Guidance on the use of equivalent viscous damping for seismic assessment

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ABSTRACT: The equivalent viscous damping (EVD) concept provides a practical means of accounting for energy dissipation effects when undertaking a response spectrum-based seismic assessment. However, expressions for EVD should be calibrated to match the results of non-linear response history analyses. This paper underlines some key considerations that are required when developing calibrated EVD expressions. In particular, it is pointed out that local hazard characteristics, such as dominant source magnitude or near-field effects, are likely to affect calibrated EVD expressions. It is also argued that while a large number of calibrated EVD (and spectral displacement reduction factor) expressions are now available, practitioners may well encounter a structural system for which calibrated expressions have not been developed. Given this and the inherent uncertainties in spectrum-based design and assessment methods, a pragmatic way forward is proposed in which such systems can be assigned an EVD value based on a qualitative assessment of their energy dissipation potential.

1 INTRODUCTION

The displacement-based seismic assessment procedure, after Priestley (1997) and Priestley et al. (2007), is indicated by the NZSEE seismic assessment guidelines as a viable analysis procedure for the seismic assessment of existing buildings. One aspect of the procedure that has undergone considerable developments in recent years is the use of equivalent viscous damping (EVD). This paper reviews some of the important considerations that need to be made when developing equivalent viscous damping expressions, highlights assessment scenarios for which the EVD approach requires further development and proposes a pragmatic way forward for practitioners who come across buildings for which calibrated equivalent viscous damping expressions are not currently available.

2 THE DEVELOPMENT CALIBRATED EVD EXPRESSIONS AND SPECTRAL DISPLACEMENT REDUCTION FACTORS

Equivalent viscous damping was proposed for earthquake engineering many decades ago, with Jacobsen (1930) and Rosenblueth and Herrera (1964) developing what is now often referred to as an area-based EVD approach. According to the area-based EVD approach, the energy absorbed by hysteretic steady-state cyclic response to a given displacement level can be equated to the energy dissipated through equivalent viscous damping of an elastic substitute structure possessing stiffness equal to the secant stiffness of the non-linear system at the peak displacement point. A benefit of this approach is that it recognizes that differences in energy dissipation, due to differences in hysteretic properties, will affect inelastic displacement demands. This is something that most building codes currently overlook because they typically (not always) advocate the use of the equal displacement rule, irrespective of the hysteretic properties of the structure. Unfortunately, however, because ground motions do not impose steady-state cyclic demands, the area-based EVD approach can be inaccurate.

In order to overcome the limitations with the area-based EVD approach, modern expressions for equivalent viscous damping are calibrated so that the inelastic displacement spectra obtained using the final EVD expressions match the results of non-linear response history (NLRH) analyses. Examples of EVD calibration studies include the work of Grant et al. (2005), Dwiari et al. (2007) and Pennucci et al. (2011). After evaluating the results obtained by Grant et al. (2005) and Dwairi et al. (2007), Priestley et al. (2007) proposed the following general form for calibrated EVD expressions:

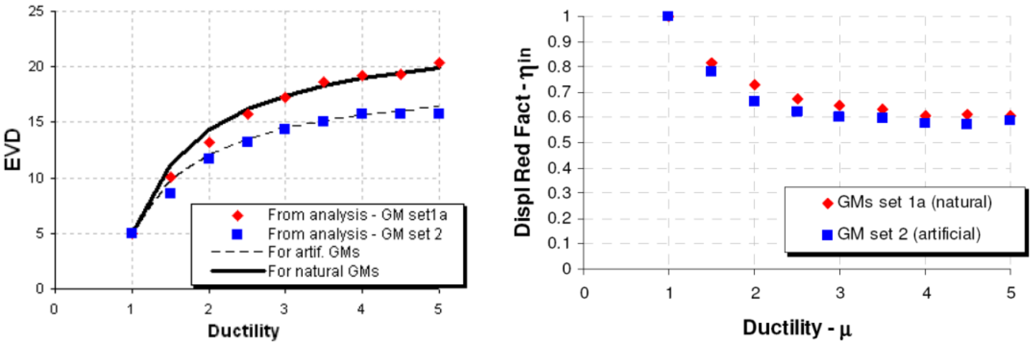
$$\xi = 0.05 + C\left(\frac{\mu - 1}{\mu\pi}\right) \tag{1}$$

where μ is the displacement ductility for which the EVD is to be computed and C is a constant that changes from one structural (hysteretic) typology to another.

Once the EVD is known, the displacement response spectrum can be scaled by a damping-dependent factor, η, which Priestley et al. (2007) recommended be computed (for far-field motions) using:

$$\eta = \left(\frac{0.07}{0.02 + \xi}\right)^{0.5} \tag{2}$$

Interestingly, Priestley et al. (2007) maintained that better correlation was obtained with the results of NLRH analyses when Eq.(2) was used even though they were aware that data from other sources supported different damping-dependent scaling expressions. Subsequent work by Pennucci et al. (2011) shed some light on the basis of this recommendation. Pennucci et al. (2011) found firstly, as shown in Figure 1a, that significant differences in calibrated EVD values could be obtained for two different sets of accelerograms, one natural (set 1a) and the other artificial (set 2). The distinguishing feature between the two sets of accelerograms was that the elastic spectra associated with set 2 reduced more quickly with increasing values of damping, and thus two different damping-dependent scaling expressions (of the type shown in Eq.2) were identified. Moreover, however, when the EVD and damping-dependent spectral scaling expressions for each set were combined, it was found, as can be seen in Figure 1b, that the final set of spectral displacement reduction factors for the two sets were practically identical. It was thus concluded by Pennucci et al. (2011) that in principle, it would appear more logical and direct to compute so called spectral *displacement reduction factors* (DRFs) directly as a function of ductility, rather than following a two-step ductility-to-damping-to-DRF process.



(a) **(b)**

Figure 1 – Results from Pennucci et al. (2011) demonstrating that (a) calibrated EVD values for two different sets of ground motions can differ greatly, even though they possess the same spectral shape, and (b) instead, the spectral displacement reduction factors obtained from the same process do not differ significantly.

The conclusion reached by Pennucci et al. (2011) implies that the EVD procedure advocated by Priestley et al. (2007) is essentially equivalent to combining Equations 1 and 2, to arrive directly at a ductility dependent DRF expression such as:

$$\eta = \sqrt{\frac{0.07}{0.07 + C\left(\frac{\mu - 1}{\mu\pi}\right)}} \tag{3}$$

Despite this observation, Sullivan et al. (2012) opted to maintain the use of EVD in a model code for Direct displacement based design, since it was felt that the use of EVD values was well established and provided the engineer with a better indication of the energy dissipation effects than the direct ductility-dependent DRF approach. Nevertheless, it should be emphasised that ductility-dependent EVD expressions should be developed by first calibrating relationships between ductility demands and spectral displacement reduction factors, and then identifying a pair of EVD and damping-dependent scaling expressions (for example, Eqs. 1 and 2) that will lead to the same DRF values.

A number of studies have since been conducted with the aim of providing engineers with reliable DRF and EVD expressions. Sullivan et al. (2013) report DRFs for SDOF systems characterised by Bi-linear, Takeda Thin, SINA or Flag shaped hysteretic properties, obtained from a very extensive numerical investigation that involved the use of 4812 accelerograms. Presuming that such DRF expressions would be used together with the spectral scaling expression given by Eq.(2), one arrives at the EVD values shown in Figure 2. Figure 2 also includes EVD curves derived from the works of Wijesundara et al. (2011), Sullivan and O'Reilly (2014), and O'Reilly and Sullivan (2015); works that again involved calibration analyses but using much fewer accelerograms, for a variety of steel structural systems, characterised by 3% elastic damping. It is apparent that for some of the steel MRF systems the EVD values are quite low and this is attributed partly to the assumption of 3% damping and partly to the fact that these MRFs possess partial-strength extended-end-plate beam-column joints. The last EVD curve indicated in Figure 2 was derived using the Wayne Stewart hysteretic model and stems from the work of Moayed Alaee (2011) who examined cold-formed steel frame timber panel shear walls, which possess hysteretic properties similar to timber-framed shear walls.

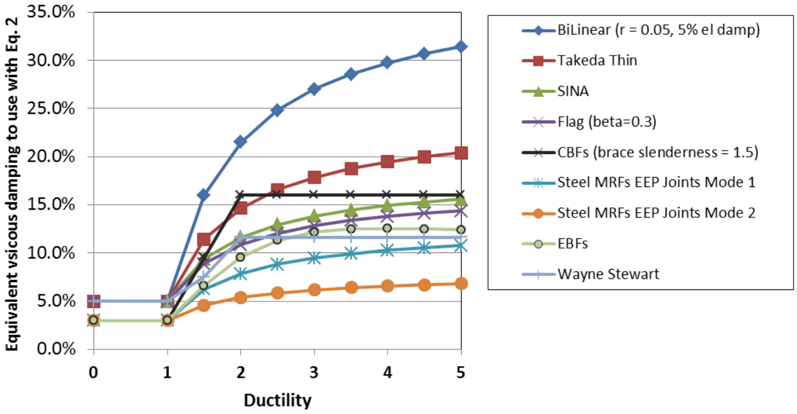


Figure 2 – Highlighting the impact of the elastic damping model on the observed ratio of the elastic spectral displacement (at the initial period) to the inelastic displacement demand.

While the results shown in Figure 2 demonstrate that a large number of calibrated EVD expressions are now available in the literature (also noting that there are others exist in addition to those shown in Figure 2), it is expected that additional calibration studies will be required in the future. As such, the next section reflects on a few key considerations that need to be made when undertaking such studies.

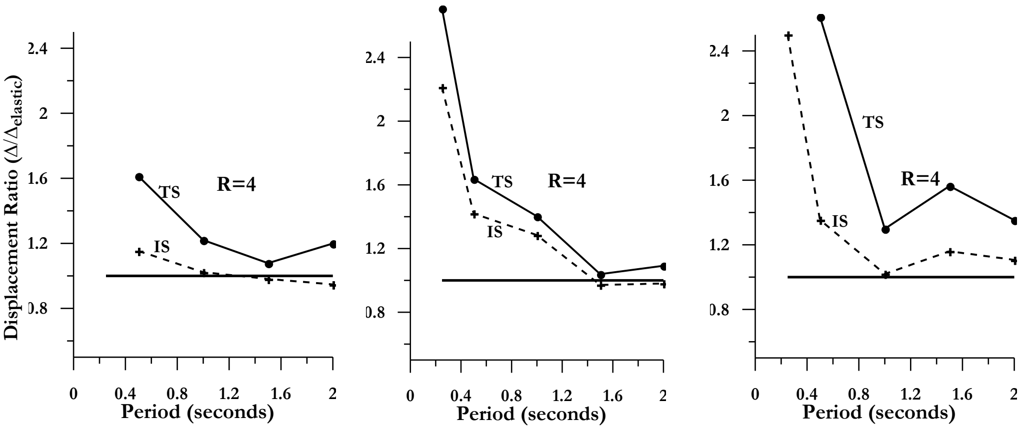
3 SOME KEY CONSIDERATIONS IN THE CALIBRATION OF EVD EXPRESSIONS

The use of NLRH analyses for the seismic assessment of buildings is becoming more common these days and yet considerable care is required to ensure that the quality of the results obtained from NLRH analyses is not jeopardised by poor modelling and analysis decisions. Such care is also required when conducting NLRH analyses of SDOF systems for the calibration of EVD expressions. The following subsections review two important considerations for calibration studies; (i) the elastic damping model and (ii) the set of accelerograms selected for the analyses.

3.1 Elastic damping

The Rayleigh damping model currently appears to be the most commonly adopted elastic damping model, for numerical convenience. However, as discussed in Priestley et al. (2007) (and elsewhere), the Rayleigh damping model is not appropriate for NLRH analyses. In particular, Priestley et al. (2007) point out that the non-modelled sources of energy dissipation (such as non-structural elements, cracking and friction, and radiation damping) that could justify the inclusion of damping within NLRH analyses, offer little energy dissipation post-yield. By adopting a standard Rayleigh damping model, the damping forces will continue to grow unrealistically post-yield, as velocity demands increase in large intensity events. A more rational alternative, advocated by Priestley et al. (2007) amongst others, with some experimental justification (Petrini et al. 2008), would be to adopt tangent-stiffness proportional elastic damping (ICTYPE=6 in Ruaumoko, Carr 2013). This is currently recommended also for EVD calibration studies, even though it is anticipated that in the future, further improved options for modelling damping may become available.

The potential impact of the choice of damping model can be gauged via Figure 3 (from Priestley et al. 2007). This figure plots the ratio of the inelastic displacement demand to the elastic spectral displacement at the system's initial period, obtained for SDOF systems via NLRH analyses conducted using either initial-stiffness (IS) or tangent stiffness (TS) proportional damping. As expected, the TS damping model leads to greater inelastic displacement demands but interestingly, the differences between displacement demands obtained using the IS versus the TS models change with the hysteretic model. Also note that the equal displacement rule is non-conservative, particularly for the Takeda and Flag-shaped hysteretic models. With these points in mind, it is again reiterated that tangent-stiffness proportional damping is recommended for NLRH calibration analyses.



(a) Takeda (concrete) hysteresis (b) Bilinear hysteresis, and (c)Flag Hysteresis

Figure 3 – Highlighting the impact of the elastic damping model on the ratio of the elastic spectral displacement to the inelastic displacement demand for SDOF systems designed with a force reduction factor of R=4.

3.2 Ground motion characteristics

As explained earlier, the work of Pennucci et al. (2011) showed that calibrated EVD expressions can be sensitive to the way that an accelerogram set's response spectra scale (e.g. Eq.2) with damping. However, the selection of a ground motion set for calibration studies should also consider other factors. For instance, Pennucci et al. (2011) found that the spectral shape around the effective period can have a significant impact on DRF values. Moreover, it has been shown by Tothong and Cornell (2006) and Stafford et al. (2016), that the ratio of inelastic displacement demand to elastic spectral displacement demand will be greatly affected by the source magnitude and distance and the oscillator's period of vibration. The earthquake magnitude was found to be particularly important and as shown in Figure 4, the ratio of inelastic displacement to elastic spectral displacement (at the initial period) can change from one magnitude level to another by more than 50 percent.

The observations above then prompt the question as to whether the accelerograms used in the calibration of EVD or DRF expressions in previous studies are appropriate for a given site? As the combination of event magnitudes and distances that dominate the hazard at a site will vary from one site to another, it is clear that there must be a sacrifice in accuracy if we are to expect that a general EVD or DRF expression is to be used at a wide variety of sites. For this reason, the alternative proposal by Stafford et al. (2016) is for inelastic displacement spectra to be developed as part of a probabilistic seismic hazard assessment (done at a national scale and incorporated in building codes), so that source magnitude and distance effects can be reliably accounted for and the engineer can work directly with the inelastic spectrum.

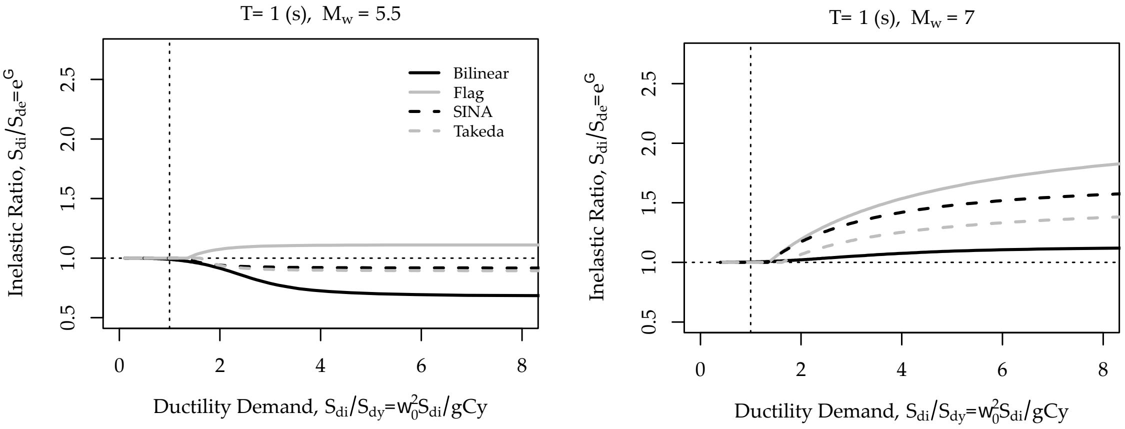


Figure 4 – Impact of moment magnitude on the ratio of inelastic to elastic spectral displacement demands (adapted from Stafford et al. 2016).

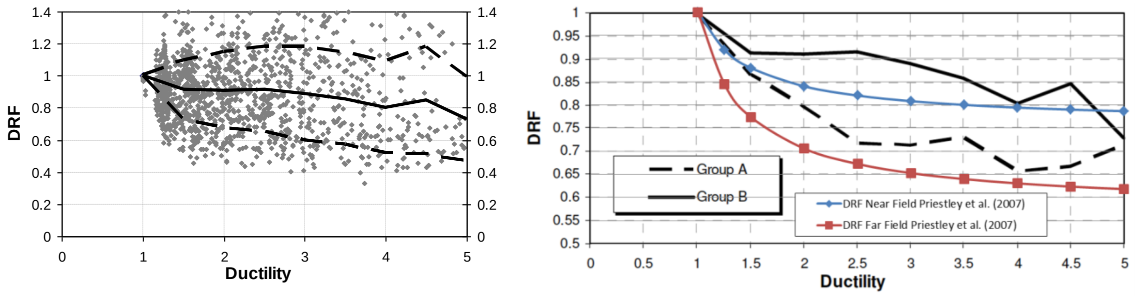
4 SITES AFFECTED BY NEAR-FIELD EVENTS

From the previous section it is clear that when developing calibrated EVD or DRF expressions careful consideration of the ground motion characteristics is required. To this extent, an important area for future research should focus on the special case of near-field events that possess velocity pulses. Priestley et al. (2007) recommended that for sites affected by near-field ground motions containing velocity pulses, Eq. 2 should be modified to:

$$\eta = \left(\frac{0.07}{0.02 + \xi} \right)^{0.25} \tag{4}$$

Other researchers, such as Bradley (2015), have queried the basis of this equation since the elastic spectra of events with velocity pulses do not appear to scale according to the above damping-dependent expression. However, as was explained in earlier parts of this paper, when Eq.4 is used together with a ductility-dependent EVD expression, the expectation is that the effect of non-linear response on inelastic displacement demands is adequately captured. Thus, in order to gauge whether Eq.(4) is appropriate or not, one must conduct calibration studies using non-linear systems and then examine whether predicted displacements match the median results obtained from NLRH analyses.

Some insight into the matter has been presented in Sullivan et al. (2013), where calibration studies were undertaken to identify DRF curves for a set of 40 ground motions containing near-field velocity pulses with pulse periods ranging from 1.0s to 4.0s. Figure 5 highlights some of the results from this study, with Figure 5a firstly showing the DRF vs ductility plot obtained using records with velocity pulses, and Figure 5b comparing the median of these results (Group B) with the median DRF curve obtained using a set of 20 far-field ground motions (Group A).

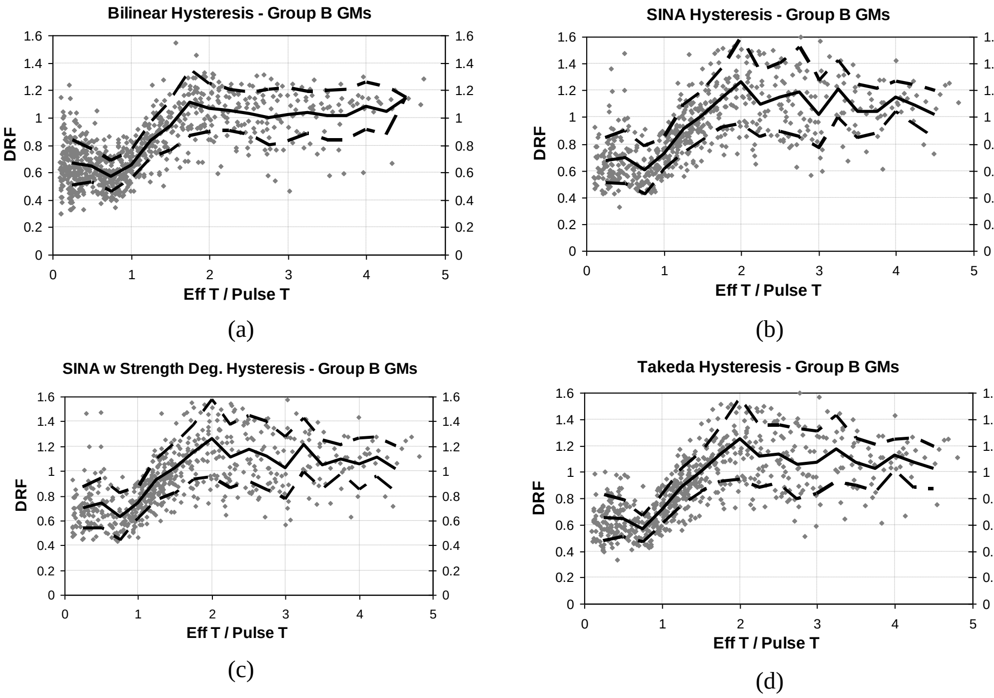


(a) **(b)**

Figure 5 - (a) Example of numerical results for the Takeda hysteresis loop using ground motions with velocity pulses and (b) comparison of median results for ground motions with and without velocity pulses (Takeda hysteresis) together with predictions according to Priestley et al. (2007).

One observes in Figure 5 that spectral displacement demands are not reduced as significantly by non-linear response when velocity pulses are present (this is evident from the DRF values, which are higher for the Group B set of motions). Furthermore, whilst the DRF values predicted by Priestley et al. (2007) do not accurately predict either the far-field nor the near-field events in this case, it appears as though the near-field correction in Eq.4 does perform reasonably well, at least on first impression.

In order to investigate the matter further, Sullivan et al. (2013) post-processed the results of their calibration study in order to examine whether any relationships between pulse period and DRF could be identified. Figure 6 shows the results obtained, illustrating trends for various hysteresis loops and for ductility demands between 2.0 and 5.0. The results in Figure 6 suggest that when the effective period of a structure is assessed to be less than the velocity pulse period for the site then no change is required to the scaling recommended for far-field motions. In contrast, when the velocity pulse period is equal or larger than the pulse period, the inelastic displacement demands tend to be equal to the elastic spectral displacement demands (suggesting no benefit of hysteretic response). This sort of trend was not evident for the general DRF results presented in Figure 5 since they corresponded to DRF values obtained over a range of periods, for a range of pulse periods.



(a) (b)

(c) (d)

Figure 6 - Variation of DRFs with the ratio of SDOF effective period to velocity pulse period for various hysteresis loops for ductility demands between 2.0 and 5.0 (effective periods from around 1.4s to 2.2s).

Reflecting on the results in Figure 6, it is apparent that since a site may be affected by a mixture of various possible pulse periods, and presumably also far-field motions, then, once again, the most robust means of accounting for non-linear behaviour in a spectrum-based seismic assessment or design approach would be to work directly with inelastic spectra obtained using ground motion prediction equations (GMPEs). However, whilst such GMPEs are available (Stafford et al. 2016) for far-field events, the author is not aware of any such GMPEs for near-field ground motions possessing velocity pulses. As such, the development of such equations should be undertaken as part of future research.

5 A PRAGMATIC POSSIBILITY FOR THE ASSESSMENT OF EXISTING BUILDINGS

The previous sections have clarified that spectral scaling expressions (via EVD or directly via DRFs) are fairly sensitive to the ground motion characteristics used in the calibration process. It has also been pointed out that while a large number of calibrated EVD and DRF expressions are now available, practitioners may well encounter a structural system for which calibrated expressions have not been developed. Given the inherent uncertainties in spectrum-based design and assessment methods, it would appear that in such cases, at least until more refined EVD expressions or inelastic spectra become available, a pragmatic way forward would be to assign the system an EVD value based on a qualitative assessment of the level of energy dissipation that the system offers. Figure 7 proposes a series of generic EVD curves for systems possessing 5% elastic damping and classified as possessing either no, low, medium or high energy dissipation characteristics. These curves have been set considering the curves in the literature, such as those shown earlier in Figure 1.

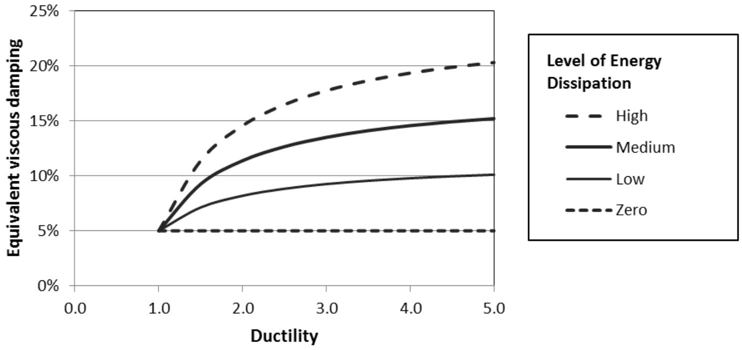


Figure 7 – Equivalent viscous damping curves that might be assumed following a qualitative assessment of the energy dissipation characteristics of a system. Note that the curves have been set using Eq. 1 with C values of 0.0, 0.20, 0.40, and 0.60 for systems characterised by zero, low, medium or high energy dissipation, respectively.

In order to be able to select an EVD value via Figure 7, it is clear that some engineering judgement should be applied in the assessment of the energy dissipation characteristics. To this extent, the engineer should reflect on the following questions: (i) is the inelastic mechanism expected to possess a distinct yield point from which the resistance will be maintained or is considerable post-yield hardening expected that will be relied on when evaluating the lateral resistance offered at the peak displacement? Generally, a higher value of post-yield stiffness will imply a lower ratio of dissipated energy to elastic strain energy and, hence, lower EVD and DRFs should be adopted; (ii) Is the unloading stiffness likely to be similar to the initial stiffness or should reductions be expected (due to, for example, bolt hole elongation at connections or slip of reinforcing bars)? Low unloading stiffness values will tend to lead to lower EVD values; (iii) Is some sort of rocking response expected? Rocking systems assist with re-centering but dissipate less energy than traditional systems; (iv) Are there many non-structural elements that could add significant dissipation (and/or stiffness that has not been modelled)? This could affect the implicit assumption of 5% damping and suggest that higher or lower values of damping might be reasonable (noting that steel buildings and taller buildings should be assumed to possess lower values of elastic/inherent damping); (v) Is the system P-delta stability coefficient high? If the P-delta stability coefficient is high (from say 0.15 up to a maximum allowable of 0.30), then second order effects will tend to amplify displacement demands considerably and if this is not accounted for via alternative means, then lower EVD values should be adopted.

By way of example, consider the bi-linear, Takeda thin and flag-shaped hysteretic rules which all had very different EVD values, as can be seen in Figure 2. Despite all systems having the same post-yield stiffness ratios, one could have anticipated that the Takeda model would give less EVD than the bi-linear model, owing to its progressively lower unloading stiffness, whereas the flag-shaped system possesses rocking response, lowering its EVD. Nevertheless, other considerations, in addition to those listed above, might affect the EVD classification, the purpose of which should be to arrive at a pragmatic assessment of the likely effects of energy dissipation on inelastic displacement demands. This type of approach would clearly benefit from additional research aimed at clarifying further the factors that affect the EVD. However, in the interim it is thought that the approach presented in Figure 7 represents a significant improvement over the equal-displacement rule, that is currently adopted widely for spectrum-based assessment methods.

6 CONCLUSIONS

This paper has reviewed the background to equivalent viscous damping (EVD) in earthquake engineering, pointing out that expressions for EVD should be calibrated to match the results of NLRH analyses. The rationale for an eventual shift to spectral displacement reduction factors (DRFs) in place of EVD has also been discussed. Subsequently, it has been shown that the results of EVD and DRF calibration studies can be very sensitive to the ground motion characteristics and the elastic damping model used for the NLRH analyses. In particular, it has been emphasized that local hazard characteristics, such as dominant source magnitude or near-field effects, are likely to affect calibrated EVD expressions. This in turn suggests that the most robust means of accounting for non-linear behaviour in a spectrum-based seismic assessment or design approach would be to work directly with inelastic spectra obtained through a probabilistic seismic hazard assessment using suitable GMPEs. Finally, while a large number of calibrated EVD and DRF expressions are now available, practitioners may encounter a structural system for which calibrated expressions have not been developed. As such, the final part of the paper has proposed a pragmatic way forward in which such systems are assigned an EVD value based on a qualitative assessment of their energy dissipation potential.

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