DAMPING PROPERTIES OF VARIABLE FRICTION BASE ISOLATION SYSTEMS

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ABSTRACT

A new family of friction bearings, referred to as Variable Friction Systems (VFS), have recently been introduced as earthquake protection devices potentially capable of achieving high performance. Further to the theoretical development, a preliminary design process has been proposed for these devices. Once the designer has selected the design parameters \( \alpha \) and \( \beta \) (the design shear to activation shear ratio and the re-centering to post-activation stiffness ratio, respectively), which define the main characteristics of the desired base isolation device, the design of the optimal VFS can be completed following a Direct Displacement Based Design (DDBD) procedure. To this end, a number of relatively empirical parameters are employed within the design framework. These parameters are the “Equivalent Viscous Damping” (EVD) of the base isolator and the associated displacement reduction factor \( \eta \), which is key in determining the displacement demand on the system. Researchers have proposed to use a classic Jacobsen approach to estimate the EVD of the VFS and have therefore derived a number of design equations to conveniently compute this parameter at the beginning of the design process. Once the EVD is calculated, it has been recommended that the displacement demand on the system be calculated as the demand on an equivalent system with an elastic damping ratio of 5%, multiplied by a reduction factor computed using an equation available in the literature, which was provided in a previous edition of the EC8. These propositions were based on the observation that the same approach has worked successfully in the past for a number of structural systems, including structures base isolated by means of Rubber Bearings and Friction Pendula. However, they have not yet been validated for the newly proposed VFS. Thus, this paper conducts a numerical study on the damping properties of generic VFS, using the results of non-linear time history (NLTH) analyses to check the validity of the current design assumptions and, when necessary, to improve on the existing design equations. The adopted analysis procedure, the ground motions, the numerical modeling assumptions, and the case study structures are first introduced; second, the results of a very large number (more than 500,000) of NLTH analyses are processed and presented along with comparisons to existing design equations; third, the reasons for discrepancy between the existing design equations and the results of the analyses are examined, and a new design equation is calibrated to better estimate the EVD for design purpose.

Keywords: Base Isolation; Variable Friction; Damping; Non-Linear Time History; Displacement Based Design

1. INTRODUCTION

Variable Friction base isolation systems have been recently proposed as new high performance seismic protection devices. These systems are the object of ongoing research investigations (e.g. Yang et al., 2018) which involve extensive numerical and experimental activities. Preliminary numerical studies have been carried out by Calvi and Ruggiero (2016), Calvi and Timsina (2017) and Calvi et al. (2016), who also proposed a simplified design process applicable to these systems. More specifically, they recommended that the design of VFS be performed employing Direct Displacement Based Design

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(DDBD) criteria, as discussed in general terms by Priestley et al. (2007). The basic procedure for base isolated structures is summarized in Figure 1. Once a target design displacement for the base isolation system and the isolated structure is selected, the isolator-structure assembly is idealized as a SDOF system (Figure 1 (a)). The equivalent SDOF structure is based on a model that takes into account both the isolation system and the structure.

The second step, shown in Figure 1 (b), consists of calculating the equivalent damping of the system. The equivalent viscous damping is used to determine a spectral reduction factor, which is used to correct the displacement demand on the structure. The equivalent viscous damping ratio of the system can be estimated combining the contributions of the structure and of the isolation system. For the structure, the equivalent viscous damping is normally assumed as 5% or lower, given that an elastic response will be enforced. For the isolation system, the equivalent damping is estimated as a function of the force-displacement relationship that characterizes the system. The effective period of the system can then be obtained entering an appropriately scaled design displacement spectrum, as shown in Figure 1 (c). The effective period of the structure is used to calculate the effective stiffness of the system which, in turn, is used in combination with the design displacement to obtain the design base shear, which is the lateral force that the system must be capable of resisting (Figure 1 (d)). At this stage, the properties of the “optimal” base isolator can be selected.

Thus, the design process for VFS, at least at a preliminary level, is overall well defined. Once the designer has selected the design parameters $\alpha$ (the ratio between the design shear and the activation shear) and $\beta$ (the ratio between the re-centering stiffness and the post-activation stiffness), which define the main characteristics of the desired base isolation device, the design of the optimal VFS can be completed following the straightforward steps summarized earlier.

![Figure 1](image)

**Figure 1.** Displacement-based design of base isolated structures

However, a number of relatively empirical parameters are employed within the design framework. These parameters are the EVD of the base isolator and the associated displacement reduction factor $\eta$, which is key in determining the displacement demand on the system.

Calvi et al. (2016) and Calvi and Ruggiero (2016) have proposed to use a classic Jacobsen approach to estimate the EVD of the VFS, and have therefore derived a number of design equations to conveniently compute this parameter at the beginning of the design process. Once the EVD has been calculated, it is
recommended that the displacement demand on the system be calculated as the demand on an equivalent system with a viscous damping ratio of 5%, multiplied by a reduction factor computed using Equation (3) reported in the next section, which was provided in a previous edition of the EC8.

These propositions were based on the observation that the same approach has worked successfully in the past for a number of structural systems, including structures base isolated by means of Rubber Bearings and Friction Pendula. However, they have not yet been validated for the newly proposed VFS. In this context, this paper presents the results of a comprehensive numerical study on the damping properties of generic VFS. The results of more than 500,000 NLTH analysis are used to check the validity of the current design assumptions and, when necessary, to improve on the existing design equations.

2. EQUIVALENT VISCOUS DAMPING AND REDUCTION FACTOR

Damping in real structures is typically represented by Equivalent Viscous Damping (EVD). This approach is based upon Jacobsen’s energy equivalency between the energy dissipated in a vibration cycle of the actual structure and an equivalent viscous system (Jacobsen, 1930).

Relying on this approach, the effective damping of a generic friction base isolation system (whose hysteresis is sketched in Figure 2) can be calculated as the ratio between the area under the force-displacement response and the area of the ellipse that crosses the axes in correspondence of the force and displacement design values, expressed in general terms as:

$$\xi_{eq} = \frac{A_h}{2\pi V_{max}\Delta_{max}}$$ (1)

Where $V_{max}$ and $\Delta_{max}$ are the maximum shear force and the maximum displacement experienced by the system.

Timsina (2017) showed that for a generic VFS, Equation (1) can be expressed as a function of the design parameters $\alpha$ and $\beta$ as:

$$\xi_{eq} = \frac{\alpha - \beta + 3}{2\pi \alpha}$$ (2)

A number of equations are available in the literature to calculate the demand reduction factor associated to the available EVD. Following the recommendations of Priestley et al. (2007), and consistently with general DDBD frameworks, Equation (3) was recommended to design VFS (Calvi et al., 2016):
\[ \eta = \frac{7}{\sqrt{2 + \xi_{eq}}} \]  

(3)

3. VFS DAMPING PROPERTIES VERIFICATION

3.1 EVD Calculation Approach Description

The process employed to estimate the EVD provided by generic VFS and the associated displacement reduction factor \( \eta \) is summarized in this section. The case study structures, consisting of rigid (i.e. characterized by very large lateral stiffness) or flexible SDOF systems, were first selected. These structures were then isolated by means of VFS with various characteristics. The case study systems were fully defined in terms of seismic weight, hysteretic response, and viscous damping ratio. A ground motion was then selected as the input for the NLTH analysis, which was conducted using the customized computer program developed by Calvi and Ruggiero (2016) and briefly described in the next section and applied to the structure.

At the end of the analysis, the maximum displacement experienced by the SDOF system, \( \Delta_{\text{max}} \), and corresponding lateral force, \( V_{\text{max}} \), were recorded. These parameters were used to estimate the effective stiffness, \( K_{\text{ef}} \), of the system (the secant stiffness at peak displacement) and the effective period of vibration, \( T_{\text{ef}} \). The parameter \( \alpha \) was also computed as \( V_{\text{max}}/V_\mu \).

At this point, a linear SDOF system with effective characteristics \( (K_{\text{ef}} \text{ and } T_{\text{ef}}) \) was analyzed using the same input ground motion. The viscous damping ratio assigned to this system was progressively increased, until the maximum displacement of the linear effective system matched that of the non-linear system. This damping ratio was therefore recorded as the EVD of the case study system.

The displacement reduction factor associated to a given value of EVD was computed as the ratio between the \( \Delta_{\text{max}} \) experienced by the previously analyzed non-linear system (or by the linear effective system with assigned damping ratio equal to the EVD) and the displacement of the linear effective system with assigned viscous damping ratio of 5%.

This process was repeated for 50 different ground motions scaled at different magnitudes, to obtain a large dataset relating the EVD, \( \eta \) and \( \alpha \).

This process was employed for both rigid and flexible case study structures. However, when flexible structures that were assigned non-zero viscous damping ratio were analyzed, the EVD estimated at the end of the process included the viscous damping of the system as well.

Because the objective at this stage was to isolate the EVD provided by the VFS alone, some post processing of the results was required. More specifically, the EVD provided by the base isolator alone was calculated using Equation (4), proposed by Priestley et al. (2007):

\[ \xi_i = \frac{\xi_{eq}\Delta_{\text{tot}} - \xi_s\Delta_s}{\Delta_i} \]  

(4)

Where \( \xi_i \) is the EVD of the VFS alone, \( \xi_{eq} \) is the total EVD computed from the NLTH analysis, \( \Delta_{\text{tot}} \) is the total displacement experienced by the SDOF system, \( \Delta_s \) is the peak displacement of the flexible structure with respect to the base isolator (computed as \( V_{\text{max}}/K_s \), \( K_s \) being the stiffness of the structure), \( \xi_s \) is the viscous damping ratio assigned to the structure (either 2% or 5%), and \( \Delta_i \) is the peak displacement of the base isolator (computed as \( \Delta_{\text{tot}}/\Delta_s \)).

3.2 Case Study Structures

The design of the case studies was performed by first selecting three target structures, isolated by means of traditional FP systems. The properties of these target FP systems were as follows:

- Lateral displacement capacity of 0.45 m
- Radii of curvature of 2.5 m, 3.1 m, and 3.7 m
- Medium friction coefficient (5.5%)
- Bearing diameter of 0.3 m (and consequently a sliding surface diameter of 1.2 m)

It was further assumed that the structures had a seismic weight of 6,000 kN and that this was also the magnitude of the total vertical load. Three FP devices with the desired characteristics were therefore selected from a manufacturer’s catalog, and all the fundamental design properties, namely the design shear $V_d$, the activation shear $V_\mu$, and the post-activation stiffness $K_p$, were calculated. At this point, a total of 24 VFS, characterized by $\beta$ values ranging from -1.0 to 0.75 (at 0.25 intervals), were designed to “mimic” the response of the target FP systems described above. The properties of the VFS were therefore assigned to guarantee that the backbone of the hysteretic curve characterizing the force-displacement response of each VFS traced that of the companion FP systems. A design outcome example is summarized in Figure 3.

![Figure 3. Example hysteretic response of designed VFS](image)

In addition, to investigate the influence of the “elastic” damping ratio and of the dynamic properties of the isolated structure on the EVD, a set of SDOF case study structures, with different characteristics were considered. It was assumed that these case study structures had to be base isolated using the VFS described earlier. Each base isolator-superstructure assembly was modeled as a SDOF system, with a hysteretic response calibrated treating the two elements as springs in series. The structures to be isolated were either “rigid” or “flexible”, with a seismic weight of 6,000 kN, and had the following characteristics:

- Rigid Structure: a very high lateral stiffness was selected (e.g. 10,000 times the post activation stiffness of the base isolator). A viscous damping ratio of 0% was assigned to the structural assembly. In this case, the energy dissipation was entirely provided by the hysteretic response of the base isolator.

- Flexible Structures: three values of stiffness (35,455 kN/m, 17069 kN/m and 7,942 kN/m) and two values of damping ratio (2% and 5%) were considered. The idea was to cover a range of periods of vibration that could be representative of structures of different heights (e.g. 4 story, 8 story and 12 story), and to target the two damping ratio most widely used in practice for traditional structural systems.

In summary, a total of 189 base isolated SDOF case study structures were selected and analyzed via NLTH analyses. More details can be found in Timsina (2017).
3.3 Non-Linear Time History Analysis: Analysis Approach and Ground Motions

In order to conduct numerical testing of the case study systems described in the previous section, the customized computer program written by Calvi and Ruggiero (2016), to compute the non-linear dynamic response of base isolated structures to base excitations, was employed. The program solves the incremental equation of motion using a linear acceleration Newmark-Beta integration algorithm (Newmark and Rosenblueth, 1971) and can perform the analysis of non-linear single and multiple degree of freedom “shear-type” structures. The isolation system is simulated using a non-linear translational spring characterized by an appropriate relationship between lateral force and displacement. The hysteresis of this spring is defined as a function of the isolator selected (i.e. as a functions of parameters such as β, R, μ etc.). More details can be found in Calvi and Ruggiero (2016).

The numerical simulations were run using a set of 50 real ground motions as input. The structures part of Subset A were only tested at the design earthquake intensity while the structures part of Subset B were tested scaling the ground motions at 10 different intensities (covering a range of PGAs from 0.3g to 2g). To this end, to study the systems’ response under rare conditions, it was assumed in the analyses that all isolation systems could undergo larger maximum displacements than the design displacement, while maintaining post-activation stiffness.

The records were selected to be compatible with the design spectra shown in Figure 4. It can be seen that the target displacement spectrum (for a damping ratio of 5%) reaches a displacement of 1.24 m at a period of vibration of 6 s (the average spectrum reads 1.45 m at the same period).

In the selection process, a preliminary screening was performed to limit the search to records pertaining to soil type C (i.e. very dense soil and soft rock) and whose closest distance to the fault was in a range of 0.56 to 218 km. These limits on distance aimed at including in the selection ground motions with different characteristics, including long duration and near-fault effects. The ground motions were appropriately scaled so that the average acceleration and displacement spectra associated to the motions matched the selected design spectra. The key characteristics of the 50 records selected can be found in Timsina (2017).

The displacement response spectra associated to each ground motion, the average spectra, and the design spectra are shown in Figure 4. It can be seen that the average spectra lie reasonably close to the target (design) spectra, while the individual curves, in some instances, diverge from the average.

![Figure 4. Acceleration (left) and displacement (right) spectra of the 50 ground motions used for the NLTH analyses, average spectrum, all 5%](image)

4. NUMERICAL ANALYSIS RESULTS

The results of the NLTH analyses emphasized that the EVD characterizing a VFS is solely a function of the parameters α and β and that the “elastic” damping and the dynamic properties of the isolated structure play a negligible role. For this reason, only the results pertaining to the rigid case study
structures are outlined in this section. It should be noted that the comments provided hold for flexible systems and for systems characterized by non-zero “elastic” damping.

Figure 5 presents the results of six of the systems analyzed in terms of $\alpha$ and $\xi_0$. While the results are shown separately for different values of $\beta$, they are not separated as a function of the radius of curvature of the target FP device, in light of the observation that this parameter had virtually no effect on the damping properties of the various systems.

Figure 5. Comparison between NLTH analysis results expressed in terms of EVD vs $\alpha$ and current design equation

In Figure 5, the thin solid curves represent the average trends, while the dashed curves represent the average plus or minus the computed standard deviation. It can be noted that the EVD of all systems is essentially identical for low values of $\alpha$ (EVD for $\alpha = 1.5$). It can also be noted that the EVD decreases with increasing $\alpha$. However, it can be observed that the EVD decreases more rapidly for systems characterized by higher $\beta$. For instance, the average EVD of a system with $\beta = 1.0$ (i.e. a standard Friction Pendulum device), drops from roughly 35% to roughly 8% as $\alpha$ grows from 1.5 to 9.0. In contrast, the average EVD of a system with $\beta = -1.0$ goes from about 35% to roughly 27%, considering the same range of $\alpha$ values. It can be seen that the EVDs for all the other systems considered, follow analogous trends. The first trends observed are consistent with the expectations: smaller $\beta$ produces “fatter” hysteretic loops, which translate into a greater amount of energy dissipated, with consequently larger EVD values.

However, while the results of Figure 5 confirm that VFS with smaller $\beta$ values have a higher energy dissipation capacity, and in turn higher EVD, it can be observed, in the same figure, that the scatter of the whole data set around the average curves is overall quite large and that it increases as $\beta$ decreases.
The mean coefficient of variation, grows from approximately 30% to 43%, for the systems with $\beta$ of 1.0 and -1.0, respectively.

The thick continuous lines in Figure 5 represent the relationship between EVD and $\alpha$ expressed by Equation (2). It can be seen that Equation (2) captures reasonably well the trends and the qualitative relationships between EVD and for all cases. However, there is always some discrepancy (sometimes significant) between the mean NLTH results and the curves recommended for use within the DDBD method for VFS. It can be seen in Figure 5 that, for VFS with higher $\beta$, Equation (2) tends to underestimate the EVD that each system possesses. However, this trend reverses as the value of $\beta$ decreases. The best overall agreement between the design equation and the NLTH results can be observed for $\beta = 0.25$, while the worst agreement occurs for systems with $\beta = -1.0$.

Overestimating the EVD may result in an excessively low design reduction factor, and in turn, in designing the base isolation systems for excessively low seismic demands. This is apparent, referring to the discussion presented in the introduction of this paper, where it was discussed that the EVD is estimated within the design process with the sole objective of calculating the demand reduction factor $\eta$. The reduction factor $\eta$, and the EVD values obtained from the NLTH analyses, are presented in Figure 6 along with the estimates obtained using Equation (3) (thick dotted line).

The mean analysis results (thin continuous line) and the mean plus and minus one standard deviation (dashed lines) are also included in the graph. It should be noted that the $\eta$ - EVD results are no longer grouped as a function of $\beta$. This is done on account of the apparent in-dependency of the relationship between these two parameters with respect to any other variables considered in the parametric study conducted.

For all systems, the most notable conclusion that can be drawn from Figure 6 is that the value of the demand reduction factor $\eta$, decreases as the EVD increases. This is consistent with the idea that higher energy dissipated corresponds to higher EVD and, in turn, in a lower seismic demand on the system. It is also interesting to note that, when expressed in terms of these two parameters, the results appear to be essentially independent of $\beta$.

It is shown in Figure 6 that Equation (3) approximates pretty well the average relationship between $\eta$ and EVD. Obviously, some discrepancy exists between the design equation and the results of the NLTH analyses with the design equation being slightly un-conservative.
5. DESIGN EVD EQUATION CALIBRATION

The previous section has emphasized that the EVD design equations recommended for use within the DDBD process for VFS have merit, in that they provide some means of capturing the relationship trends between the EVD, and the design parameters $\alpha$ and $\beta$.

![Graphs showing force-displacement response of VFS](image)

Figure 7. Force-displacement response of VFS with: (a) $\beta = 1.0$, (b) $\beta = 0.25$, (c) $\beta = -0.25$, (d) $\beta = -1.0$, (e) Displacement histories for these systems.

However, it has also been pointed out that some discrepancies exist between the NLTH analysis results and the outcome provided by the design equations. In particular, while the estimates provided for systems characterized by positive $\beta$ values may be acceptable from both a qualitative and quantitative perspective, this is not necessarily the case for systems with low $\beta$.

To this end, a thorough post-processing of the results of the NLTH analyses showed that VFS characterized by positive $\beta$ tend to produce a symmetric response (i.e. the recorded positive peak displacements roughly correspond to the negative peak displacements), while VFS with negative $\beta$ are...
prone to a non-symmetric response. This is shown in Figure 7, in which the force-displacement response of systems with different values of $\beta$ (namely: 1.0, 0.25, -0.25 and -1.0) to one of the input ground motions is outlined. With reference to the same figure, it can be further seen that the asymmetry is more pronounced as the value of $\beta$ decreases. While these are only the results of one of the analyses, it should be noted that they are representative of the whole numerical campaign and that this trend is observed, to different extents, for all input ground motions at all intensities.

Figure 8. Comparison between NLTH analysis results expressed in terms of EVD vs $\alpha$ and proposed design equation

The symmetry or asymmetry of the force-displacement response of a system is extremely relevant with respect to the EVD that a system possesses, as current design equations were derived relying on the assumption that all systems manifest a symmetrical hysteretic response. However, as the results of the NLTH analyses have shown, the response of a VFS may be highly non-symmetrical, particularly for decreasing values of $\beta$. Treating a non-symmetrical hysteresis as symmetrical, leads to overestimating the area under the force-displacement curve and, in turn, the available EVD (since the EVD is directly related to the hysteretic area). Thus, relying on the results of the analysis, a new design equation that is capable of accounting for the asymmetry in the hysteretic response of the base isolation system was calibrated:

$$\xi_{eq} = \frac{a - \beta a + \beta + 3}{2\pi a} + (0.07\beta - 0.03) \quad (5)$$
The mathematical derivation of Equation (5) can be found in Timsina (2017). Its performance can be appreciated in Figure 8, where it can be seen that the new equation matches the mean results of the analyses well for all $\beta$ values (particularly considering that a reasonable lower-bound value for the design parameter $\alpha$ is 2.5).

6. CONCLUSIONS

This paper has presented the results of an extensive numerical study aimed at investigating the damping properties of the recently proposed VFS. Of particular interest were the relationship between the design parameters $\alpha$ and $\beta$, the EVD that a device can rely on, and the relationship between the EVD and the design demand reduction factor $\eta$.

The results of the analyses have demonstrated that the EVD that a VFS possesses is not affected by fundamental characteristics of the isolated structures such as their viscous damping ratio or their period of vibration.

VFS may rely on high energy absorption and, in turn, on higher EVD coefficients. This is particularly true as the systems are hit by stronger ground motions and are therefore characterized by high values of $\alpha$. Decreasing the value of the design parameter $\beta$ has the effect of creating devices with fatter hysteretic loops and high damping. However, decreasing $\beta$ has also the effect of causing a greater scatter in the results, and of enhancing the probability of non-symmetrical response.

Current design equations for VFS that relate the design parameters $\alpha$ and $\beta$ to the EVD of the device, are fairly accurate for systems with positive $\beta$, but they lose in accuracy as the value of $\beta$ decreases. This trend was attributed to the non-symmetrical response that VFS, and particularly those characterize by low values of $\beta$, tend to experience a non-symmetrical response and by the fact that current design equations were derived assuming perfectly symmetrical response. Thus, a new general design equation capable of accounting for the asymmetry in the response of a VFS was proposed.

Finally, it was observed that available design equations relating the EVD to the design demand reduction factor $\eta$ are reasonably accurate at approximating the mean results of the NLTH analyses.

7. REFERENCES


