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DEVELOPMENT OF VARIABLE FRICTION PENDULUM SYSTEMS

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Abstract

This paper provides an overview of the current state of development of a relatively new type of seismic base isolation systems, referred to as Variable Friction Pendulum Systems (VFSs). These systems utilize the coexistence of different frictional properties within the same sliding surface to achieve force-displacement responses that differ from that of traditional friction devices, potentially resulting in better performance.
The theoretical derivation of the mechanical behavior of VFSs is presented, followed by its numerical implementation. A displacement based design procedure for buildings isolated with VFSs is also reviewed. Finally, the results of a recent experimental program are presented that includes the characterization of bearing tests under harmonic loading conditions and hybrid tests of a full-scale single-story structure isolated with VFS devices under realistic ground motions.

Keywords: base isolation, seismic protection, variable friction pendulum systems, friction-based isolation system

1. Introduction

Base isolation systems have been employed widely as effective means of protecting structural and non-structural systems from the effects of seismic events. Among these, laminated lead rubber bearings and Friction Pendulum devices have been extensively investigated and implemented into practice. Kelly [1] provided a thorough review on the historical development of base isolation systems. A state-of-the-art review on the evolution of friction-type seismic isolation systems can also be found in Calvi and Calvi [2].

In the context of developing high performance bearings capable of reaching multi-performance objectives, several variations of the Friction Pendulum system have been proposed and studied in recent years. Examples include Multi-Surface Friction Pendulum systems (e.g. [3-5]), Variable Frequency Pendulum isolators [6, 7], Uplift Restraining systems [8, 9] and, most recently, Variable Friction base isolation Systems (VFSs) [10, 11].

This review paper focuses on the formulation and current state of development of VFSs. VFSs were initially postulated by Panchal and Jangid [10], who proposed sliding base isolation systems in which the variable friction coefficient between the slider and the sliding surface is modeled using a non-linear continuous function. This concept was recently revisited by Calvi et al. [11], who proposed to achieve variable friction devices by using sliding surfaces characterized by multiple friction coefficients. This can be achieved in practice by treating the stainless steel sliding surface to obtain a series of concentric rings characterized by different roughness, as shown in Fig. 1(a) and Fig. 1(b).

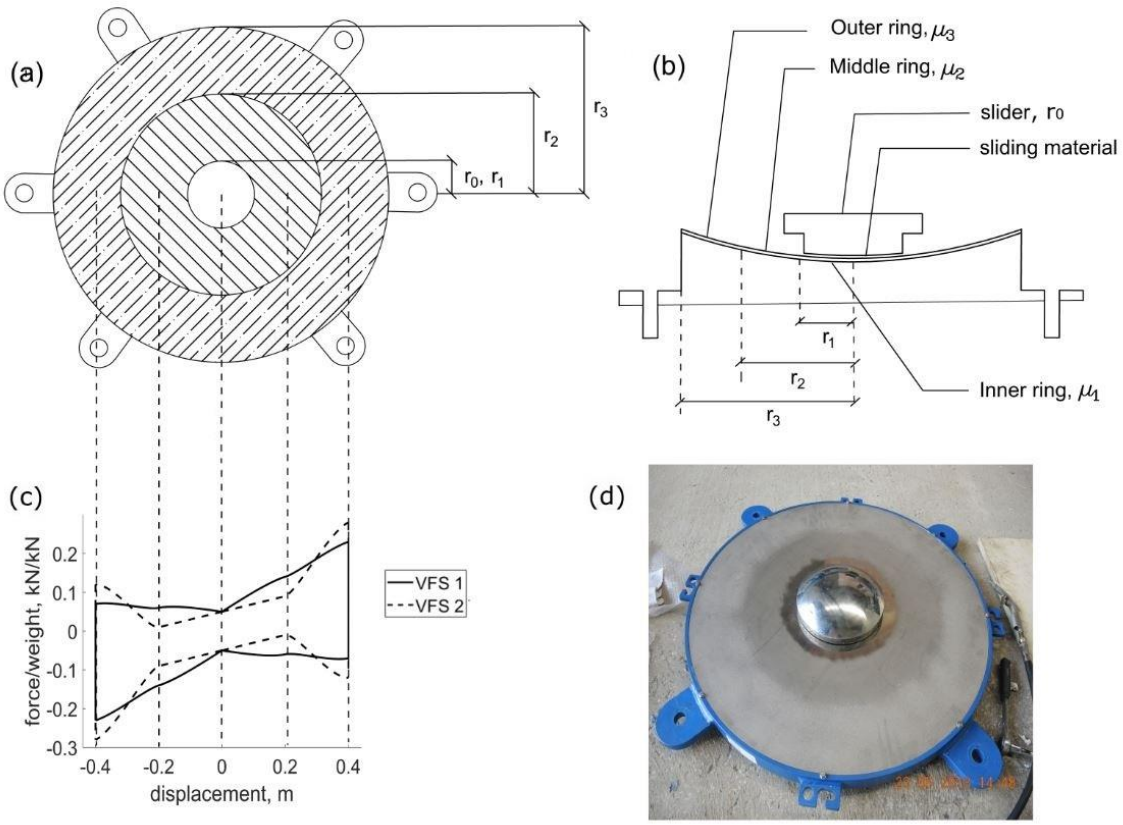

Fig. 1 – (a) plan view of a VFS device, (b) cross section of a VFS device, (c) example hystereses of VFSs, and (d) VFS protocol from a full-scaled experiment. Figure retrieved from [12].

The coexistence of different frictional properties within the same sliding surface effectively results in variable friction between the slider and the sliding surface as a function of the slider's position, providing the possibility of achieving more advantageous hysteretic responses. For example, this approach may be used to target devices characterized by adaptive behavior with increasing energy dissipation as the displacement demand increases, without the need for multiple sliding surfaces, as shown in Fig. 1(c) - VFS 2. One of the benefits of such a hysteretic response is that engineers may be able to design the system to simultaneously satisfy multiple performance objectives, under various seismic hazard levels.

This and other aspects of the response of VFSs are discussed in this paper, alongside their mechanics, theoretical development and 3-D numerical implementation. Furthermore, the experimental results obtained from the testing of a series of VFS prototypes are briefly presented. An overview of the preliminary design procedures developed for VFSs and some preliminary results pertaining to their performance in the context of Non-Linear Time History Analysis (NLTHA) are also included.

2. Theoretical Development

The mechanics and detailed theoretical development of the behavior of VFSs can be found in Calvi and Ruggiero [13]. The aim of this section is limited to providing a brief overview that should serve as the basis for the numerical implementation of VFSs discussed later in the paper.

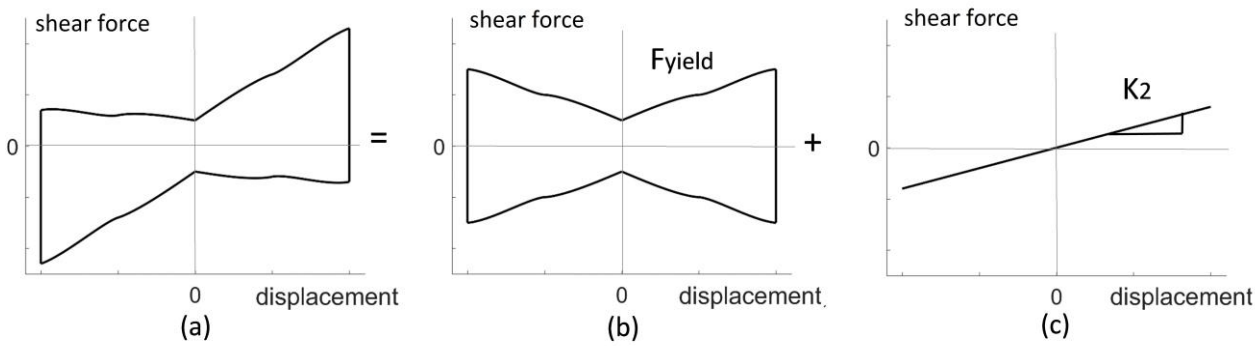

Fig. 2 – Illustration of hysteretic behavior of VFSs for motion in radial direction, (a) total response, (b) frictional response, and (c) elastic restoring force due to radius of curvature. Figure retrieved from [12].

As shown in Fig. 2, a VFS can be treated as the combination of a flat friction device and an elastic spring with stiffness, K_2, which is equal to the total weight carried by the slider, W, divided by the radius of curvature, R, of the sliding surface. This is analogous to the response idealization adopted to derive the hysteretic behavior of a traditional Friction Pendulum System (FPS). However, the frictional shear force is constant for FPS (if coulomb friction model is considered), while it varies as a function of displacement for the VFS. The purely frictional force-displacement response of VFSs depends on the geometrical and frictional properties of the slider and sliding surface as discussed by Calvi and Ruggiero [13]. To this end, the complete detailed mathematical derivation of the frictional component of the shear force that is generated in a VFS can be found in [12].

3. Numerical Implementation

Numerical formulation and implementation of VFSs were recently carried out to provide the foundation for studying structural response in the context of non-linear static and dynamic analyses. To this end, details pertaining to the numerical implementation of a full 3D VF element can be found in Yang et al. [12]. In brief, the horizontal behavior follows the framework of the bidirectional plasticity model with circular yield surface, which is outlined in [13]. The vertical force-displacement behavior is modeled as linear elastic with different stiffness values in tension and compression. While theoretically VFSs are compression-only

systems, a comparably small tensile stiffness was assigned to the system to ensure numerical stability when uplift occurs.

It should also be noted that when the sliding surface is curved, the force normal to the sliding surface is not aligned with the vertical direction. It is known that friction force equals to the product of the normal force and the friction coefficient. To achieve a more accurate representation of the bearing response, at each step, normal force was used in the numerical model instead of the total weight acting on the isolation system, which is aligned with the vertical direction.

4. Experimental Study

Full-scaled experiments were conducted on three VFS prototypes at the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) structural Laboratory in Pavia (Italy), using the Bearing Tester System. The details on the experimental testing can be found in [14].

The tested prototypes are two-ring VFSs, with a lower friction coefficient of 7.0% and a higher friction coefficient of 9.2%. The prototypes were tested under (1) harmonic cyclic loadings with different pressures (up to 25 MPa) and different peak velocities (up to 0.5 m/s), and (2) dynamic hybrid testing with a realistic ground motion. An example of the comparison on hysteretic behavior between the numerical predictions and experimental data is shown in Fig. 3.

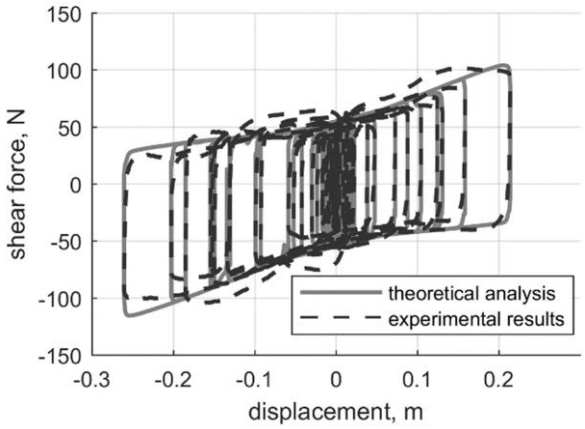

Fig. 3 – Comparison between the hysteretic response from numerical model and experimental data. Figure retrieved from [14].

Overall, the results from both cyclic testing and dynamic hybrid testing were in good agreement with the numerical predictions, suggesting that the numerical model developed by Yang et al. [12] can effectively capture the behavior of VFSs..

5. Design Procedure

Simplified methods are often used to analyze base isolation systems (e.g. ASCE 7-16 [16], EC 8 [17]). In general, code provisions idealize base isolation systems as single-degree-freedom-system oscillators that are characterized by an equivalent stiffness and an equivalent natural period at design displacement of the isolation system. Numerous researchers [18-22] have successfully studied the accuracy of using such an approach for Friction Pendulum systems and other “traditional” base isolators.

It was found that VFS isolated structures can be designed and analyzed adopting the same simplified procedure. Timsina and Calvi [23] calibrated a suitable expression to compute the VFS equivalent damping and validated the accuracy of using a simplified displacement-based design method to analyze VFSs with smooth backbone curves, as qualitatively shown Fig. 1(c) VFS type 1. Bergquist et al. [24] performed the same study on VFSs that exhibit the adaptive behavior qualitatively shown in Fig. 1(c) VFS type 2.

Bergquist et al. [24] also proposed a simplified design method to achieve VFSs that can target several performance objectives, at various level of seismic hazards.

6. Performance

Single-degree-of-freedom VFSs were studied by Yang et al. [12], Timsina and Calvi [23], and Bergquist et al. [24]. Extensive parametric studies that considered a variety of VFSs under suites of realistic design-spectrum compatible ground motions were conducted using non-linear time history analysis. Yang et al. [12] and Timsina and Calvi [23] studied the performance of VFS type 1 (see shown in Fig. 1(c)), while Bergquist et al. [24] investigated the performance of VFS type 2 (see Fig. 2(c)).

The results of these preliminary studies showed that VFSs can decrease the displacement and force demand experienced by a structure, due to their increased energy dissipation capacity. However, it was found that VFSs are generally characterized by increased residual displacement due to the larger radius of curvature value of the sliding surface.

It should be noted that all performance studies conducted so far are limited to single-degree-of-freedom systems. Before drawing definitive conclusions, a robust parametric study with more realistic superstructure models needs to be considered. Such a study is underway.

7. Conclusions

This paper provided a brief summary of the current state of development of VFSs, touching on the mechanics and theoretical behavior, the numerical implementation, the available experimental evidence, the developed design philosophy and the performance. While more in-depth numerical and experimental investigations are required, the results obtained thus far suggest that VFSs may be capable of high seismic performance in light of their beneficial features that include: (i) larger energy dissipation capacity; and (ii) capability of exhibiting adaptive behavior.

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9. Copyrights

10. References

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