Numerical Study of the Seismic Behaviour of Variable Friction Base Isolation Systems

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Abstract

Variable Friction Systems (VFS) have been recently proposed as potential alternatives to traditional friction devices. VFS come with an extra design “degree of freedom”, in the form of coexisting multiple friction coefficients across the sliding surface, so that the properties of the base isolators can be adjusted to achieve enhanced seismic performance. In particular, the principal benefit of VFS is their capacity of dissipating a larger amount of energy with respect to their constant-friction counterparts, reducing the displacement demand on the system, and the lateral forces and accelerations transmitted to the isolated structure.

This paper presents the results of more than 450,000 non-linear time history analyses, illustrating key differences in the response of VFS as a function of the systems’ properties and showing that generic VFS can be capable of high seismic performance.

Keywords: Base Isolation; Friction Pendulum; Variable Friction; Time History; Single Degree.

1 Introduction

Variable Friction Base isolation systems (VFS) are recently proposed alternatives to existing friction devices (Calvi et al., 2016[1]; Calvi and Ruggiero, 2016[2]).

VFS consists of sliding systems in which materials with different frictional properties coexist on the sliding surface (see Fig. 1). Analogous to traditional friction devices (e.g. Friction Pendulum (FP) systems[3]), a VFS may consist of a fixed base plate overlaid by a sheet of stainless steel with rings of different friction coefficient (see Fig. 2), and a slider composed of steel plate and sliding pad of low friction material (e.g. polytetrafluoroethylene). The slider is free to move with respect to the base-plate surface when a lateral force is applied to the system. The rings are arranged so that the friction coefficient between the slider and the base plate increases as the slider moves outward from the center of the device.
The sliding surface of a VFS can be flat or curved. The presence of a radius of curvature provides re-centering properties and modifies the hysteretic response of the device. More details, can be found in the work of Calvi et al., (2016)\cite{1} and Calvi and Ruggiero, (2016)\cite{2}.

Examples of force-displacement responses that can be achieved using VFS are qualitatively shown in Fig. 3, where the response of a traditional FP is compared to that of a “BowTie” and a “BowC” (i.e. a VFS with flat sliding surface and a VFS with curved sliding surface calibrated to have a flat re-centering branch). It can be seen that the hysteresis of both VFS encompass more area than that of an FP with the same backbone curve. This is the key attribute to VFS that is making efficient usage of the hysteretic space, allowing the dissipation of a greater amount of energy for a given force-displacement envelope.

The results of preliminary analyses conducted on “BowTie” and “BowC” devices have demonstrated that VFS can guarantee high seismic performance in certain situations. However, no studies on systems with behavior other than that shown in Fig. 3 have been conducted.

2 Mechanics of VFS

The use of multiple friction coefficients, in combination with properly calibrated curved sliding surfaces, consents the formulation of base isolation devices with “non-conventional” hysteresis. In particular, force-displacement responses characterized by arbitrary values of post-activation-to-re-centering stiffness ratios (referred to as $\beta$) can be obtained.

A curved VFS can be seen as a system made of flat VFS and frictionless pendulum working in parallel. Combining the hysteresis of a flat VFS and frictionless pendulum shown in figure 4 and 5 respectively, the hysteresis of a curved VFS can be derived.

This paper generalizes the response equations for VFS with arbitrary characteristics and force-displacement responses and uses extensive non-linear time history analyses (more than 450,000 analyses) to study their response to earthquake excitations.
It can be seen that a curved VFS behaves as a rigid elastic system under increasing or decreasing loads. The lateral motion begins when the applied shear overcomes the activation shear $V_\mu$. At this point, the lateral stiffness of the system, $K_{\text{tot}}$, is engaged. The lateral force can be increased up to a certain maximum value referred to as $V_d$ (or $V_{\text{max}}$). As the lateral shear decreases, the system responds again rigidly until the re-centering shear, $V_{d1}$, is overcome. At this stage, the bearing begins to move back toward the center of the sliding surface. The re-centering stiffness is a function of the frictional properties and of the radius of curvature that characterize the device and its slope could assume positive, neutral or negative sign. It should be noted that a curved VFS converges to a traditional FP if the frictional properties of the sliding surface are maintained constant (i.e., $\mu$ is single-valued).

Considering a curved VFS, the activation shear, $V_\mu$, can be calculated as $W \cdot \mu_l$ that are the weight carried by the isolation system and the lowest friction coefficient (which characterizes the central ring of the device). $V_d$ and $\Delta_d$ (or $V_{\text{max}}$ and $\Delta_{\text{max}}$) are the design values of lateral shear and displacement, while $V_{d1}$ is the re-centering force. In this context, the post-activation stiffness of the system can be expressed as:

$$K_{\text{tot}} = \frac{V_d - V_\mu}{\Delta_d} \tag{1}$$

The radius of curvature and the frictional stiffness of a VFS can be derived as:

$$R = \frac{W \Delta_d}{(0.5\beta + 0.5)(V_d - V_\mu)} \tag{2}$$

$$K_\mu = K_{\text{tot}} - (0.5\beta + 0.5)K_{\text{tot}} \tag{3}$$

Where $\beta$ is the re-centering-to-post-activation stiffness ratio, computed as:

$$\beta = \frac{V_{d1} + V_\mu}{V_d - V_\mu} \tag{4}$$

Eqs. (2) and (3) allow a designer to determine all the geometrical and mechanical properties of the base isolation device right after selecting the design displacement and the coefficient $\beta$, and after having determined the magnitude of the design and the activation shear forces.

More specifically, as discussed by Calvi and Ruggiero (2016), at this point the designer has two options:

1. Select the geometry of sliding surface, and calculate coefficient assigned to each ring

$$\mu_i = \mu_L + \frac{K_\mu}{W} \cdot \bar{x}_i \tag{5}$$

Where $\bar{x}_i$ is the center-point of ring $i$.

2. Select the friction coefficients to be assigned to various rings and calculate ring radii recursively.

$$r_1 = r_0 \tag{6}$$

$$\bar{x}_i = \frac{\mu_i - \mu_L}{K_\mu/W} \tag{7}$$

$$r_i = 2\bar{x}_i - r_{i-1} \tag{8}$$

The number of rings that is necessary to achieve a nearly linear response is recommended as:

$$n \geq \frac{2\Delta_d}{\Delta_0} \tag{9}$$

A more comprehensive discussion of the mechanics of VFS can be found in Calvi and Ruggiero (2016).
3 Verification Study

This section presents a numerical study of the response of VFS under earthquake loads. One set of case study structures is selected, modelled and tested in the context of non-linear time history analyses under a suite of ground motions of varying characteristics and intensities. The objective of this section is to gauge how the seismic response of VFS is affected by their properties and to verify the effectiveness of VFS with respect to their single-valued friction counterparts.

3.1.1 Case study structures

The VF case study systems have been designed to mimic the response of three standard FP systems extracted from a producer’s catalogue\(^4\). The three systems selected are characterized by radii of curvature of 2.5 m, 3.1 m and 3.7 m, respectively, and by a friction coefficient equal to 5.5%. Each device has a peak displacement capacity of 0.45 m and the vertical load considered is equal to 6,000 kN. Note that, to study the systems’ response under rare conditions, it is assumed in the analyses that all isolation systems can undergo larger maximum displacements than the design displacement, while maintaining post-activation stiffness.

For the design, all the bearing pads have a diameter of 0.3 m and all the sliding surfaces have a diameter of 1.2 m. For these three target FP systems, properties such as design shear \(V_d\), activation shear \(V_\mu\), post-activation stiffness \(K_p\) are known. These pieces of information used in combination with the equations provided in Section 2, allow the calculation of the properties to be assigned to the “equivalent” VFS. The numerical study is conducted considering VFS with \(\beta\) values ranging from -1.0 to 1.0 at intervals of 0.25. Therefore, a total of 27 VFS are designed in line with the recommendations reported earlier. In particular, it is decided that that the sliding surface of each device is made of four rings with diameters equal to 300, 600, 900 and 1,200 mm, respectively.

The radius of curvature of each surface and the frictional properties of each ring are calibrated to achieve the desired hysteretic response.

Examples of hysteretic responses obtained for different values of \(\beta\) are outlined in Fig. 7.

Figure 7. Force Displacement response of an FP with \(R = 2.5\ m\) and of “equivalent” VFS

3.1.2 NLTHA and ground motions

To carry out the numerical analysis of the selected case study systems, a customized computer program is compiled in Matlab (Matlab 2012)\(^5\). The program solves incremental equation of motion using linear Newmark-Beta integration algorithm (Newmark and Rosenbleuth 1971)\(^6\) for “shear type” structures. The isolation system is simulated using a non-linear translational spring characterized by appropriate relationship between lateral force and displacement as discussed by Calvi and Ruggiero (2016). The hysteresis is defined as a function of isolator selected, as discussed earlier. In the present study, the structure is idealized as a single mass connected to the ground by a translational spring representing the isolation system. In this context, the mass is allowed to translate exclusively in the x-direction. The program treats the viscous damping as proportional to the tangent stiffness, as recommended by Pant et al. (2013)\(^7\). However, a 0% damping ratio is specified in the analyses, so that the hysteretic component provided by the isolation system was the only source of damping in the numerical model.

The input to the numerical simulations consisted of 50 real ground motions extracted from the PEER database\(^8\). The ground motions are scaled to be compatible with the selected target response spectrum (type C soil in the region of San Francisco). The target spectrum PGA is 0.59g while
The corner period of the displacement spectrum is at $T = 6$ s, corresponding to a displacement of 1.24 m.

The acceleration and displacement response spectra associated to each ground motion, the average spectra, and the design spectra are shown in Fig. 8 and Fig. 9. It can be seen that the average spectra lie reasonably close to the target (design) spectra.

Magnitude scale factors ranging from 0.1 to 10 times the magnitude of the “design earthquake” are considered. However, only characteristic intensities ranging from 0.3g to 2.0g are considered realistic and therefore studied in detail.

![Average Spectrum](image1)

*Figure 8: Acceleration spectra of selected 50 GMs*

![Average Spectrum](image2)

*Figure 9: Displacement spectra of selected 50 GMs*

3.1.3 Results and comparisons

The main parameters of interest are maximum force, maximum displacement, maximum acceleration, and residual displacement experienced by the various case study systems. The key results for associated to the “design level” earthquake are summarized in Fig. 10.

The main observation that can be made is that lowering the value of $\beta$ has beneficial effects with respect to lateral forces and accelerations but tends to produce systems with lower re-centering capabilities.

This trend is confirmed in Fig. 11, which provides additional information on the effects of the earthquake intensity. Note that, only the results associated to four EQ multipliers (0.5, 1, 1.5, and 2) are shown.

It can be seen that for a hypothetical frequent event (e.g. EQ multiplier = 0.5), all systems experience analogous maximum displacements, in the order of 25% of the “nominal capacity”. As the EQ multiplier is increased, the displacement demand also increases. It can be seen that by the time the earthquake intensity doubles that of the design level, the demand on a FP is 2.9 times the nominal capacity while the demand on the system with $\beta = -1.0$ only corresponds to 1.75 times the nominal capacity. Systems with intermediate values of $\beta$ fall within these two bounds. It should be pointed out that the displacement demand on an FP seems to grow more rapidly than on the other systems, particularly with respect to those characterized by low $\beta$. Similar trend is seen with reference to the normalized maximum lateral forces.

The bottom figure shows the residual displacements of the various systems normalized with respect to the associated maximum displacements. It can be seen that FP systems have the best re-centering capacity while BowTie ($\beta = -1$) has virtually none. However, systems with $\beta$ values ranging from 0 to 0.75 show good to excellent re-centering capabilities, while maintaining low seismic demands in terms of the other parameters of interest.
Figure 10. Results of Non Linear Time History Analysis for EQ multiplier = 1
Figure 11. Average results for structures as function of different EQ intensities

Figure 12. Normalized residual displacement for different base isolators
It is interesting to note that the normalized residual displacement appears to be somewhat independent of the earthquake intensity, particularly for EQ multipliers greater or equal to 1.0 (Fig. 11, bottom). The normalized residual displacement can therefore be represented in a more convenient way solely as a function of $\beta$, as shown in Fig. 12. These kinds of graphs could be used to link the design displacement to the residual displacement so to explicitly consider this important parameter over the course of the design phases.

With knowledge of demands posed by aftershocks, the information regarding normalized residual displacement could be useful in establishing an acceptable value of residual displacement, hence selecting the optimal isolation device to achieve the overall desired performance.

4 Conclusions

This paper has studied the seismic response of VFS characterized by arbitrary combinations of radius of curvature and frictional properties. The results of a comprehensive numerical study have shown that VFS can theoretically achieve high seismic performance, with respect to a number of parameters of interest. The general outcome was that lowering the value of $\beta$ tends to produce devices capable of higher performance with respect to parameters such as maximum displacement, maximum forces and maximum accelerations. However, lowering the value of $\beta$ tends to reduce the re-centering properties of the systems. To this end, the re-centering properties of the systems remain high for all positive values of $\beta$ and acceptable for negative values of $\beta$ greater than -0.5. Particularly critical in this regard are systems with $\beta = -1.0$, for which the residual displacement is on average around 80% of the maximum displacement reached.

Good re-centering capacities are of most relevance with respect to aftershocks, which may induce further motion before the device has been forcibly returned to its initial state. These aspects should be explicitly taken into account during the design phases and residual displacement issues, along with aftershock induced demands, should be incorporated into a rational design framework.

In general, different base isolation devices may have benefits and drawbacks, depending on specific situations and particular needs. It should also be noted that, although not addressed in this paper, there might be practical constraints that may limit the freedom to select certain values of friction coefficients or radii of curvature.

Finally, even though VFS represent, in the opinion of the authors, promising alternatives to existing base isolators, further research including numerical simulations and laboratory experiments is required, to verify the behavior of the devices under more complex conditions.

5 References


