DEVELOPMENT AND ANALYSIS OF A HYBRID PASSIVE CONTROL DEVICE

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ABSTRACT:

Engineers are renowned for their ability to creatively solve problems through the application of the fundamentals of science and mathematics. In the field of structural engineering typical problems include designing structures to be safe. Many innovative methods have been developed, tested and implemented to protect structures from earthquakes. Passive energy dissipation devices are one class of these protection strategies. The development of a hybrid passive control device (HPCD) including a high damping rubber sandwich damper in series with a buckling-restrained brace (BRB) presents an innovative way to reduce structural response to dynamic loads. The criteria used to develop this device include energy dissipation for all levels of vibration, significant energy dissipation capacity for large events and an increasing stiffness with displacement. To adequately analyze this device, experimental characterization of highly damped natural and butyl rubber specimens was completed to generate the data necessary to correlate experiment and finite element analysis. The experimental data for the rubber was used to create the static and dynamic material properties in Abaqus. The hybrid device was analyzed using a sinusoidal displacement protocol at various maximum displacements. The hysteresis loops generated from the analysis demonstrate the behavior expected of the hybrid device. The hybrid device shows potential for reducing structural response under everything from wind to major seismic events.

KEYWORDS: passive control, high damping rubber, passive energy dissipation, seismic protection

1. INTRODUCTION

Engineers are renowned for their ability to creatively solve problems through the application of the fundamentals of science and mathematics. In the field of structural engineering typical problems include designing structures to be safe throughout its lifetime. The success of the solution resides in the economy, the visual appeal and effectiveness of the structure. Unfortunately in many cases when the structure fails, not only has the engineer lost face but the loss of life can be significant. There are many examples, some recent, where drastic failure of a structure has significant costs both financially and emotionally. These failures can be due to natural disasters including wind, floods, tsunamis and earthquakes to name a few. Earthquakes generate forces as the building inertia resists motion while the foundation shakes with the surrounding earth. The practice of increasing the strength of the structure serves in many cases to also increase the inertial forces.

Many innovative methods have been developed, tested and implemented to protect structures from earthquakes. Passive energy dissipation devices are one class of these protection strategies. They dissipate energy as the structure deforms based on the relative displacement or velocity between attachment points. There are two general classifications of passive devices, rate independent and rate dependent. Rate independent devices include hysteretic and friction devices. The energy dissipation for these devices is dependent on the displacement across the device. Examples of these include buckling-restrained braces (BRB) (Watanabe et al. 1988), added damping and stiffness devices (Bergman and Goel 1987), Pall friction devices (Pall and Marsh, 1982) and the slotted bolted connection (Grigorian et al. 1993) to name a few. The strength of these devices is the large capacity for energy dissipation and reduction in displacement. The drawback is that the energy dissipation only occurs upon yielding or slip. The increased stiffness of the structure can also have the effect of increasing the seismic loads.

Rate dependent devices include viscous fluid dampers and viscoelastic solid dampers. For these devices, the amount of damping is based on the relative velocity across the device or in some cases both the velocity and displacement. The strength of these devices is energy dissipation over all levels of motion. Viscous fluid dampers dissipate energy through deformation of fluid in a sealed cylinder. They have been successfully implemented in the United States and around the world (Symans et al. 2008). These devices also have the flexibility to be used in unique configurations, including the scissor-jack and toggle brace, which increases their effectiveness (Constantinou et al. 2001, Sigaher and Constantinou 2003). Viscoelastic solids are elastomeric materials which dissipate energy upon deformation. One class of VE materials that has shown promise is high damping rubber (HDR). HDR consists of vulcanized rubber filled with carbon black to increase the stiffness and damping properties. It was initially used in highly damped bearing pads for base isolated structures (Derham et al. 1985, Fuller et al. 1996) but has since been investigated for use in structural dampers as well (Lee et al. 2004).

In an attempt to create a hybrid passive control device (HPCD) utilizing the strengths of both rate dependent and rate independent devices the Visco-Hyperelastic Device (Murthy, 2005) and the Visco-Plastic Device (VPD) (Ibrahim et al. 2007) were developed. These devices use a combination of HDR and a metallic yielding element in a unique geometry. Under small scale deformations, they function as a viscoelastic device. Under larger scale events, energy would be dissipated additionally through yielding. The unique geometry creates a hyperelastic or stiffening effect. The stiffening effect helps overcome problems with p-delta effects as the structure is displaced from center. The VPD, illustrated in Figure 1, also has the benefit of displacement amplification across the rubber element which increases the effectiveness under small excitation.

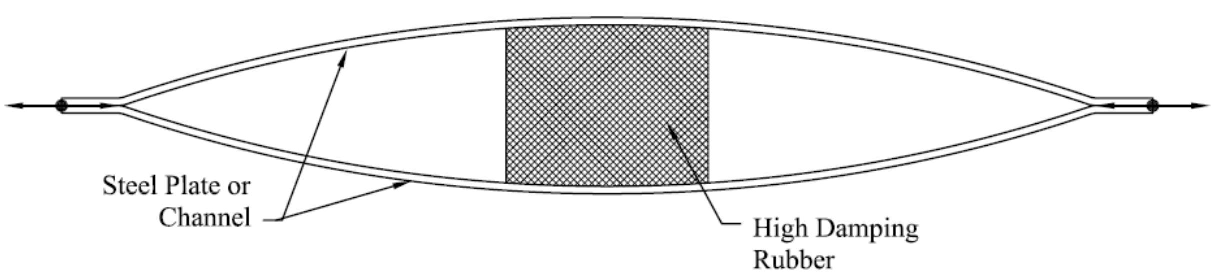

Figure 1 – Visco-Plastic Device

2. HYBRID DEVICE DESCRIPTION

The first criterion considered in the development of the hybrid device was a two phase behavior. The first phase consists of an energy dissipation element effective at all levels of vibration. The original intent was to further develop the VPD. Based on discussions with rubber a manufacturer, production of a block of rubber of the required size was prohibitively expensive. An additional criterion of having a symmetric device would not have been achieved due to the difference in the behavior of the rubber in tension and compression. The material properties are the same but the geometric differences cause asymmetry. Another consideration was that rubber is typically not employed in tension due to problems with micro-cracking. In addition to high inherent damping, HDR has the advantage of being a hyperelastic material and having significant strain capacity. For these reasons, a high damping rubber sandwich damper was chosen for the damping element.

Several alternatives were considered for the selection of the rate independent element. A BRB was selected because of the simplicity and effectiveness. It also fulfilled the symmetry requirement. There are two options to engage the second phase and induce yielding. The first is to ensure that the shear force in the rubber element exceeds the yield force of the BRB at the desired displacement. The problem with this method is that the size of the damper is primarily controlled by the amount of damping required in the structure. Using this method, the size of the damper would be controlled by two separate constraints increasing the complexity of the design. The second option is to lockout the damper at a specified displacement. The lockout mechanism would provide the increased stiffness and strength to yield the BRB. With this method, the device is actually a three phase device. The second phase is the increasing stiffness after damper lockout with the third phase being the braces yielding.

The lockout mechanism is designed to be as simple as possible. Although there are multiple possibilities, a slotted bolt hole was chosen. The outside plates of the sandwich damper have slotted holes while the center plate has a standard hole. The same system is used in a slotted bolted friction connection. The difference being that the bolts must be designed for the shear and the moment due to the separation of the plates by the rubber layers. A simple schematic of the hybrid device is shown in Figure 2.

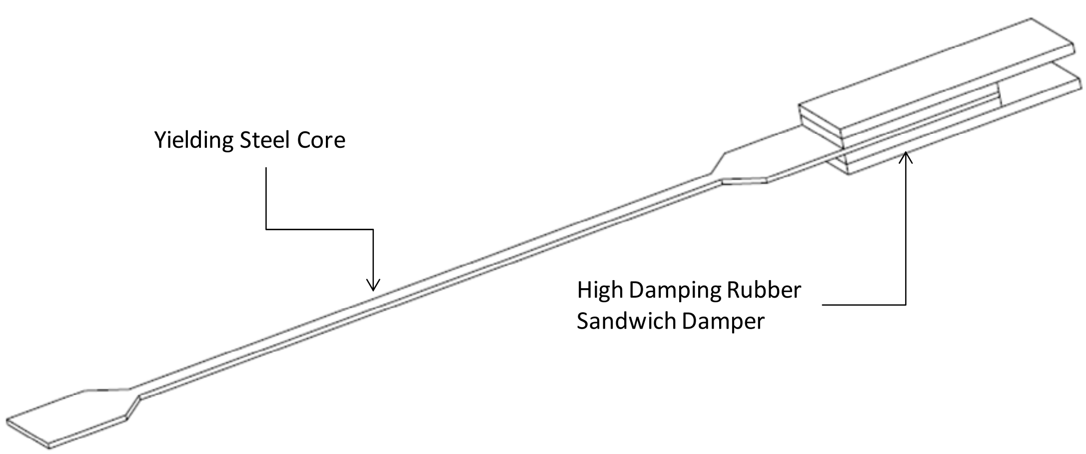

Figure 2 – Schematic of Hybrid Passive Control Device (Lockout mechanism in damper and buckling restraining member not shown)

3. RUBBER MATERIAL TESTING

3.1. Rubber Compounds

Six rubber compounds were experimentally tested to determine the static and dynamic properties although only four of the compounds are discussed. Two types of vulcanized carbon black filled rubber, natural and butyl, were included. For both types of rubber one sample had a Shore A hardness of 40 and one had a hardness of 60. A larger Shore hardness value is indicative of a higher stiffness. The natural and butyl HDR compounds tested were specifically formulated for energy dissipation applications. The rubber samples were manufactured and donated by Corry Rubber in Erie, PA. For reference, butyl rubber with a Shore hardness of 60 is abbreviated BR60. The same convention is used for all the samples with NR for natural rubber samples.

3.2. Material Testing

The material testing program included static, cyclic and time dependent testing of three types of samples. Parallel sided specimens were tested in uniaxial tension statically, cyclically and for stress relaxation. Planar tension specimens with a width ten times greater than the length were subjected to static loads and stress relaxation. The final type of specimen is the dual lap shear specimen. The shear specimens were tested in simple shear under static, cyclic and stress relaxation conditions. The shear specimens were tested over a range of frequencies and strain levels expected in service in a structure. The primary purpose of the test program is developing the data for correlation with FEA in Abaqus (Abaqus 2007). Uniaxial and planar tension data are input to determine which hyperelastic material model provides the best model. The stress relaxation and cyclic data are used to develop the dynamic properties. Five specimens were tested for each compound of the uniaxial and planar tension samples. Three simple shear specimens were tested for each compound.

The testing protocol was developed to account for the stress softening of the samples, referred to as the Mullins effect (Mullins 1969). The samples were statically cycled through the desired range until a steady state static property was achieved, typically 10 cycles. The mechanical conditioning was used because currently the FEA software cannot account for both the Mullins effect and the inherent material damping. Raw test data showing this softening can be seen in Figures 3 and 4. The nonlinear stress-strain and the hyperelastic properties of the HDR compounds can also be seen in the figures.

3.3. Test Results

The data used for FEA was based on the steady state response which occurred in the later cycles of the static tests. The stress-strain curves for the steady-state cycles had a permanent set that had to be accounted for prior to determining the mean properties. The curves with the permanent set removed from all the specimens were averaged by creating curve fits of each test so the stress could be averaged at a given strain. The dynamic properties were determined from the cyclic tests by calculating the phase lag between the stress and the strain. The material loss factor for each compound over the range of frequencies and strain levels tested is shown in Table 3.1. The reduced stress-strain data including uniaxial tension, planar tension and simple shear for NR60 is shown in Figure 5.

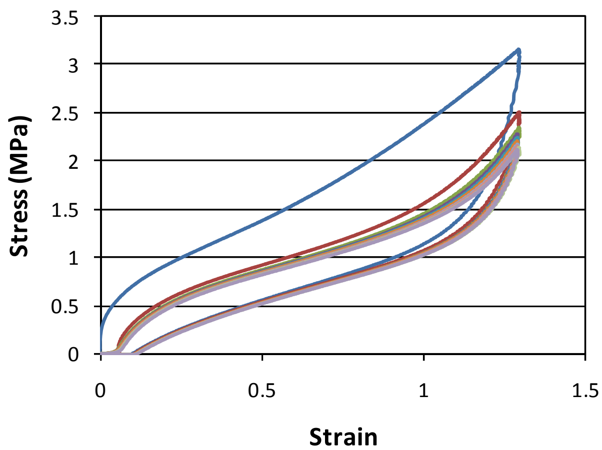

Figure 3 – NR60-3 Uniaxial Tension Data

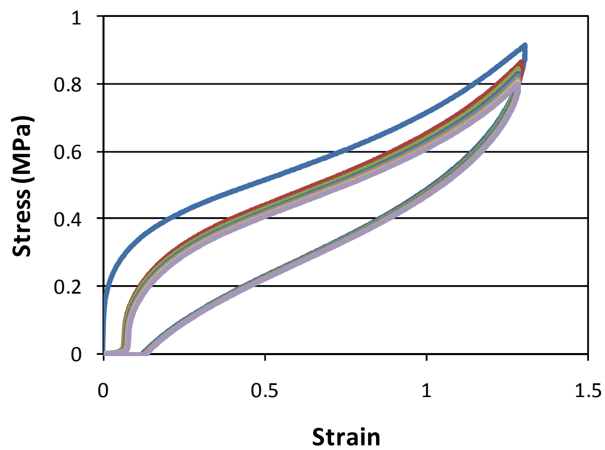

Figure 4 – BR60-5 Uniaxial Tension Data

Table 3.1 – Material Loss Factor

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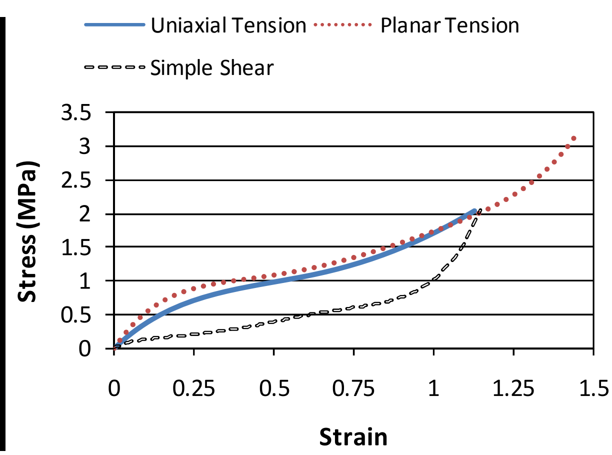

Figure 5 – NR60 Stress-Strain Curves

4. FINITE ELEMENT MODELING

4.1. Correlation of Material Data

Abaqus was used to model the HPCD. The steel components were modeled using a 250MPa (36 ksi) yield stress with kinematic strain hardening. Only NR60 and BR60 were used to analyze the device. The first step was inputting the nominal stress-strain data and choosing the appropriate hyperelastic model. The automatic material evaluation module allows selection of multiple models and outputs the data for visualization. Completion of the process also requires modeling the time dependent nature of HDR. The two available options are the finite strain viscoelasticity model and the Hysteresis model. In this case, the Hysteresis model provides better correlation with the data. Four constants were determined through a trial and error process for the Hysteresis model. The difficulty was that the material loss factor and dynamic stiffness are a function of the strain level and frequency. To overcome this problem, a set of constants were found that matched the variation in strain level at a specified frequency. For these analyses a frequency of 1 Hz was used.

The comparison between the experimental and analytical hysteresis loops for BR60 is shown in Figures 6 through 8. The analytical and experimental curves match reasonably well up to a displacement of 50% of the rubber thickness. Upon increasing the displacement to the thickness of the rubber, the correlation is significantly reduced. The static fit between the Arruda-Boyce model and the experimental data is shown in Figure 9. The analytical model provides a nearly linear fit to a nonlinear curve with a significant difference in the slope. The selection of the Arruda-Boyce model using only the uniaxial test data in combination with the Hysteresis model provided the best match for the experimental hysteresis loops. The fit for the NR60 material was done in the same fashion using the Arruda-Boyce model with both uniaxial and planar tension data in combination with the Hysteresis model. A different set of constants for the Hysteresis model was determined using the same process.

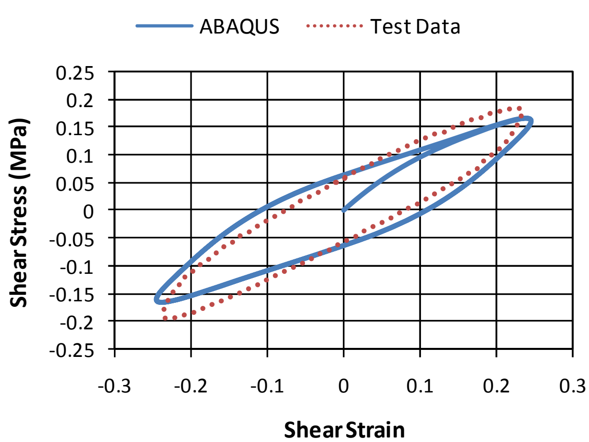

Figure 6 – BR60 Hysteresis Loops

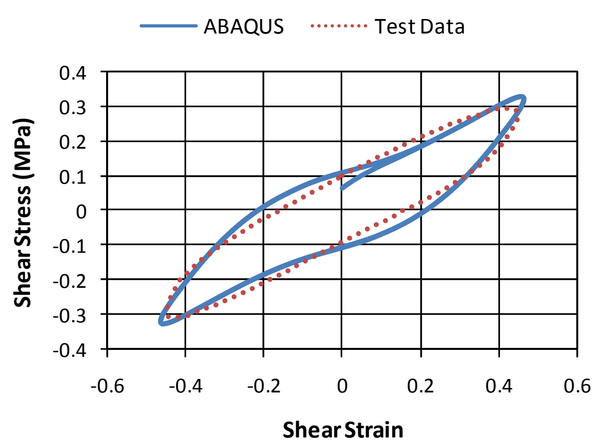

Figure 7 – BR60 Hysteresis Loops

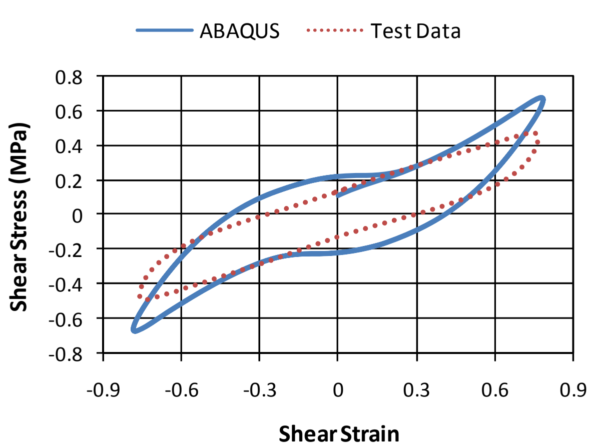

Figure 8 – BR60 Hysteresis Loops

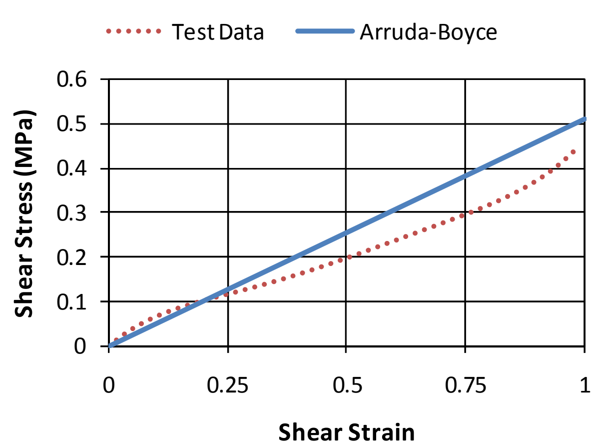

Figure 9 – BR60 Static Simple Shear

4.2. Hybrid Device Analysis

Using the material models developed in the previous section the hybrid device was analyzed in Abaqus. The locking of the damper was simulated using nonlinear elastic springs. A sinusoidal displacement pattern was run at several levels of displacement. The results show that for displacements below the lockout of the damper, the device performs as a viscoelastic solid device. The same yield force is used for both the BRBs. The difference in the stiffness and damping of the HDR compounds is apparent by the hysteresis loops prior to lockout and force at which the change in stiffness occurs. Once the damper locked out, an increase in stiffness occurrs followed by yielding of the BRB element. The hysteresis loops for the hybrid device are shown in Figures 10 and 11. The figures show the device performing as expected with a two phases of energy dissipation. The energy dissipation is as expected with the HDR dissipating energy at small displacements and the BRB dissipating significant amounts of energy.

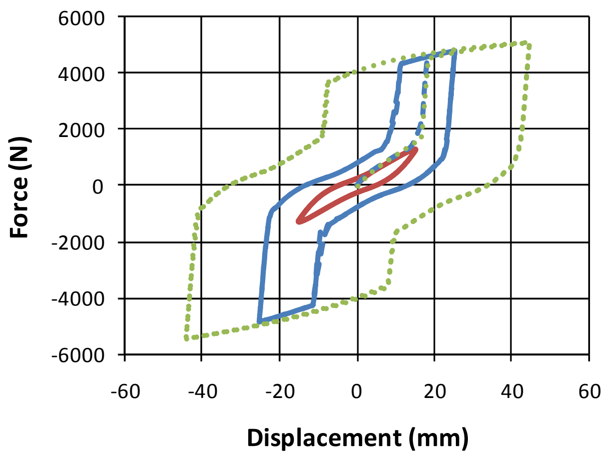

Figure 10 – Hybrid Device Hysteresis Loops (BR60)

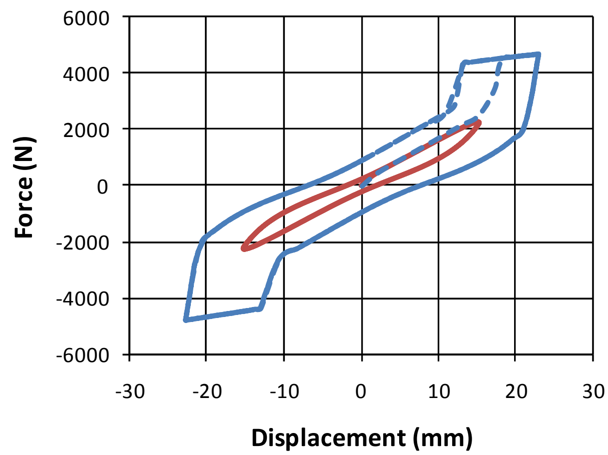

Figure 11 – Hybrid Device Hysteresis Loops (NR60)

5. CONCLUSION & RECOMMENDATIONS

A hybrid passive control device was developed to take advantage of the combined strengths of rate dependent and rate independent dampers. The device consists of an HDR sandwich damper in series with a BRB. The benefits of this device include energy dissipation at all levels of vibration with considerable capacity for significant seismic events. This capacity is present without the initial increased stiffness which is accompanied by increased seismic demand. The hyperelastic effect reduces the collapse probability through increased stiffness as the structure moves from center. The nonlinear FEA confirms the theorized behavior of the device.

Great potential is demonstrated for this device based on the initial analysis. Prior to implementation of such a device, further experimental testing and analysis is required to completely verify that the device performs as expected. The experimental testing should include component and full or scaled testing of an HPCD in a structural frame. Additionally, dynamic response history analysis of structures needs to be completed to verify reduced structural response. These studies need to determine the critical parameters for design, analysis and performance of structures with the HPCD. One particular area of concern is the lockout mechanism of the damper. The effect of the change of the stiffness on the structure needs to be investigated and methods to soften that transition need to be developed.

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