et al, 2006)

3. Case Study

3.1 Building description

The Regional Veterinary Laboratory of Azores (RVLA) was used as structural model of a real structure. RLVA, constructed in 2008-2013, was built in Angra do Heroísmo, Terceira, Azores. It is the second building protected with base isolation in Portugal. The maximum risk of contamination imposed zero level of allowable cracking. Performance requirements as well as construction zone's seismic hazard justified the adoption of a base isolation system.

RVLA's base isolation project chose elastomeric bearing HDRB. RVLA was selected to this study because the structural model was already adapted to use a base isolation system. The HDRB system was replaced for FPB in the computational model and the behaviour of the structure according to EC8's regulations of Lisbon was analysed. Computational models were developed using SAP2000.

The structure is in reinforced concrete class C25/30 and consists of three floors of square plan. The structural system has a central core, 8 interior columns and a peripheral frame system. The total weight of the building (dead load + reduced live loads) is about 3854 tons

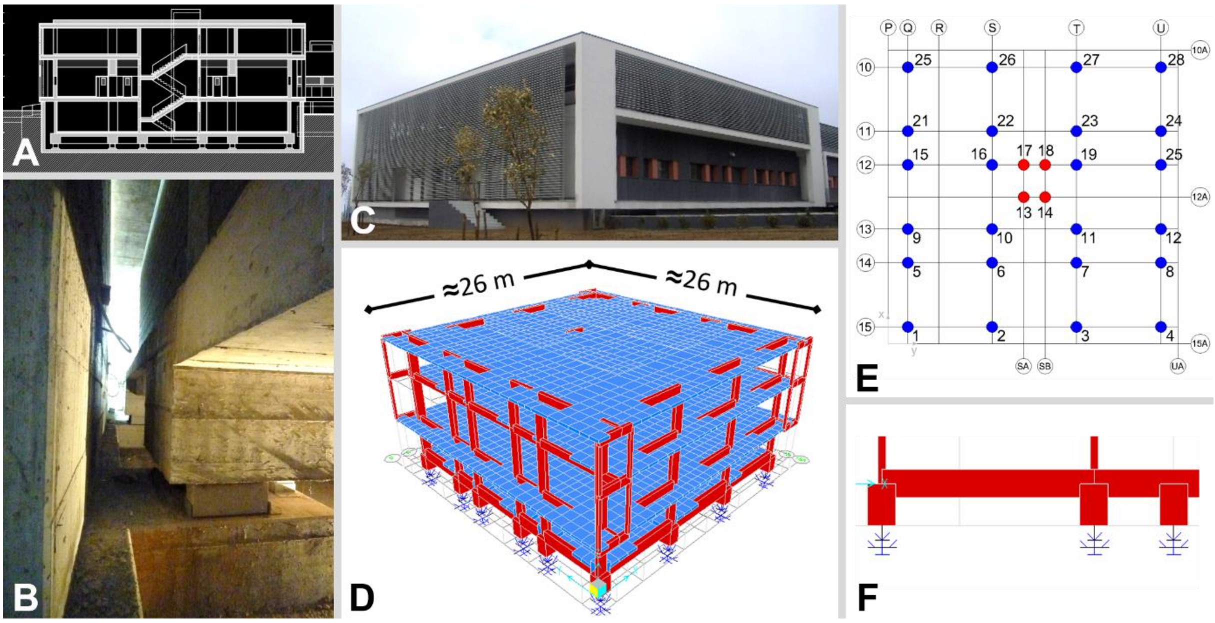

Figure 6 - – RVLA: (A) Architecture cross-section view; (B) Seismic gap with HDRB isolators; (C) External final view (D) Computational Model; (E) Isolators bearing's location; (F) Connection between superstructure and base isolation system

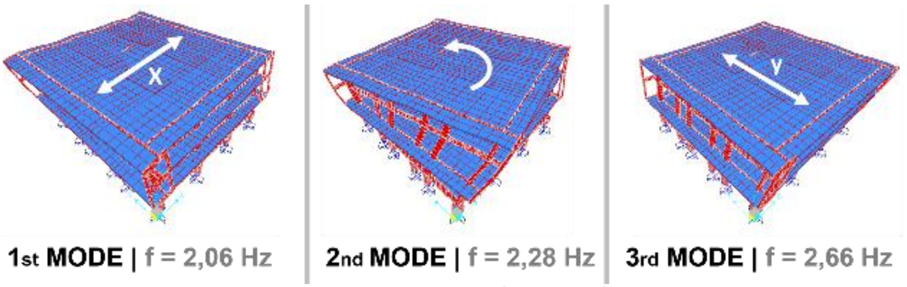

Figure 7 - Fundamental vibration modes of RVLA's fixed base structure

irregularly distributed on 28 base isolation devices.

The design process of an isolation system starts with the analysis of the fixed base structure. Modal dynamic analysis demonstrated that the structure under study is characterized by a fundamental frequency of 2,06 *Hz*. The configuration of the main structural modes of vibration shows that this building exhibits an irregular behaviour: the first and the third vibrational modes match to translational deformations in the horizontal plan, while the second vibration mode matches with the global torsion of the structure.

3.2 FPB isolation system design

The design process of FPB isolators is practically focused on the definition of the curvature radius (*R*) of the spherical sliding surface and on the friction coefficient (μ) between surfaces.

The desired frequency for the isolation system defines R: to confer a frequency of 0,50*Hz* to RVLA's isolated structure, the curvature radius of the sliding surface was obtained from equation [1] and is equal to 0,993m.

The damping shows that the necessary shear force (*F*) to initiate the oscillatory movement is selected by choosing the friction coefficient. Static and dynamic frictions are considered constant (Coulomb's friction) and equal to 0,1.

Table 1– FPB's nonlinear properties

FPB's nonlinear properties		
R [m]	μ_{static}	$\mu_{dynamic}$
0,993	0,1	0,1

3.3 Analysis and Results

FPB's response is evaluated by nonlinear time-history analysis. As the main goal of this study is not to design FPB's isolators but to analyse the influence of earthquake's vertical component, seismic action is defined just in one horizontal direction. Thus, the seismic responses of the isolated structural system with and without consideration of the vertical component of earthquake are compared.

First of all, the designed FPB was analysed in a Test structure. The Test structure is simple, regular, symmetric and very rigid resulting in a predictable behaviour, which was useful and effective to confirm the performance and modelling of FPB supports. The Test structure authenticates the results obtained to RVLA's structure -Test structure's results are present in Amaral (2013).

Table 2 presents the maximum displacement verified for all 28 bearings subject to different combinations of seismic action. Maximum displacements are greater for seismic action type 1 (seismic source interplate) than for type 2 (intraplate). For this fact, the following analysis focus just seismic action type 1.

Table 2 – RVLA's results: bearing's maximum displacement (alignment 10)

RVLA's Results		
Seismic Action	$|u|_{MAX}$	
	w/ Ez [m]	**w/o Ez** [m]
Type 1	0,062	0,061
Type 2	0,018	0,019

Vertical component of earthquake produces insignificant and random variations in FPB's displacements. The random nature of the seismic action makes the influence of the vertical component in FPB's response unpredictable.

All 28 FPBs almost present the same maximum displacements, for the same instant, independently of their position, showing that torsional motion is reduced (or eliminated) and the structure slides like a rigid body with translational motion.

Figure 8 resumes the main results of load combinations involving seismic action type 1. The negative sign of axial forces corresponds to compression forces.

Axial force mean value is not affected by seismic action: as the mean of seismic wave is zero, the mean value of axial force does not

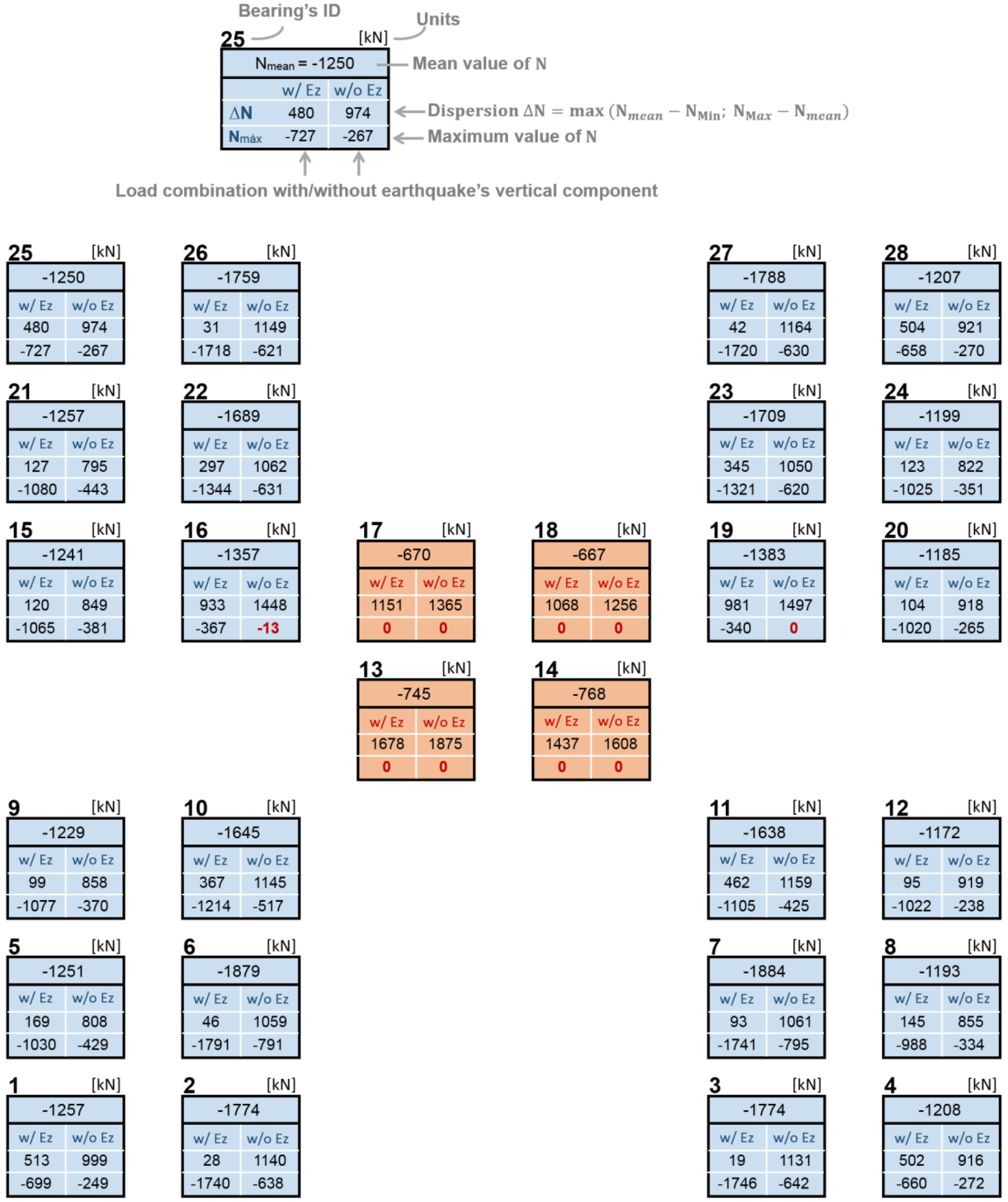

Figure 8 - RVLA's results: Axial force on the bearing for seismic action type 1.

change regardless of different load combinations. As RVLA's structure has irregular mass distribution, FPB's axial force is not uniform and depends on the location. The mean axial force in FPB that supports the central core of the building is low, i.e. it does not exceed 750kN.

Although there is no influence in the design displacement, the variation about the mean axial force increases with earthquake's vertical component. The increase is not uniform but occurs for all 28 FPBs: the dispersion around mean axial force increases both where it was already high (e.g. corner bearing 1 or 25, central core bearing 13, 14, 17, and 18) and also where it could be neglected before (peripheral bearings 2 or 26, interior bearings 6 or 22).

The greater amplitude of the axial force increases the prospect of no compression on some bearings (e.g. FPBs on central core support). No compression on the bearings (Nmax=0) result in no friction forces or energy dissipation. This fact does not change FPB's base isolation system global response but, from

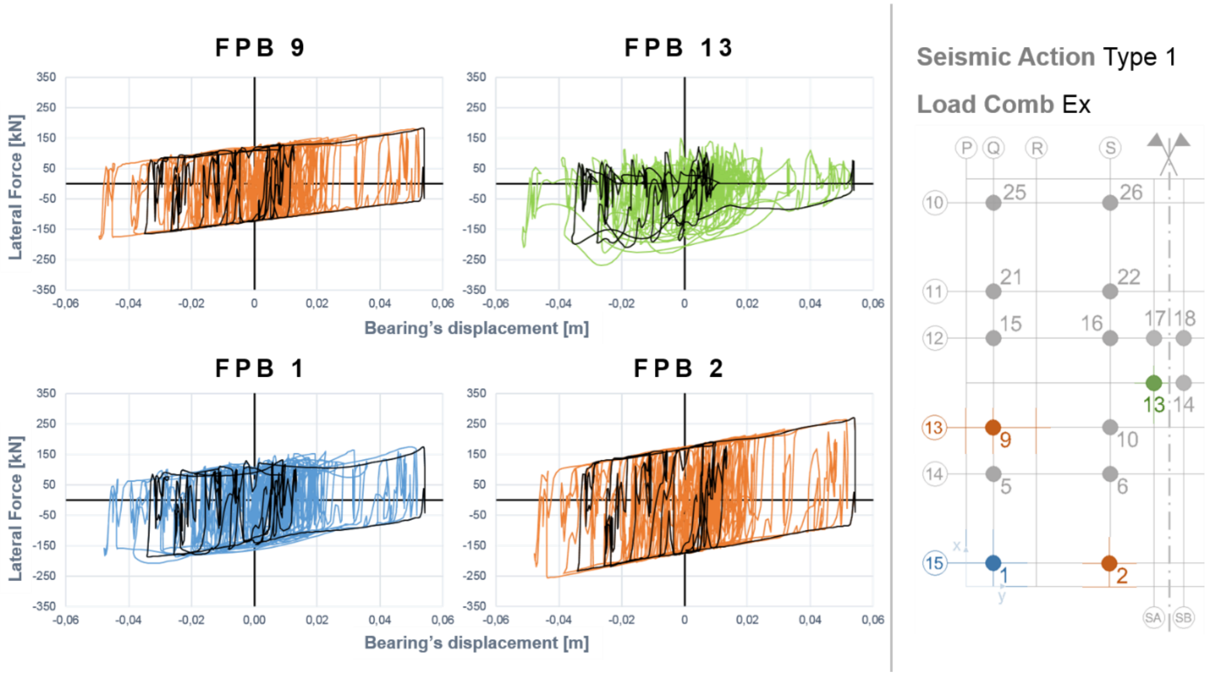

Figure 9 – Hysteresis loop of 4 FPBs involving only horizontal component of seismic action (type 1)

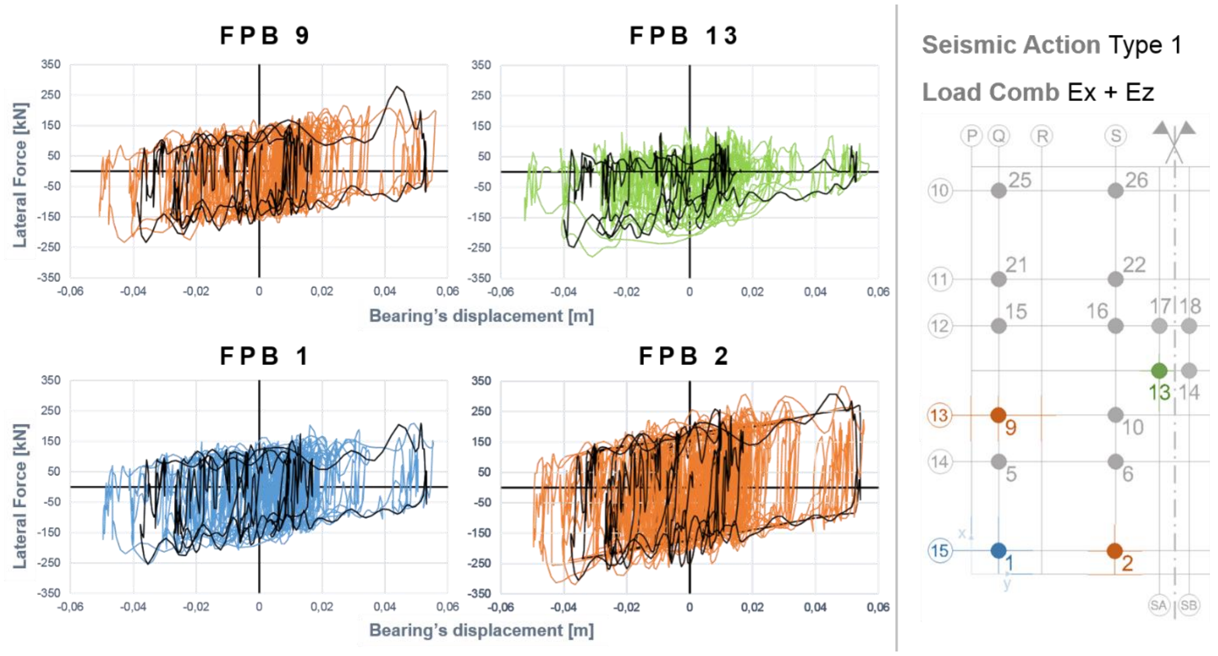

Figure 10 - Hysteresis loop of 4 FPBs involving both horizontal and vertical component of seismic action (type 1).

the designer's point of view, the existence of tension in the isolation system should be avoided.

In order to understand the consequences of earthquake’s vertical component in FPB’s response, the hysteresis loop of 4 bearings in various locations are presented: corner bearing 1, peripheral bearings 2 and 9 and central core bearing 13. The hysteresis loop for a seismic combination with just horizontal components (Figure 10) and with both horizontal and vertical component (Figure 9) are compared. A single hysteresis loop, between 12 and 17,5 seconds of seismic action, is identified in black.

Force-displacement relation depends on the location of FPBs. Despite differences between hysteresis loops, displacements in the four FPB bearings are practically the same. For both load combinations, FPBs have the same displacements in the same instant, i.e. the isolator moves synchronized as a group independently of the seismic action considered.

Hysteresis loop shape could be related to the dispersion around the mean axial force on the bearing: the more significant the amplitude in axial load is, the larger imperfections the hysteresis curve has.

Bearings 2 and 9 present a hysteresis loop close to ideal. From Figure 8 is possible to identify that both isolators’ axial force on the bearing is practically constant during load combinations acts (particularly if earthquake’s vertical component it is not considered).

On the other hand, hysteresis loop of bearing 1 and 13 is out of the ideal behaviour. The amplitude of the axial force in bearing 1 and 13 is very high: bearing 1 shows variations close to 50% about the mean axial force, while axial force in bearings 13 almost duplicates its value.

Changes in the axial force on the bearing affect, on one side, the lateral stiffness and, on the other side, the friction force resistance. Stiffness change is random and caused by instantaneous variations of vertical force on the bearing due to earthquake’s vertical component.

Instantaneous variation of stiffness due to earthquake’s vertical component occurs, in the 4 bearings presented, for the same stage of deformation (e.g. when the displacement on the bearings is about 0,04m, the slope of the hysteresis loop increase in the 4 bearings) – Figure 9. As FPBs in the base of the structure moves synchronized as a group, the punctual change on stiffness happens in the same instant for the 4 bearings when earthquake’s vertical component affects FPS’s response.

Hysteresis loops, with and without consideration of earthquake’s vertical component, present the same tendency of motion but the loop shape is lightly influenced by arbitrary variations on the friction force (static and dynamic) due to earthquake’s vertical component. The maximum displacement in the bearing or the lateral force transmitted to the structure is similar for both load combinations.

There are two main parameters that control FPB’s response: the curvature radius (R) and the friction between surfaces. In this paper the influence of curvature radius (i.e. frequency of isolated structure) isn’t focus because, on one hand, the influence of frequency is more

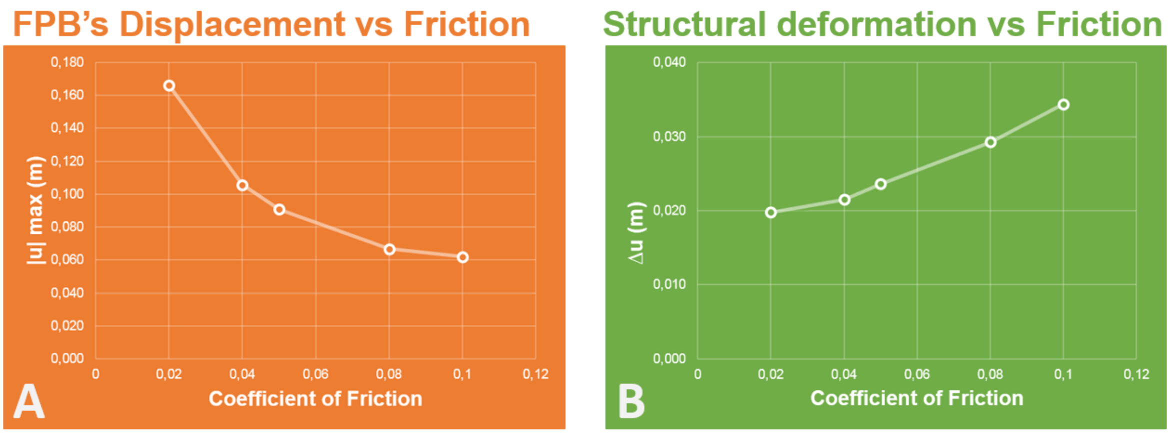

Figure 11 - The influence of friction (A) on FPB’s maximum displacement and (B) on RVLA’s structural deformation.

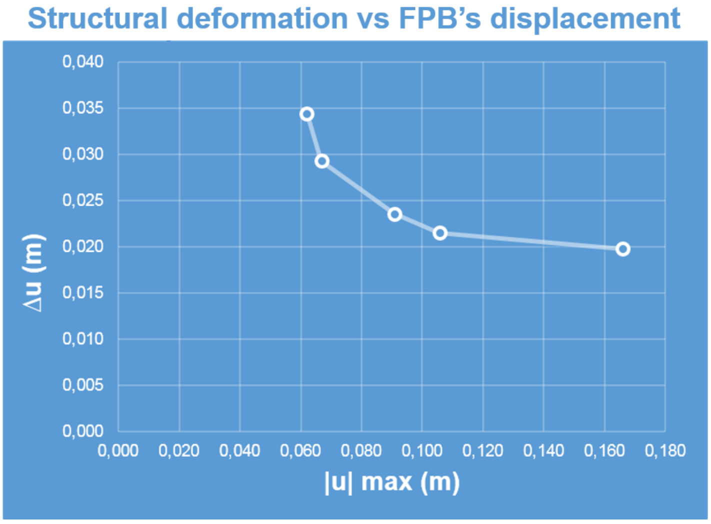

Figure 12 - RVLA’s structural deformation function of FPB’s maximum displacement.

predictable as a result of many studies about base isolation systems and, on another hand, the frequency used in this study (0,5 Hz) guarantees that the structural motions are uncoupled from dynamic modes. Next, friction is analysed.

Friction in FPB response controls both the force transmitted to the superstructure and the bearing’s displacement: the higher the friction is, the lower is the bearing’s displacement but higher is the force transmitted to the superstructure. Figure 11 presents the influence of friction in FPB’s displacement, through the maximum displacement in the bearing, and in the deformation of the structure, through the relative displacement of the top in relation to the base of the superstructure (Δu). Five different coefficient of friction are considered: 2%, 4%,5%, 8% e 10%.

Bearing’s displacement has a negative correlation with the friction coefficient according to a nonlinear pattern – Figure 11A. The effectiveness of friction to reduce FPB’s displacements is not uniform and decreases as the coefficient of friction increases.

The deformation in the superstructure (i.e. force transmitted to the superstructure) increases with the friction coefficient and, for medium-high lateral forces transmitted to the structural system, the variation is almost linear – Figure 11B.

The chart in Figure 12 presents the relation between the structural deformation and the FPB’s maximum displacements. Each point corresponds to one coefficient of friction related to Figure 11A and B.

The higher the bearing’s maximum displacement is, the lower the structural deformation is. FPB’s design is a trade-off between the isolator’s costs – the higher the design displacement is, higher the cost of the bearing is – and the acceptable structural deformation level. There isn’t a point where structural deformation is minimum. Nevertheless, the design procedure should optimize the friction to obtain the best efficiency in structural deformation reduction.

4. Conclusion

The influence of the vertical component of the earthquake on FPB’s response was studied by application in a real structure of a reinforced concrete lab. Based on the various studies performed the following is concluded:

1. Earthquake’s vertical component has no influence on the value of the maximum displacement of FPB (for both types of seismic action 1-interplate or 2-intraplate). The variation on the bearing’s displacement is insignificant and arbitrary (unpredictable).

2. The deformation pattern of the structure is not influenced by earthquake’s vertical component. FPBs move synchronized as a group, independently of the load combination. Structural torsion is practically annulled by FPB isolation system and the structure moves as a rigid body in translational motion.

3. The mean value of axial force on the FPBs isn’t influenced by earthquake’s vertical component. Despite the constant change of the seismic waves’ sign, the average of the vertical seismic acceleration is zero and therefore has no influence on the average value of the axial force in the FPB support.

4. The variation about the mean axial force increases with earthquake’s vertical component. The increase is not uniform but takes place for all FPBs. The changes in the axial force on the bearing affect both lateral stiffness and friction force resistance. However, the envelope of force-displacement FPB’s response is almost not influenced by earthquake’s vertical component.

5. The greater amplitude of the axial force increases the probability of no compression on the bearings This fact does not change FPB’s base isolation system global response but, from the designer's point of view, the existence of tension in the isolation system should be avoided and the solution should be studied.

6. The influence of friction in FPB’s response is not affected by earthquake’s vertical component. FPB’s design should choose the most effective friction in the reduction of structural deformation, keeping bearing’s displacement in acceptable levels. In the iterative design procedure, the radius of the concave surface should be optimized according to the desirable frequency.

The analysis suggests that the influence of the vertical component of earthquake on FPB’s response may be extended to new cases of study, considering extreme cases such as irregular and tall structures. Future developments should include case studies constrained by seismic action type 2 (intraplate – near field fault). In addition, the latest developments in FPB isolation systems could be further studied, in particular the sliding materials with frictional coefficient dependent on the surface pressure of the bearing and the new FPB isolation systems with multiple sliding surfaces

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