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IMPACT OF DYNAMIC MULTIAXIAL EXCITATION ON THE PERFORMANCE OF A HIGH DAMPING RUBBER BEARING

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Abstract

In an earthquake event, base isolators installed under a building are subjected to dynamic multiaxial excitation. The response of an isolated building or bridge can impose deformations in multiple degrees of freedom simultaneously. Despite this, prototype testing required by current design codes is typically performed under unidirectional dynamic excitation. Since an isolator's performance parameters are derived from unidirectional testing under constant axial load, it is usually unknown how an isolator will respond when subjected to simultaneous dynamic excitation in multiple degrees of freedom.

A high damping rubber (HDR) bearing was tested at the Caltrans Seismic Response Modification Device (SRMD) testing facility on the University of California, San Diego campus. The bearing was subjected to an extensive test protocol, which consisted of a variety of loading conditions to assess the bearing's properties in each degree of freedom, understand the impact of multiaxial excitation, high velocities, temperature, and axial loading. For the first time at a testing facility, a full scale HDR bearing was subjected to different combinations of dynamic excitation in all six degrees of freedom, representing different loading scenarios. This unique information is used to determine how rotation, torsion and axial loading affect the unidirectional and bidirectional response of the HDR bearing. This paper discusses the horizontal hysteretic force-shear strain response of the bearing subjected to a variety of possible loading conditions in addition to a unidirectional and bidirectional motion, including high overturning moments, torsion, uneven bearing installation or settlement, high velocities and bidirectional loading. A comparison of the bearing's hysteretic response and performance parameters is made between the bearing subjected to unidirectional or bidirectional loading with the addition of pitch, roll and yaw. The bearing's axial load and loading rate dependency will also be assesed.

Keywords: Seismic isolation; high damping rubber beading; full scale testing; multiaxial loading; experimental data

1. Introduction

Current design practices for base isolators require prototype testing to characterize the performance parameters chosen in design such as peak force, energy dissipation per cycle, and effective stiffness. To determine the performance characteristics of a bearing, prototype testing is a code requirement for bearings. A typical prototype test protocol for a bearing to quantify performance parameters consists of multiple fully reversed unidirectional cycles at various displacement amplitudes, including the calculated design displacement and maximum displacement [1]. Using data from prototype testing, parameters such as the energy dissipated per cycle, which can be used to approximate the equivalent viscous damping ratio of the isolation system through a method first proposed by Jacobsen [2], maximum isolator displacement, and peak forces are determined. While current code requirements for base isolated buildings only consider performance parameters derived from unidirectional testing, the bearing will experience motion in more than just a single degree of freedom during a seismic event. These loading conditions that may be encountered include low axial load, multiaxial horizontal movement, high velocities, bearing settlement or uneven installation, conditions that can generate a high overturning moment, and torsion.

A high damping rubber (HDR) bearing was tested at the Caltrans Seismic Response Modification Device (SRMD) testing facility located on the University of California, San Diego (UCSD) campus. The test protocol for this bearing was designed to investigate the effect that shear strain rate, axial load and multiaxial excitation have on the hysteretic response of a high damping rubber bearing. To do this, the bearing was tested at different shear strain rates, and in each degree of freedom individually as well as combined with each other. Using this information, it is possible to discern which scenarios would have the greatest impact on the test results obtained from unidirectional and bidirectional testing of this HDR bearing.

2. Experimental Program

2.1 Test Protocol

The SRMD testing facility is capable of exciting the bearing in all six degrees of freedom individually or simultaneously. Figure 1 shows the directions for each degree of freedom. The bearing was oriented such that the longitudinal shear corresponds with the H1 direction, the transverse shear corresponds to the H2 direction, compression is applied along the vertical axis, and roll, pitch and yaw are rotations about each of those axes, respectively. The testing protocol took advantage of the facility's capabilities by performing 33 tests, which were designed to obtain the bearing's response characteristics in each degree of freedom individually as well as combined with other degrees of freedom (Table 1). The test program was also designed to observe any velocity dependency and thermal effects. This paper will focus on those tests that determine how the bearing's performance in the longitudinal and transverse (H1 and H2) directions are affected by different loading conditions.

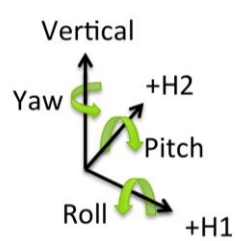
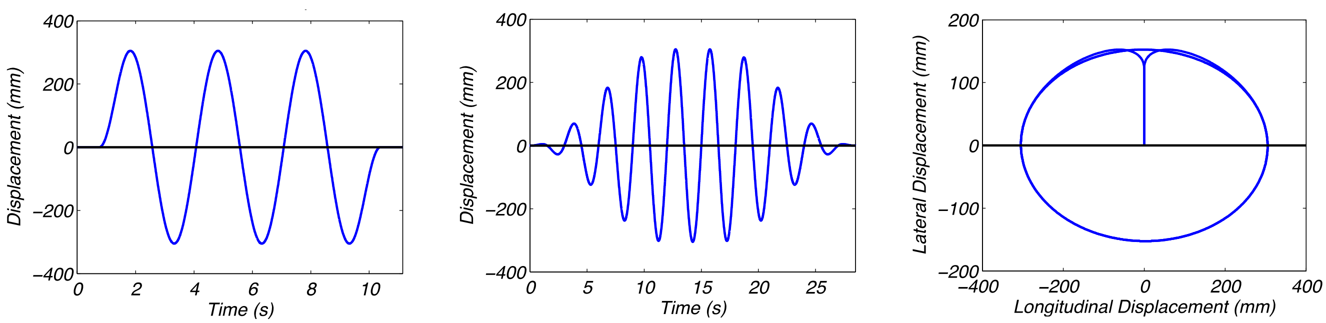


Figure 1 - Directions for each degree of freedom with arrow indicating positive rotation or displacement.

Depending on the test objective, different input waveforms were used as input load patterns for the bearings. The three waveforms discussed in this paper are a sine waveform with three complete cycles at a specified peak amplitude (Figure 2a), a variable amplitude sine waveform (var. sine) which had a total of 9.5 cycles (Figure 1b), 1.5 of which were at the specified peak amplitude, and an elliptic waveform (for bidirectional H1 and H2 testing) (Figure 2c). The ellipse is comprised of two displacement sine waveforms - in the longitudinal (H1) and lateral (H2) directions (displacement amplitude in the H2 direction is only half of that in the H1 direction).

The maximum input amplitudes in each degree of freedom were ±305 mm or 150% shear strain in the longitudinal (H1) direction; ±153 mm or 75% shear strain in the lateral (H2) direction; ±0.25º pitch and roll angle; and ±1.613º yaw angle, which corresponds to a 4.5% bearing torsional rotation. The maximum angles for the roll, pitch and yaw degrees of freedom were chosen to exceed expected values. Input for the vertical degree of freedom was in terms of force, which varied between a maximum of 2489 kN to a minimum of 778 kN in compression, corresponding to a maximum vertical pressure of 7.7 MPa and 2.4 MPa, respectively. These values were chosen based on realistic maximum and minimum vertical loads for the bearing's application. The three values of the input periods that were considered are 1.25 s, 2.0 s, and 3.0 s, which corresponded to peak shear strain rates of 313 %/s, 469 %/s, and 750 %/s, respectively, or peak velocities of 0.638 m/s, 0.957 m/s, and 1.53 m/s, respectively.



(a) sine waveform *(b) variable amplitude sine waveform (var. sine)* *(c) elliptic waveform*

Figure 2 - Input waveforms for a 3.0 s period

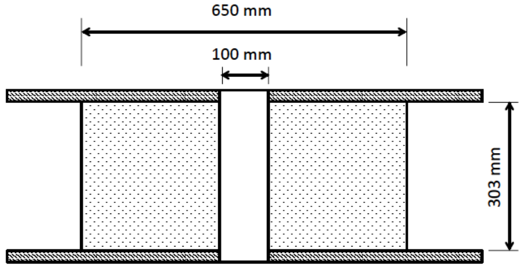
Table 1 - Test protocol

					Amplitude for Degree of Freedom					
Test no.	**Date**	**Degree(s) of Freedom**	**Wave Form**	**Period (s)**	**H1 (mm)**	**H2 (mm)**	**P (deg)**	**R (deg)**	**Y (deg)**	**C (kN)**
1	6/18/14	H1	sine	3	305					2489
2	6/18/14	H1	sine	30	305					2489
3	6/18/14	C	var. sine	3						778-2489
4	6/18/14	C	var. sine	2						778-2489
5	6/18/14	C	var. sine	1.25						778-2489
6	**6/18/14**	**H1**	**var. sine**	**3**	**305**					**2489**
7	**6/18/14**	**H1**	**var. sine**	**2**	**305**					**2489**
8	**6/19/14**	**H1**	**var. sine**	**1.25**	**305**					**2489**
9	**6/19/14**	**H1**	**var. sine**	**3**	**305**					**778**
10	6/19/14	Y	var. sine	3					1.613	2489
11	6/19/14	Y	var. sine	2					1.613	2489
12	6/19/14	Y	var. sine	1.25					1.613	2489
13	6/19/14	Y	var. sine	3					1.613	778
14	6/19/14	P	var. sine	3			0.25			2489
15	6/19/14	P	var. sine	2			0.25			2489
16	6/19/14	P	var. sine	1.25			0.25			2489
17	6/19/14	P	var. sine	3			0.25			778
18	**6/19/14**	**H1**	**sine**	**3**	**305**					**2489**
19	6/20/14	H1+P	var. sine	3	305		0.25			2489
20	**6/20/14**	**H1+P**	**var. sine**	**3**	**305**		**0.25**			**2489**
21	**6/20/14**	**H1+Y**	**var. sine**	**3**	**305**				**1.613**	**2489**
22	6/23/14	H1+C	seismic motion	-						778-2489
23	6/23/14	H1+C	seismic motion	-						778-2489
24	6/23/14	H1+H2	elliptic	30	305	153				2489
25	**6/23/14**	**H1+H2**	**elliptic**	**3**	**305**	**153**				**2489**
26	**6/23/14**	**H1+H2**	**elliptic**	**2**	**305**	**153**				**2489**
27	**6/24/14**	**H1+H2**	**elliptic**	**1.25**	**305**	**153**				**2489**
28	**6/24/14**	**H1+H2**	**elliptic**	**3**	**305**	**153**				**778**
29	**6/24/14**	**H1+H2+P+R**	**elliptic**	**3**	**305**	**153**	**0.25**	**-0.125**		**2489**
30	**6/24/14**	**H1+H2+P+R+Y**	**elliptic**	**3**	**305**	**153**	**0.25**	**-0.125**	**1.613**	**2489**
31	6/24/14	H1+H2+P+R+Y+C	elliptic	3	305	153	0.25	-0.125	1.613	778-2489
32	6/24/14	H1	sine	3	305					2489
33	6/24/14	H1	sine	3	610					2489

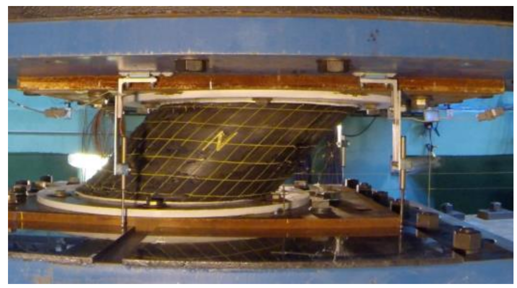
* Tests listed in **bold** will be discussed in this paper. H1: longitudinal, H2: lateral, P: pitch, R: roll, Y: yaw, C: compression.

2.2 Test Specimen

The test specimen is a 650 mm diameter high damping rubber bearing (Figure 3) with a 100 mm hollow core. The bearing height is 303 mm, which consists of 33-0.03 mm steel shims sandwiched between 34-0.06 mm high damping rubber layers, resulting in a total rubber height of 204 mm. The bearing was also incorporated in a full-scale five-story building unidirectional shake table test [3],[4]. For consistency, the bearing was tested with the same longitudinal axis for both component testing and shake table testing.



(a) General dimensions



(b) Photo during component testing

(c) Photo of bearing installed under building on shake table

Figure 3 - Test specimen - high damping rubber bearing.

3. Experimental Results and Discussion

In current design practice, a bearing's performance parameters are typically derived from unidirectional prototype testing. Since a bearing will experience multiaxial excitation during earthquake excitation, a comparison between the bearing's hysteretic force-shear strain responses is made for the bearing subjected to a variety of loading conditions. In the following sections, the effects of bidirectional (H1 and H2) loading, high velocities, axial pressure, torsion (yaw), and rotation (pitch/roll) will be discussed by comparing the response to these loading conditions to the bearing's response to unidirectional or bidirectional input motion.

3.1 Unidirectional vs. Bidirectional Loading

Figure 4 compares the longitudinal hysteretic response of the bearing subjected to unidirectional input motion (Test #18) to the bearing subjected to bidirectional motion (Test #25). Similar experimental comparisons have been made to prove the existence of coupling behavior between the horizontal directions [5]. These results are important for improving models that may consist of two uncoupled springs. For both tests, the bearing is displaced 305 mm or 150% shear strain in the longitudinal (H1) direction. However, for Test #25, the bearing is displaced in an elliptical motion, which consists of a shear strain of 75% in the lateral direction as well. Comparing the shape of the hysteretic response, it can be seen that the hardening effect is less pronounced in bidirectional loading so the peak forces are lower (203 kN for Test #18 vs. 233 kN for Test #25), resulting in an effective stiffness of about 88% of the effective stiffness of the unidirectional motion. Nevertheless, the energy dissipated per cycle from bidirectional motion is higher than that found from unidirectional motion, dissipating 30% more energy than with just unidirectional motion, calculated using the second cycle in both tests (and plotted at a small scale as an inset in Figure 4). This trend is also seen in other tests of HDR bearings [6],[7]. The opposite result is found for friction pendulum bearings [8], where bidirectional loading results in a reduction in frictional force compared to unidirectional loading, which is attributed to the increase in temperature and the effect of sliding diagonally.

Another difference between the longitudinal hysteretic response from Test #18 and #25 is the force at which the bearing experiences zero shear strain in the longitudinal direction; in other words, the point at which the curve crosses the Y-axis differs. The average Y-intercept for Test #18 is 38 kN, whereas the average for Test #25 is 55 kN, which corresponds to a 45% higher force at zero longitudinal shear strain in the bidirectional test compared to the unidirectional test. It is noted that the bearing reaches a peak velocity in the longitudinal direction at zero shear strain during Test #18, but not during Test #25 since the bearing is also being displaced in the lateral direction.

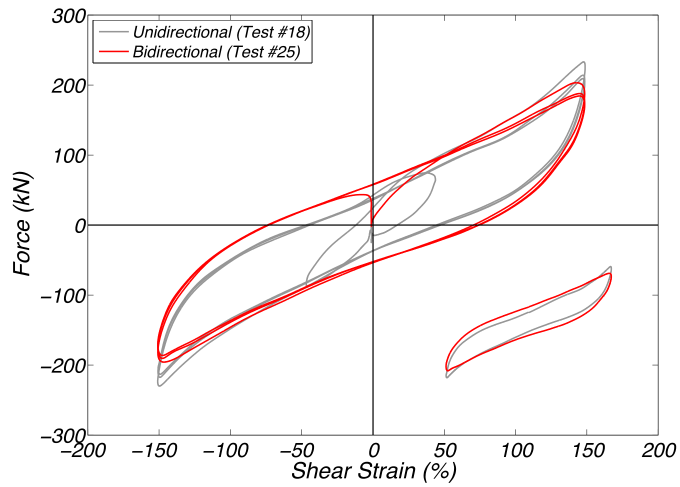


Figure 4 - Longitudinal hysteretic force-shear strain response.

3.2 Influence of Pitch, Roll and Yaw

This section describes the tests conducted to observe any interaction between longitudinal shear strain and pitch/roll as well as longitudinal shear strain and yaw for the bearing loaded unidirectionally and bidirectionally. The pitch, roll and yaw input rotations were applied with the same waveform as the longitudinal displacement (variable amplitude sine wave) such that the minimum and maximum rotations occurred at the minimum and maximum displacements. The longitudinal force vs. shear strain response is shown for a bearing loaded in the longitudinal direction only and in the longitudinal direction with the addition of pitch in Figure 5a. Similarly, Figure 5b compares the longitudinal force vs. shear strain response of the same test with longitudinal loading only with the response from a test that loaded the bearing in the longitudinal direction as well as with yaw.

The differences in the hysteretic response when the rotational components are added to the input are slight compared to the response of the bearing to only longitudinal movement, but some additional comparisons can be made. For the unidirectional tests, the addition of yaw and pitch decreased the peak force (and therefore the effective stiffness) slightly compared to Test #6 (peak force = 220 kN), with about a 5% reduction of peak force and effective stiffness for Test #20 and a 3% reduction for Test #21. When comparing a cycle at full amplitude (plotted at a small scale) from the test with longitudinal input only, the energy dissipated per loop is slightly less with the addition of yaw (about 4% less), however, slightly more energy is dissipated with the addition of pitch (about 5% more).

A similar comparison is made for the bidirectional motion. Figure 6a compares the longitudinal force vs. shear strain response of the bidirectional motion with pitch and roll to the response with bidirectional motion only. The peak force reached from the bidirectional motion only (Test #25 peak force = 203 kN) was slightly higher than the test with the addition of pitch and roll (Test #29 peak force = 191 kN). Likewise, the effective stiffness from Test #25 is about 6% higher that Test #29. Compared to the bidirectional motion only, the energy dissipated per loop reduced about 3% with the addition of pitch and roll. Figure 6b compares the bidirectional motion with pitch and roll (Test #29) to the response from the bidirectional motion with pitch, roll and yaw (Test #30). The addition of yaw had minimal influence on the bearing's response, with less than 2% lower peak force and less than 2% lower stiffness compared to Test #29. The energy dissipated per cycle is less than 1% lower in Test #30 than in Test #29, which is negligible.

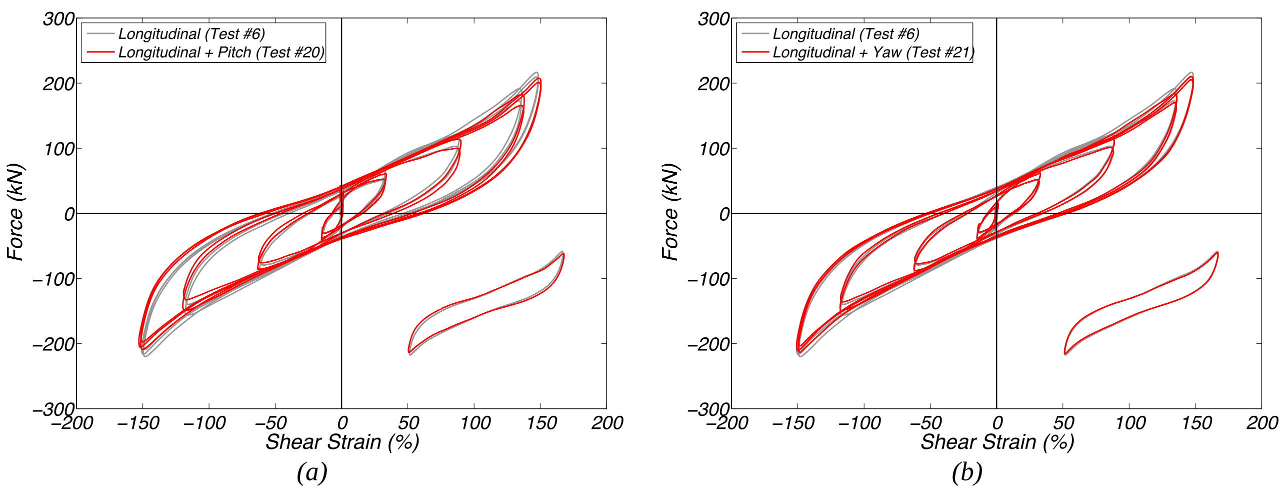


Figure 5 – Longitudinal force-shear strain hysteretic response

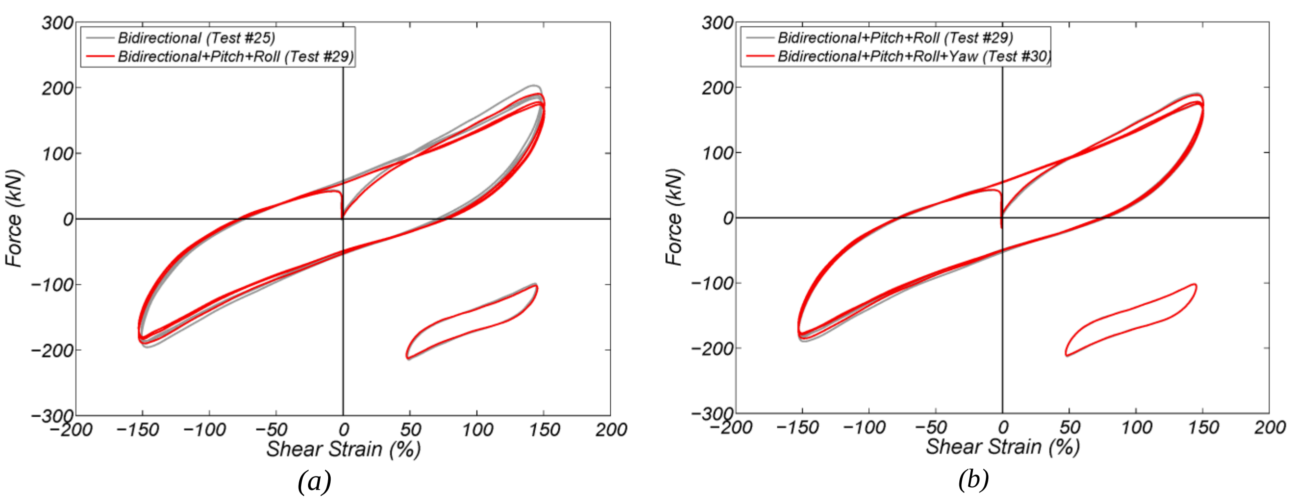
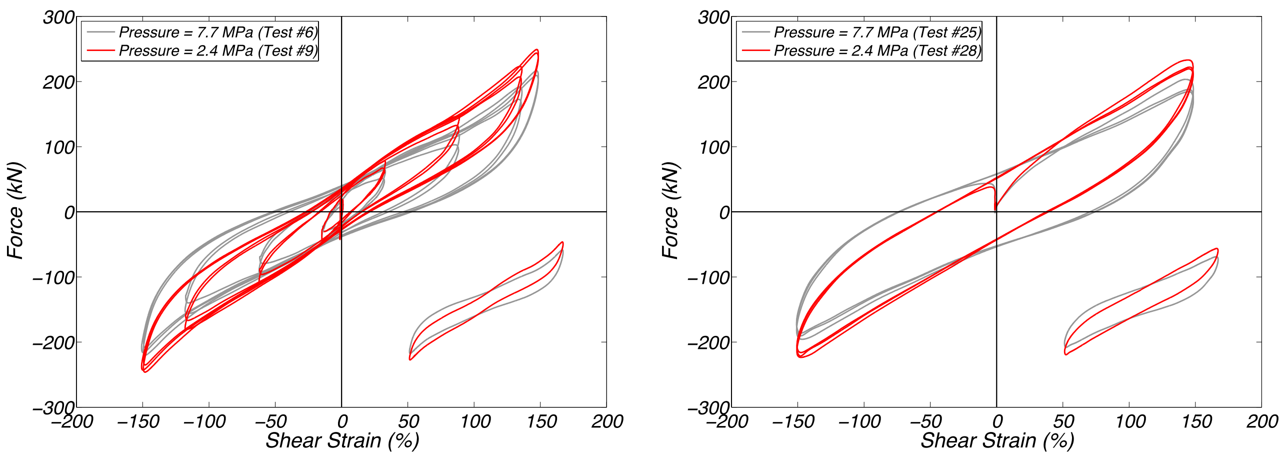


Figure 6- Bidirectional force – shear strain hysteretic response in longitudinal direction

3.3 Influence of Axial Load

The effect of the vertical load on the bearing's longitudinal hysteretic force-shear strain response was also investigated in this test protocol. The bearing was tested with a constant compressive axial load for most of the tests. The maximum axial load, used for all tests but tests #9, #13, #17 and #28, was 2489 kN, corresponding to an axial pressure of 7.7 MPa. In tests #9, #13, #17 and #28 the minimum constant axial load applied to the bearing was 778 kN, which corresponds to an axial pressure of 2.4 MPa. To determine the effect that the two different constant axial pressures have on the bearing's hysteretic response, a test was repeated with identical loading parameters except for the axial load. These tests were performed with unidirectional loading as well as bidirectional loading (Figure 7a and Figure 7b, respectively). The impact of a lower axial pressure appears to have the same effect on both the unidirectional and bidirectional tests. Compared to the response with the maximum axial pressure, the hysteretic response with the minimum axial pressure has a higher stiffness (about 13% higher), with a higher peak longitudinal force for 150% shear strain. For the unidirectional tests, Test #6 reaches a peak force of 220 kN, only 88% of the 249 kN experienced during Test #9. Similarly, Test #25 reaches a peak of 203 kN, which is 87% of the peak reached in Test #28 (233 kN). From the extracted loop for both sets of tests, it was found that 20% more energy was dissipated by the bearing loaded unidirectionally with the maximum pressure than the minimum pressure; likewise, 30% more energy is dissipated in the bidirectional test with the maximum pressure than with the minimum pressure. This result is similar to that found from HDR bearing testing [6],[7] but differs from the results from lead rubber bearing testing, which did not exhibit significant axial load dependency [9].



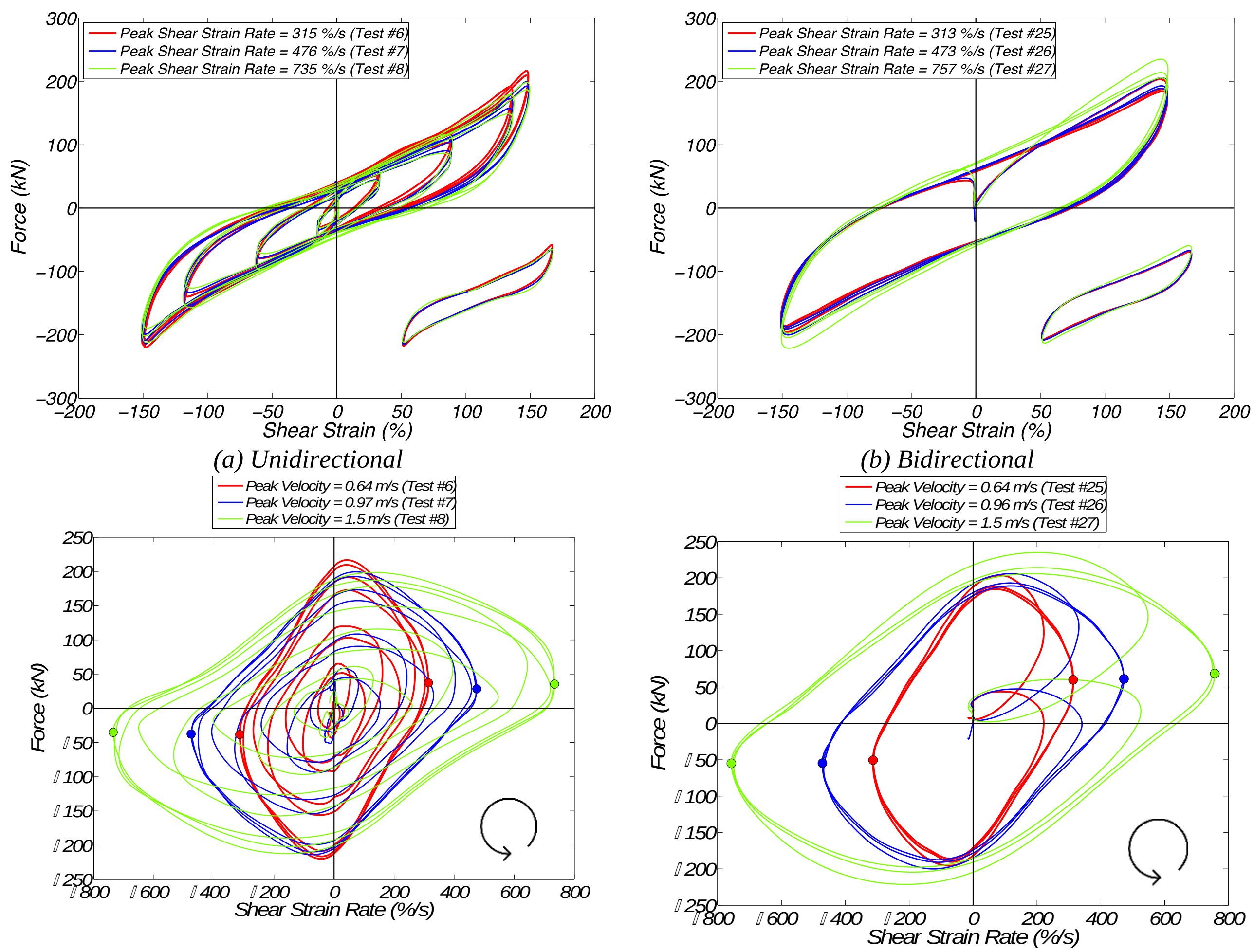
(a) Unidirectional loading *(b) Bidirectional loading*

Figure 7 – Longitudinal force-shear strain hysteretic response

3.4 Velocity / Shear Strain Rate Dependence

The velocity/shear strain rate dependency of the HDR bearing tested is discussed in this section. The HDR bearing was tested at different velocities in order to determine if any velocity/shear strain rate dependency exists. The longitudinal force-shear strain hysteretic loops in Figure 8a for unidirectional motion (Tests #6-8) and Figure 8b for bidirectional motion (Tests #25-27) both show the response from three tests, in which the only difference between the tests is the period of the displacement input motion (3 s, 2 s and 1.25 s were investigated). The different input motions correspond to a peak velocity of about 0.64 m/s for Tests #6 and #25; 0.97 m/s for Tests #7 and #26; and 1.5 m/s for Tests #8 and #27. As indicated in the legends, the peak shear strain rate for the different input velocities were 315 %/s, 476 %/s and 735 %/s for Test #6, #7 and #8, respectively; and 313 %/s, 473 %/s and 757 %/s for Test #25, #26 and #27, respectively. The second loop is extracted and also plotted with the figures, from which the energy dissipated per loop is calculated. From this loop, it is determined that the shear strain rate does not greatly affect the energy dissipated per cycle, with less than 10% variation from the mean for the three tests investigated with unidirectional motion (6%) as well as bidirectional motion (8%). This result differs from results found for other types of bearings such as lead-rubber bearings and friction pendulum bearings, in which the response was found to be velocity dependent [8],[9]. However, it is consistent with the results from small-scale HDR bearings reported by others [6].

As mentioned in a previous section, the plot of the unidirectional test intersects the Y-axis at the peak velocities, or shear strain rates, while this is not true for the bidirectional tests. Since the shear strain rate is the parameter under investigation, Figure 8c and Figure 8d plot the force vs. shear strain rate for the same three unidirectional and three bidirectional tests, with a counter clockwise arrow indicating the direction of motion. The peak positive and negative shear strain rate is indicated with a circle color-coordinated to the test. The forces corresponding to the peak shear strain rates for Tests #25, #26 and #27 are fairly constant; the minimum and maximum peaks are within 5% and 9% of the mean, respectively, with a trend of slightly increasing forces with higher magnitude peak shear strain rates. Likewise, the forces at peak shear strain rates for Tests #6, #7 and #8 were found to be within 5% of the mean for the minimum peaks and within 16% of the mean for the maximum peaks. Although the forces at peak shear strain rates for both sets of tests are somewhat constant, it is noted that for lower shear strain rates, the bearing experiences higher forces for the tests performed at higher velocities, indicating an acceleration dependency and implying that the bearing has a memory of where it has been. Overall, the forces at peak shear strain rates for the bidirectional tests (average = 58 kN) are higher than those for the unidirectional tests (average = 35 kN), as expected from previous results.



(a) Unidirectional (b) Bidirectional

(c) Unidirectional (d) Bidirectional

Figure 8 – Hysteretic force-shear strain and force-shear strain rate response.

4. Conclusions

The impacts that various scenarios that may be encountered during a seismic event will have on an HDR bearing's performance was analyzed through a comprehensive test protocol at the University of California, San Diego's SRMD laboratory. While results from a single bearing cannot be considered conclusive, from the tests investigated in this study, it was observed that the axial compression has the most significant impact on the performance, and therefore performance parameters, of the bearing in the longitudinal direction. In other words, high velocities, torsion, and rotation did not alter the hysteretic force-shear strain performance of the bearing as significantly as the change in axial compression. Overall, the energy dissipated per cycle was not drastically different between the unidirectional and bidirectional tests, where the velocity was altered or the rotations were added. The largest difference between the energy dissipated per cycle from the tests compared was around 20% for the unidirectional tests and around 30% for the bidirectional tests, both achieved by changing the axial compression onto the bearing. While the HDR bearing investigated was not very sensitive to different velocities or shear strain rates in terms of energy dissipated per cycle or stiffness, from the force-shear strain rate plots, it was evident that the bearing had an acceleration dependency. While this paper discussed results from only a select number of tests which included movement in up to three degrees of freedom, the combined effect of four, five, and six degrees of freedom should also be investigated for a complete study on multiaxial excitation of this bearing. Additionally, individual degrees of freedom should be investigated in order to assess the bearing's stiffness in each degree of freedom. These subjects and the remaining tests from this testing protocol will be discussed in an upcoming paper.

5. Acknowledgements

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6. References

[1] ASCE/SEI. [2010] "Minimum design loads for buildings and other structures*", SEI/ASCE 7-10,* American Society of Civil Engineers, Reston, VA.

[2] Jacobsen, LS. [1930] "Steady forced vibrations as influenced by damping". *Trans. ASME*; **52**(15): 169-181.

[3] Chen, M., Pantoli, E., Astroza, R., Ebrahimian, H., Mintz, S., Wang, X., Hutchinson, T., Conte, J., Restrepo, J., Meacham, B., Kim, J., Park, H. [2013], "BNCS report #1: full-scale structural and nonstructural building system performance during earthquakes and post-earthquake fire - specimen design, construction and test protocol," *Structural Systems Research Project Report Series, SSRP 13/9*. University of California San Diego, La Jolla, CA.

[4] Chen M., Pantoli, E., Wang, X., Astroza, R., Ebrahimian, H., Hutchinson, T., Conte, J., Restrepo, J., Marin, C., Walsh, K., Bachman, R., Hoehler, M., Englekirk, R., Faghihi, M. [2016], "Full-scale structural and nonstructural building system performance during earthquakes: part I – specimen description, test protocol and structural response." *Earthquake Spectra*.

[5] Huang, W., Fenves, G., Whittaker, A., Mahin, S. [2000] "Characterization of seismic isolation bearings for bridges from bidirectional testing." *Proc, of the 12th World Conference on Earthquake Engineering,* Auckland, New Zealand.

[6] Abe, M., Yoshida, J., and Fujino, Y. [2004a]. "Multiaxial Behaviors of Laminated Rubber Bearings and Their Modeling. I: Experimental Study." *J. Struct. Eng.*, 130(8), 1119–1132.

[7] Abe, M., Yoshida, J., and Fujino, Y. [2004b]. "Multiaxial Behaviors of Laminated Rubber Bearings and Their Modeling. II: Modeling." *J. Struct. Eng.*, 130(8), 1133–1144.

[8] Lomiento, G., Bonessio, N., Benzoni, G. [2012] "Effects of loading characteristics on the performance of sliding isolation devices," *Proc, of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

[9] Benzoni, G. and Casarotti, C. [2009] "Effects of vertical load, strain rate and cycling on the response of lead-rubber seismic isolators," *Journal of Earthquake Engineering* **13**(3), 293-312.