NUMERICAL IMPLEMENTATION AND INVESTIGATION OF VARIABLE FRICTION SLIDING BASE ISOLATORS

T.-Y. Yang¹, P. M. Calvi² and R. Wiebe³

ABSTRACT

Variable Friction Systems (VFSs) have recently been introduced as a new method of seismic base isolation. Preliminary numerical studies have shown that these newly proposed systems are potentially capable of high seismic performance. This paper presents the results of a numerical investigation conducted in OpenSees on a case study structure isolated via VFSs and subjected to a suite of real ground motions with different characteristics and intensities. The preliminary results of the non-linear time history analyses indicate that VFSs can potentially achieve high seismic performance by reducing maximum displacement and base shear of the supported structure. However, before drawing any conclusions, the purpose of this study was to set the groundwork for developing a three-dimensional model that is capable of capturing the true behavior of VFSs to disclose all the advantages (and potential drawbacks) of using VFSs to protect structures from the effects of earthquakes.

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Variable Friction Systems (VFSs) have recently been introduced as a new method of seismic base isolation. Preliminary numerical studies have shown that these newly proposed systems are potentially capable of high seismic performance. This paper presents the results of a numerical investigation conducted in OpenSees on a case study structure isolated via VFSs and subjected to a suite of real ground motions with different characteristics and intensities. The preliminary results of the non-linear time history analyses indicate that VFSs can potentially achieve high seismic performance by reducing maximum displacement and base shear of the supported structure. However, before drawing any conclusions, the purpose of this study was to set the groundwork for developing a three-dimensional model that is capable of capturing the true behavior of VFSs to disclose all the advantages (and potential drawbacks) of using VFSs to protect structures from the effects of earthquakes.

Introduction

Sliding base isolation systems, such as friction pendula, have been employed as earthquake protection devices for buildings and bridges for their effectiveness in reducing the lateral force transferred to the protected structure, and their relative simplicity of fabrication and modeling. However, while acknowledging their undeniable virtues, it should be recognized that pertaining to certain situations, the efficacy of existing friction bearings can be compromised. For instance, recent experimental campaigns have suggested that full functionality in critical base-isolated buildings during a strong multi-directional seismic event may only be achieved by means of base isolation devices capable of high performance with respect to events with different intensities [1, 2].

To this end, a new family of friction bearings, referred to as Variable Friction Systems (VFSs), has been introduced as part of recent studies [3-5]. As shown in Figure 1, VFSs are friction base isolators, in which all, or part of the lateral stiffness variation is provided using sliding surfaces with spatially-varying friction coefficients, making it possible to tailor more

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desirable hysteretic responses.

![Diagram of VFS device](image)

Figure 1. (a) Cross section of a VFS device; (b) aerial view of a VFS device.

Preliminary numerical studies have shown that VFSs may represent promising solutions in that they are capable of achieving high seismic performance, particularly in light of their superior energy dissipation capacity [3, 6]. Figure 2 shows a comparison between the hysteresis of two particular VFSs and that of a Friction Pendulum System (FPS). It should be noted that, unlike what is shown in Figure 2, the actual post-activation stiffness of the VFSs is not necessarily linear. However, the linear approximation has been proven to be sufficiently accurate if appropriate radii of the rings (R_i) and corresponding coefficient of friction values (μ_i) are chosen [5]. It can be seen that VFSs exhibit higher energy dissipation properties than a Friction Pendulum when reaching the same maximum displacement. It is also important to mention that, with the same post activation stiffness, the sliding surface of a VFS has larger radius of curvature, which not only reduces the undesirable vertical motion and acceleration of the supported structure, but also makes the new device flatter and thus more economical. Another potential advantage of using VFSs is that by properly calibrating their radius of curvature and frictional properties, they can be used as passive “adaptive” devices [7] capable of achieving high performance for multiple earthquake intensities. As shown in Figure 3, while an isolator with R0<R1 is activated and behaves like a standard Friction Pendulum during the design level earthquake, the stiffening that occurs once the displacement demand exceeds that induced by the design event prevents the supported structure from catastrophic failure that may be otherwise caused by a rare event. This hysteresis behavior can be achieved by adding a ring with a higher friction coefficient to a regular FPS.

The numerical results pertaining to VFSs collected thus far are somewhat limited, particularly because of the lack of computer programs that are capable of simulating the non-linear response of these bearings in the context of non-linear time history analyses of realistic case study structures. Thus, the research summarized in this paper sets the groundwork for more advanced numerical investigations on the performance of VFSs by implementing a new non-linear spring element into OpenSees software [8] that represents the hysteretic behavior of these systems. The preliminary results collected in this paper suggest that VFSs can achieve high performance, particularly in terms of reducing the maximum displacement demand and the base shear. However, being able to disclose all the advantages (and potential drawbacks) of using
VFSs to protect structures from the effects of earthquakes requires extensive experimental and further numerical evidence.

Figure 2: Comparison between the hysteresis of a BowC (BC), a BowTie(BT) and a Friction Pendulum.

Figure 3: Example of an adaptive hysteretic behavior of VFSs family.

**Implementation of VFSs into OpenSees and Numerical Validation**

A 2D nonlinear spring element capable of capturing the hysteretic behavior of VFSs (such as that shown in Figure 2) was implemented in OpenSees. The element was obtained by modifying the original “2D Single Friction Pendulum Bearing Element” readily available in OpenSees. This was done by introducing an additional parameter, the coefficient \( \beta \), to define the force-displacement response of the new bearings. The coefficient \( \beta \) represents the ratio between the returning stiffness, \( k_2 \), and the forward post-activation stiffness, \( k_1 \), characterizing the hysteretic response of the isolator. For instance, \( \beta \) equals to 1.0 represents a traditional Friction Pendulum device, and \( \beta \) equals to -1.0 represents a flat device.

Figure 4 provides a flowchart describing how the new VFSs elements are implemented into OpenSees. Variable Friction Systems are treated as two-node elements, in which one node represents the concave/flat sliding surface and the other node represents the slider. The element accounts for horizontal-vertical coupling effects. The vertical force-displacement relationship can be defined using “UniaxialMaterial” (an in-built material) with no-tension behavior to capture the uplift effect. A comparably small tensile stiffness is recommended for the stability of the analysis. A velocity and pressure dependent friction model can be used. Other models such as “velocity dependent friction model”, “Coulomb friction model”, “multi-linear friction model” can also be implemented.
Figure 4: Variable Friction Systems algorithm in OPENSEES.
To validate the behavior of the new element, a single-degree-of-freedom system was created and a non-linear time history analysis was performed under a real ground motion to compare against the results obtained using a customized program developed in Matlab [9]. Example results for VFSs with different $\beta$ values are shown in Figure 5 and Figure 6 in terms of force-displacement response and displacement histories. It can be seen that the displacement histories obtained from the OpenSees model are very close to the curves obtained from the non-linear time history analyses from Matlab. In light of this evidence, it indicates that the new OpenSees element is accurate. The slight differences are mainly due to the fact that, unlike Matlab, the model in OpenSees accounts for horizontal-vertical coupling, thus the horizontal force may reduce or increase the normal force based on the position of the slider, which affects the activation force from non-sliding to sliding motion. If pressure dependent coefficient of friction is used, the differences between these two models would be larger, however, when Coulomb friction model is used, the differences, as observed, are negligible.

![Figure 5. Hysteresis comparison between OpenSees and Matlab.](image1)

![Figure 6. Displacement history comparison between OpenSees and Matlab.](image2)

**Case Study Structure**

A one-story one-bay case study structure was modeled in OpenSees to study the behavior of a VFS coupled with a realistic structure. The structure is modified based on the experiment described in [10] using the displacement-based seismic design method [11] to better suit the purpose of this study. To this end, a displacement-based design example for structures isolated with VFSs can be found in [5]. The structure above the isolation layer was designed to stay elastic throughout the analyses. The key outcomes of the design are listed in Table 1. More specifically, a description of the system properties on the left side of Table 1 can be found in [5]. VFSs properties on the right side of Table 1 represent the following parameters: design pressure on each isolator, effective radius of curvature, radius of the slider, radii of each ring, corresponding coefficient of friction for each ring, initial stiffness for numerical modeling, and the vertical stiffness of the bearing. The initial stiffness is calculated such that the activation displacement of the bearing is on the order of 0.01 mm [12]. It should be noted that the vertical stiffness for the bearing is for compression only, and it is calculated such that the vertical period
is 0.03 seconds based on results from [13].

Table 1. Key design parameters of the case study structure.

<table>
<thead>
<tr>
<th>System Properties</th>
<th>Values</th>
<th>VFP Properties</th>
<th>Values</th>
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</thead>
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<tr>
<td>$\zeta_{e, sys}$ (%)</td>
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<td>$\Delta_c$ (m)</td>
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<td>$R_{eff}$ (m)</td>
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<td>$r_p$ (m)</td>
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<td>$r_1$, $r_2$, $r_3$ (m)</td>
<td>0.1, 0.3, 0.5</td>
</tr>
<tr>
<td>$V_{d, sys}$ (kN)</td>
<td>228</td>
<td>$\mu_1$, $\mu_2$, $\mu_3$</td>
<td>0.05, 0.1, 0.15</td>
</tr>
<tr>
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<td>kInit (kN/m)</td>
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<td>$k_{vert}$ (kN/m)</td>
<td>$7\times10^6$</td>
</tr>
</tbody>
</table>

Figure 7 and Figure 8 show the target acceleration and displacement spectra used to carry out the design and the non-linear time history analyses of the case study structure. A set of 15 pairs of ground motions was selected from NGA-WEST2 ground motion database. The associated acceleration and displacement spectra are plotted in Figure 7 and Figure 8, respectively. The following criteria were adopted for the ground motion selection: magnitude from 5.5 to 7.0, Joyner-Boore distance from 10 to 65 km, and effective duration of motion from 10 to 60 seconds. Pulse-like ground motions were excluded from the selection.

Figure 7. Acceleration design spectrum.  
Figure 8. Displacement design spectrum.

In this study, five $\beta$ values (from -1.0 to 1.0 with an increment of 0.5) were selected for the VFSs. Four intensities (50%, 100%, 200%, and 300%) of the design level earthquake were considered when conducting the non-linear time history analyses. Figure 9 and Figure 10 show the boxplot results of the maximum displacement and residual displacement of the isolators, under 200% of the design earthquake intensity. Compared to a traditional friction pendulum ($\beta = 1.0$), the other four VFSs, with $\beta$ values varying from -1.0 to 0.5, respectively have a median maximum displacement reduction of 16.5%, 17.4%, 12.3%, and 2.3%, respectively. However, they also have a median residual displacement increase of 2150%, 605%, 140%, and 25%. As observed, decreasing the value of the coefficient $\beta$ reduces the maximum displacement of the isolators, as well as the base shear that is transferred from the isolation layer to the supported
structure. However, the reduction of the displacement and base shear comes at the cost of a higher residual displacement. Thus, more detailed parametric studies are needed to investigate what values of \( \beta \) produce the overall highest performance. Based on the limited results collected thus far, systems with \( \beta = 0.0 \) appear to be capable of high performance with respect to multiple parameters of interest. Figure 11 shows an example hysteresis comparison between systems with \( \beta = 0.0 \) and \( \beta = 1.0 \), which comes from the results pertaining to one of the input ground motions scaled at 200% of the design intensity.

Figure 9. Maximum displacement comparison. Figure 10. Residual displacement comparison.

Figure 11: Force-displacement history comparison between \( \beta = 1.0 \) and \( \beta = 0.0 \).
In order to further compare the behavior of a VFSs with $\beta = 0.0$ and systems with $\beta = 1.0$, maximum displacement and maximum base shear for all four intensities of the selected ground motion set are plotted in Figure 12 and Figure 13. For the four intensity levels considered, compared to the VFS with $\beta = 1.0$, the mean maximum base shear value using a VFS with $\beta = 0.0$ decreased by 0.35%, 3.45%, 6.10%, and 7.55%. The mean maximum displacement value at the same time decreased by 1.85%, 5.98%, 7.18%, and 7.42%. These results show that the larger the intensity of the input ground motion, the more effective the VFSs at reducing the maximum displacement and base shear. It can also be observed that, with increasing intensity of the input ground motion, the displacement demand and base shear transferred from the isolation layer to the supported structure increase nonlinearly (i.e. more rapidly) for a traditional friction pendulum, while they have seemingly slower growth rate for a VFS with $\beta = 0.0$, which makes the VFSs more attractive when dealing with large intensity earthquakes.

Another set of analyses were conducted to study the restoring capacity of the VFSs, in which the case study structure supported by a VFS with different $\beta$ values was subjected to a sequence of ground motions with different intensities. A set of 19 ground motions was randomly selected from the available 30 ground motion samples. The intensity sequence of the ground motions was taken from a study described in [10], in which the authors studied the restoring capacity of a double concave friction pendulum system. Figure 14 shows the input ground motion and the displacement histories of the VFSs with different $\beta$ values. As can be observed, the system with $\beta = 1.0$ exhibits the best restoring capacity. However, for $\beta$ value greater than or equal to 0, all VFSs exhibit relatively good restoring capacity. When $\beta$ is negative, the VFSs tend to have large residual displacement after each ground motion and they show poor restoring capacity.
Conclusions

Variable Friction Systems were recently introduced as a new type of friction bearing that can potentially achieve high seismic performance. A simplified two-dimensional nonlinear element to simulate the response of these new systems in the context of non-linear dynamic analyses was implemented into OpenSees to study the performance of the new bearings coupled with realistic structures. The preliminary results obtained show that by decreasing the value of $\beta$, both maximum displacement and base shear decrease. However, when $\beta$ is negative, the residual displacement of the structure at the end of the analyses tends to increase, sometimes
significantly. Thus VFSs with $\beta = 0.0$ was identified as a possible candidate to achieve overall high performance. It was also found that the ability of VFSs with $\beta = 0.0$ to decrease displacement and force demand, increases when the intensity of the ground motion increases. It should be noted that all the results presented in this study are of preliminary nature and that more investigations are required before conclusions can be drawn. No optimization of the radii and the corresponding friction coefficients were performed and thus significant improvement may be possible.

The primary purpose of this preliminary study was to set the ground for developing a three-dimensional model that is capable of capturing the true behavior of VFSs, to be validated experimentally. This fits into a larger ongoing research project, which has the full development of VFSs as its key objective, and which involves extensive numerical and experimental activities. As briefly discussed in the introduction of this paper, it is believed that the coexistence of material with different friction properties and a well-designed combination of sliding surfaces, VFSs can offer a number of advantages with respect to some of the existing base isolation systems.

References