PROPERTY MODIFICATION FACTORS FOR ELASTOMERIC SEISMIC ISOLATION BEARINGS

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SUMMARY

Property modification factors have been introduced into the AASHTO Guide Specification for Seismic Isolation Design to account for likely variations in isolation bearing properties over the life of a seismically isolated bridge. The design of an isolated bridge in the United States must now account for variations in temperature, ageing, velocity (strain rate), travel, contamination, and scragging. In the absence of elastomer compound test data, the Guide Specification provides de facto values for likely variations in temperature, ageing, and scragging for use in design. Experimental data from tests of high-damping and lead-rubber bearings were analyzed to assess the de facto values listed in the Specification. The AASHTO values for the scragging factor should be increased from 1.2 to between 1.5 and 2.0 for HDR-A elastomeric bearings and left unchanged for lead-rubber bearings. Full recovery of virgin (unscragged) properties following scragging should be assumed. No change in the AASHTO ageing factors for high-damping and lead-rubber bearings are recommended at this time. The data support the listing of a velocity (strain rate) factor in the Guide Specification with a value equal to 1.2 for high-damping elastomer compounds.

INTRODUCTION

Effective stiffness, equivalent viscous damping ratio, zero-displacement-force intercept, and post-yield stiffness, are four parameters that are widely used to characterize the response of elastomeric seismic isolation bearings. See figure 1. The first two are used for linear response-history and response-spectrum analysis and the last two for nonlinear response-history analysis. Values of these four parameters are typically calculated using material property data supplied by bearing manufacturers.

Single estimates of these values are used for design because state-of-the-practice computer code cannot account for path-history or load-history effects. Manufacturers typically report property data from the results of full-scale and moderate-scale component tests such as that shown in figure 2 for a high-damping elastomeric bearing. For this bearing, the shape of the hysteresis loop changes with repeated cycling, with the loop shape essentially stabilizing after three cycles. Third-cycle data, representing stabilized material properties, are often used by elastomeric bearing manufacturers to calculate material-property values.

Unlike conventional civil engineering materials such as structural steel and reinforced concrete, seismic isolation bearings are composed of materials such as elastomers and composites whose properties can vary significantly as a function of time, temperature, load history, strain-rate and velocity, among others. To date, designers of seismic isolation systems have routinely ignored potential changes in material properties and the effect of such changes on the response of isolation systems. Property modification factors as introduced in the 1999 AASHTO Guide Specifications for Seismic Isolation Design [American, 1999] serve to address the impact of material-property changes on isolation system response.

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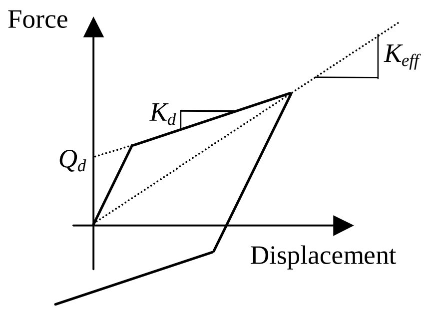


K_{eff} = effective stiffness
K_d = post-yield stiffness
Q_d = zero-displacement-force intercept
β = damping ratio = $EDC \big/ (2\pi K_{eff} \Delta^2)$
EDC = area contained within hysteresis loop
Δ = displacement amplitude

Figure 1. Bilinear force-displacement relations for elastomeric bearings

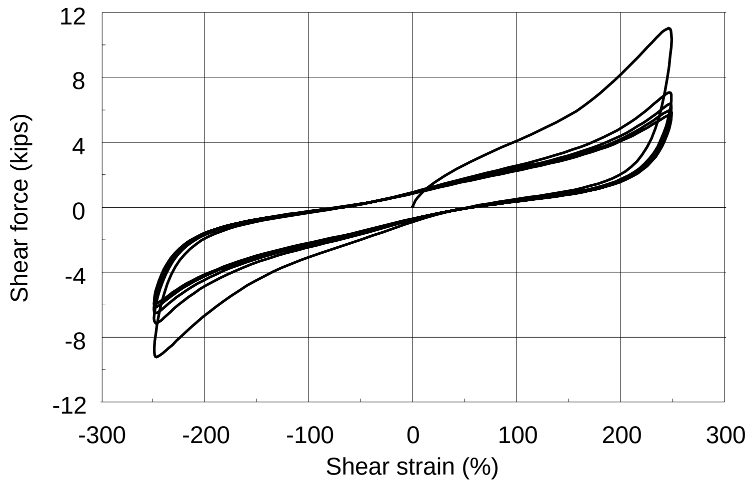


Figure 2. Force-displacement relation for a high-damping elastomeric bearing

The AASHTO Guide Specification writes that the minimum and maximum effective stiffness of the isolation system shall be calculated using the minimum and maximum values of K_d and Q_d, calculated as the product of (1) the nominal values of these parameters, and (2) the minimum and maximum values of the corresponding property modification factors, respectively. Minimum and maximum values of the post-yield stiffness and the zero-displacement-force intercept are used to calculate the maximum displacements of the isolators and maximum forces in the substructures, respectively. Minimum values of λ are set equal to unity in the Specification. Maximum values of λ for both the post-yield stiffness and zero-displacement-force intercept are calculated as the product of six component factors related to temperature, ageing (including corrosion), velocity, travel (wear), contamination, and scragging.

In the absence of elastomer-specific test data, AASHTO presents de facto maximum values of λ for ageing, temperature, and scragging and notes that values for velocity and travel should be established by test. The values listed in the Specification for ageing and scragging of elastomeric bearings are presented in table 1. In this table, (1) low-damping elastomeric bearings are assumed (by the authors) to have no more than 5-percent equivalent viscous damping; all other elastomeric bearings are considered to be high damping, (2) for ageing, HDR-A is an elastomer whose unscragged stiffness is less than 1.25 times the scragged stiffness; all other non-lead-rubber high-damping elastomeric bearings are considered to be HDR-B, (3) for scragging, HDR-A is an elastomer with less than 15-percent equivalent viscous damping; all other non-lead-rubber elastomeric bearings are considered to be HDR-B, and (4) the ageing factor for post-yield stiffness in a lead-rubber bearing is not given because it is a characteristic of the elastomer.

The values assigned to the component λ factors in the Guide Specification are primarily based upon the work of Constantinou et al. [1999]. Constantinou presents significant information for sliding isolators and these data are included in the Specification. For elastomeric isolators, the specification notes that "The factors [values] listed herein are based upon the available limited data. In some cases the factors could not be established and need to be determined by test." This lack of data for elastomeric bearings was the key motivation for the study described below.

Table 1 AASHTO values of λ for ageing and scragging

	$\lambda_{\max,ageing}$		$\lambda_{\max,scrag}$	
Elastomeric Bearing Type	K_d	Q_d	K_d	Q_d
Low-Damping Natural Rubber	1.1	1.1	1.0	1.0
High-Damping Rubber – A	1.2	1.2	1.2	1.2
High-Damping Rubber – B	1.3	1.3	1.8	1.5
Lead-Rubber	-	1.0	1.0	1.0

PROPERTY MODIFICATION FACTORS

Caltrans Protective Systems Research Program

One component of the Caltrans Protective Systems Project being undertaken at the University of California, Berkeley involves characterizing the response of elastomeric and sliding seismic isolation bearings to unidirectional and bidirectional displacement-histories and using those characterizations to predict the response of a simple isolated bridge to bidirectional earthquake shaking. The bidirectional test setup and results of some of these studies are reported by Huang et al. [2000]. An integral part of this study is the investigation of the effects of scragging and recovery, ageing, velocity (strain rate), and temperature on the response of elastomeric bearings. These effects were studied by experimentation in a single-component bearing test machine and on the Berkeley earthquake simulator and by re-analysis of bearing data collected at Berkeley over the past 15 years.

Experimental data were collected from tests of 23, moderate-scale, high-damping elastomeric bearings supplied by five manufacturers: Alga, Andre, Bridgestone, Malaysian Rubber Producers Research Association, and Rubber Consultants, and 6 identical, moderate-scale, elastomeric lead-rubber bearings supplied by Dynamic Isolation Systems. Elastomer compounds are not identified in the paper for two reasons. First, the intent of the study is to establish compound-independent values suitable for inclusion in the AASHTO Guide Specification. Second, curing procedures for moderate-scale elastomeric bearings differ from those employed for prototype (full-scale) isolators; compound-specific values determined from moderate-scale tests may not be identical to those obtained from prototype tests.

At the time of this writing, the studies on scragging, recovery, ageing, and strain rate are substantially complete. The results of these studies are described in the following sections. The data presented below can be used to provide improved estimates of component modification factors for inclusion in the next edition of the AASHTO Guide Specifications for Seismic Isolation Design.

Scragging and Recovery

The force-displacement loops for non-lead-rubber elastomeric bearings change with repeated cycling. Larger values of stiffness and strength are observed in the first half-cycle of loading of an untested bearing than in subsequent cycles. Properties calculated from first half-cycle data are often termed *unscragged* or virgin properties. Properties calculated from subsequent cycles are termed *scragged* properties.

Mullins' effect [Mullins, 1969] or scragging is the cyclic reduction of the bulk modulus of elastomers at moderate-to-high shear strains. Mullins showed that most of the reduction (softening) occurred during the first cycle of deformation to a given level of strain and that subsequent cycling to that strain level produced incrementally smaller reductions in modulus. Such stabilization in the hysteresis can be seen in Figure 2. More recently, Clark et al. [1997] parsed the modulus reduction into two effects: scragging and Mullins' effect wherein scragging was described as the permanent reduction and Mullins' effect as the temporary reduction in modulus due to cyclic straining. However, for the purpose of this paper, any reduction in modulus, permanent or temporary, is termed scragging.

The percentage reduction in effective modulus with cycling depends on the formulation of the elastomer compound, the process used to fabricate the isolator, and strain history. Filler materials are routinely added to natural rubber to modify the modulus and/or damping of the elastomer. Mullins [1969] observed that the addition of filler materials increased the percentage reduction in effective modulus. This trend is reflected in the AASHTO Guide Specification wherein larger values of the scragging factor are assigned to high-damping (filled) rubber bearings than low-damping natural rubber bearings (see table 1).

Data from both previously conducted component tests and the test program described above were analyzed to provide improved estimates of the scragging factor. Figure 3 presents the relation between the ratio of effective shear modulus calculated from first and third cycle test data, and third-cycle effective modulus at 100-percent shear strain (selected because this parameter is often used to characterize high-damping rubber bearings) for 34 high-damping elastomeric bearings. The 34 bearings were fabricated by 5 manufacturers using a total of 10 different compounds. Most of the 34 bearings would be classed HDR-A in the Guide Specification. The first-cycle effective modulus was calculated from first half-cycle data. Most of the data points represent values for virgin (previously untested) bearings. The damping ratio corresponding to each of the data points are identifed in the figure. The effective shear modulus and damping ratio were calculated using the effective shear stiffness at maximum displacement (shear strain) as defined in the Guide Specification. Maximum shear strains ranged between 150 and 250 percent.

The data of figure 3 represent the effect of added filler material on the reduction in effective modulus with cycling. For effective moduli below 100 psi, values for the scragging factor range between 1.4 and 2.1. For elastomers with moduli greater than 100 psi, the values for the scragging factor do not exceed 1.5. The data of figure 3 suggest that the scragging factor is independent of damping ratio.

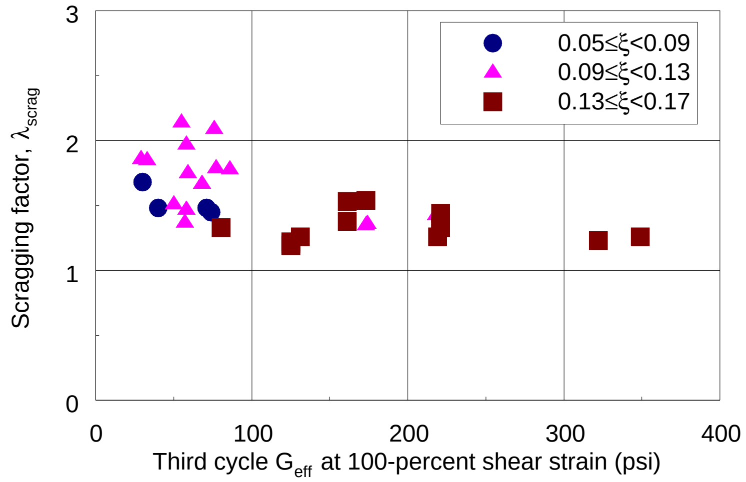


Figure 3 Values of the scragging factor, λ_{scrag}, for high-damping elastomeric bearings

Data from the tests of 6 nominally identical lead-rubber bearings were studied to characterize the scragging factor. The size of the lead core in this moderate-scale isolator was smaller, as a percentage of the bonded diameter of the isolator, than that typically used in practice. As such, if scragging effects were important for lead-rubber bearings incorporating a low-damping natural rubber elastomer, such effects would be evident in the test data. The elastomer used in the fabrication of the bearings was a low-damping rubber with an effective shear modulus of 80 psi at 100-percent shear strain. There was no evidence of scragging in any of the 6 bearings. (Nor have the authors observed scragging in data from tests of moderate- and full-scale lead-rubber bearings.)

Production seismic isolators are often scragged as part of a manufacturer's quality control practices. Such scragging always involves unidirectional shearing of the isolator to a strain level that is typically less than the maximum design strain. Two design-oriented questions arise from this practice: (1) If an isolator is scragged along one axis, can one consider it to be scragged along all axes?, (2) Are the unscragged (virgin) properties recovered with time? Bi-directional tests of seismic isolation bearings were conducted using the Berkeley earthquake simulator to address the first question. Data from the cruciform-orbit test of a low-modulus, high-damping elastomeric bearing are shown in figure 4. This test involved one fully reversed cycle to 250-percent shear strain in the *x*-direction followed by one fully-reversed cycle to 250-percent shear strain in the *y*-direction. If scragging along one axis of the isolator had no effect on response in the perpendicular direction, the two loops would be essentially identical. The data in figure 4 clearly indicates that scragging along one axis significantly influences response on the perpendicular axis. Data from cruciform-orbit tests of another low-modulus, high-damping elastomeric bearing from a different manufacturer support this observation but the degree of interaction appears to be compound dependent.

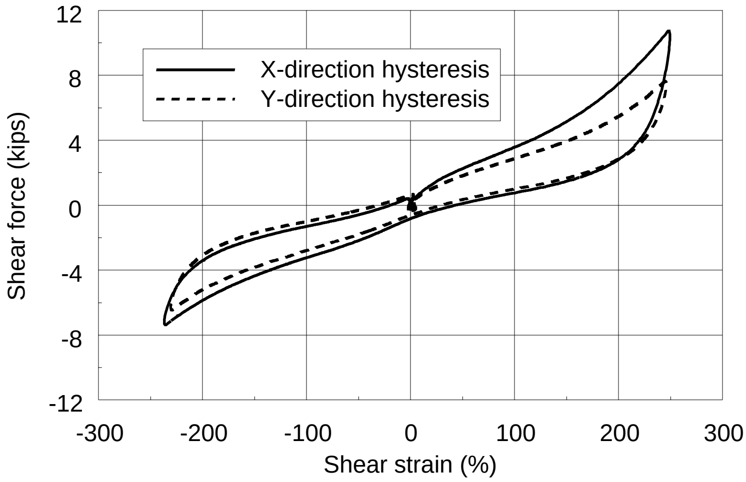


Figure 4. Bi-directional displacement-history hysteresis loops

If the effective modulus of an elastomer recovers with time following repeated cycling, design of a seismic isolation system incorporating such elastomers should be based on unscragged properties. Conversely, if all isolators in a seismic isolation are scragged to the maximum design strain along all axes, and if the effective modulus of the elastomer does not recover with time, design of the isolation system should be based on scragged properties with the scragging factor set equal to 1.0.

Kulak et al. [1998] reported recovery data from overstrain tests of high-modulus, high damping elastomers and concluded that "…elastomer compounds do recover…scragging of a bearing before installation is not important." Mullins [1969] observed that "…rubber which had been softened by previous stretching showed recovery toward its initial stress-strain properties upon standing. Recovery was slow at normal temperatures but was more rapid and more complete at higher temperatures." Data from the Berkeley test program and elsewhere [Constantinou et al., 1999] support this observation although the degree and rate of recovery likely vary as a function of elastomer compound, manufacturing process, and frequency of testing (an increase in strain rate will increase the temperature in the bearing that will accelerate recovery). Figure 5 shows first- and third-cycle hysteresis loops from two tests of one high-modulus, high-damping elastomeric bearing. The bearing was first tested in 1994 (virgin test) and re-tested in 1999 using the same axial pressure, strain history, and loading frequency. The bearing was not loaded in the interval between tests. The ageing factor (discussed below) is estimated as the ratio of the two *third*-cycle effective shear moduli (=G[1999]/G[1994]). The percentage recovery is estimated as the ratio of the two *first*-cycle effective shear moduli (=G[1999]/G[1994]) divided by the ageing factor. The data of figure 5 show that recovery was complete in the five-year period.

Data from tests of 3 other high-damping elastomeric bearings were analyzed (one high-modulus and two low-modulus compounds). For 1 high-modulus and 1 low-modulus compound, 100-percent recovery was observed in a five-year period; more than 65 percent of the recovery in the low-modulus compound was observed in the first 12 month period. For the remaining low-modulus compound, 60-percent recovery was observed in 1 month. None of these bearings were statically loaded between tests.

Ageing

Long-term changes in the mechanical properties of elastomer compounds can result from hardening due to continued vulcanization of the elastomer and degradation of the elastomer due to exposure to ozone and oxgen. Protection against ozone and oxygen degradation can be achieved by including various waxes and chemical anti-oxidants in the rubber matrix [Roberts, 1988]. Although bulk components are generally not significantly affected by such degradation, elastomeric bearings are normally fabricated with a layer of cover rubber that is compounded with anti-oxidants to protect the core of the bearing from oxygen and ozone attack. Age hardening due to continued vulcanization of the elastomer can lead to significant increases in effective shear modulus with time. The percentage increase in effective modulus will vary depending on a number of factors including completeness of the initial vulcanization and temperature [Lindley, 1974].

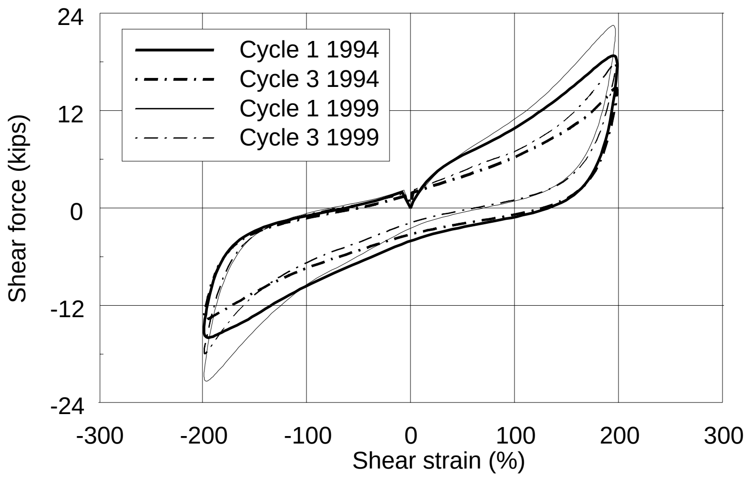


Figure 5. Hysteresis loops for evaluation of recovery and ageing

Nakazawa et al. [1991] conducted accelerated ageing tests on low-damping, moderate-scale rubber bearings. Putting aside the adequacy of accelerated ageing tests [Constantinou et al., 1999], Nakazawa predicted increases in effective shear modulus of 3 percent, 7 percent, and 17 percent in 5, 10, and 50 years, respectively. Clark et al. [1996] reported the results of ageing tests conducted on prototype and production high-damping and lead-rubber bearings fabricated in the mid-1980s. Although a 20-percent increase in the effective shear modulus of the prototype bearings was observed, the increase in effective modulus of the production bearings was small. No measurable change in the effective shear modulus of the lead-rubber bearing was observed.

Seven-year ageing tests on one high-damping rubber coupon are described by Kulak et al. [1998]. Average increases of 10 percent in effective shear modulus and 6 percent in damping ratio were reported for strains ranging from 10 to 50 percent. Such increases are likely an upper bound on the increase expected in a bulk component of the same compound.

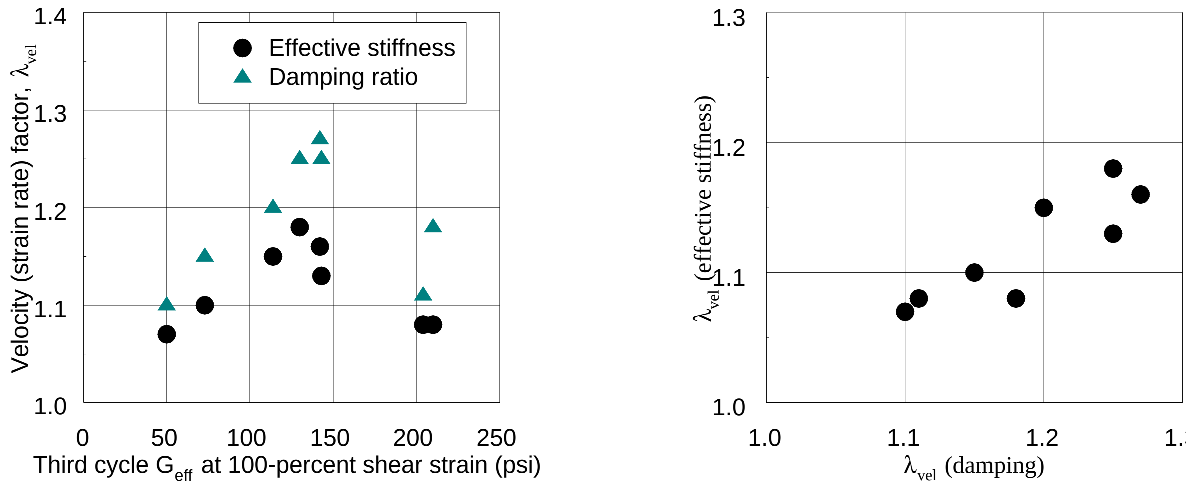
The procedure described in the section entitled Scragging and Recovery was used to estimate ageing effects in the moderate-scale, high-damping rubber bearings tested at Berkeley. Ageing factors were calculated for bearings fabricated with different compounds supplied by two manufacturers. None of the bearings were statically loaded between tests. The 5-year ageing factor for the high-modulus, high-damping rubber bearing of figure 5 is 1.20. The 5-year ageing factors for the high-damping, high- and low-modulus bearings supplied by the other manufacturer are 1.0 and 1.0, respectively.

Velocity (Strain Rate)

Prototype tests of elastomeric bearings for bridges and buildings are typically undertaken at psuedo-static rates because of test-machine limitations. Manufacturers often supplement prototype test data with data from dynamic tests of moderate-scale bearings to increase the rated damping of prototype bearings. However, although the increase in damping is beneficial, an increase in effective modulus would often considered to be detrimental, especially for low-modulus elastomer compounds.

Figure 6a shows the effect of strain rate on effective modulus and damping ratio for 5 high-damping elastomer compounds supplied by 4 manufacturers. Values for effective modulus and damping ratio were calculated using the procedures set forth in the Guide Specification using response data from maximum shear strain cycles that ranged in amplitude from 150 to 250 percent. The velocity factors were calculated as the ratio of the effective modulus (damping ratio) at high and low strain rates. Because some of the experimental data presented in figure 6a were prepared for other test programs, the high and low strain rates are not unique. However, the low velocity (strain rate) tests were conducted at frequencies between 0.01 Hz and 0.1 Hz, where rate effects are not expected to be significant, and the high velocity tests were conducted at realistic frequencies for the similitude scale of the tested isolator. The increase in damping and effective stiffness ranged between 10 and 28 percent, and 7 and 19 percent, respectively. Figure 6b compares the values of the velocity factor for effective stiffness and damping.

The trend in this figure is clear, namely, the greater the increase in damping due to dynamic testing, the greater the increase in effective stiffness.



a. Values of the velocity factor, λ_{vel} **b. Comparison of rate effects**

Figure 6 Effect of strain rate on response of high-damping elastomeric bearings

CONCLUSIONS

Property modification factors have been introduced into the AASHTO Guide Specification for Seismic Isolation Design to account for likely variations in isolation bearing properties over the life of a bridge. The design of an isolated bridge in the United States must now account for variations due to six factors: temperature, ageing, velocity (strain rate), travel, contamination, and scragging. System property modification factors are calculated as the product of the six component factors. Values of these component factors should be determined by test but the Guide Specification provides de facto values if test data are unavailable.

The Specification notes that the de facto values assigned to the component factors for high-damping elastomeric bearings were based on limited test data. To provide better estimates for the component factors for elastomeric bearings, data were collected from both component and system tests conducted at Berkeley as part of the Caltrans Protective Systems Research Project and from previously conducted tests at Berkeley of high-damping elastomeric bearings. The data were analyzed to assess the effects of scragging, ageing, and velocity. The key conclusions of the study to date are:

1. Values for the scragging factor range between 1.4 and 2.1 for high-damping elastomers with third-cycle moduli (at 100-percent strain) below 100 psi, and between 1.2 and 1.5 for high-damping elastomers with third-cycle moduli greater thn 100 psi. The AASHTO values for the scragging factor for HDR-A elastomers, which is the classification that would be assigned to most the elastomers discussed in this paper, is 1.20. The data suggest that the de facto value should be increased to 1.5 for high-modulus (greater than 100 psi) elastomers and 2.0 for low-modulus (smaller than 100 psi) elastomers, and that AASHTO should use modulus rather than damping ratio to differentiate between HDR-A and HDR-B elastomers.

2. Scragging produces a significant drop in effective shear modulus in most high-damping elastomer compounds. Data from the Berkeley research program suggest that much of this drop in modulus is recovered in a short-period of time following scragging. Unless there is experimental evidence to the contrary, full recovery of virgin properties should be assumed for the purpose of design.

3. Values for the ageing factor ranged between 1.0 and 1.2 for a small number of high-damping elastomer compounds that were tested over a 5-year period. These values do not conflict with the AASHTO ageing factors of 1.2 (HDR-A) and 1.3 (HDR-B).

4. The effective stiffness and damping ratio of high-damping elastomer compounds increase with strain rate (velocity). Increases in damping ratio are accompanied by smaller, yet significant increases in

effective stiffness. In the absence of test data, a de facto velocity factor of 1.2 should be assigned to HDR-A and HDR-B elastomeric bearings.

ACKNOWLEDGEMENTS

This project is sponsored by the California Department of Transportation under Contract 59A169. Caltrans engineers Ms. Dorie Mellon, Mr. Thomas Post, Mr. Roberto LaCalle, Mr. Timothy Leahy, and Mr. Li–Hong Sheng have worked closely with the project team. Messrs. Wei-Hsi Huang and Troy Morgan, graduate students in the Department of Civil and Environmental Engineering at the University of California at Berkeley, and Dr. Peter Clark of Seismic Isolation Engineering, Inc., made significant contributions to the studies described in this paper. Andre Silentbloc and Dynamic Isolation Systems fabricated moderate-scale isolation bearings for the research project. The support and advice of Caltrans and the above-noted individuals and companies is gratefully acknowledged.

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