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EXPERIMENTAL STUDY OF BI-DIRECTIONAL SPRING UNIT IN ISOLATED FLOOR SYSTEMS

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ABSTRACT

In the US, isolated floor systems are gaining interest in various applications to protect nonstructural components that can be moved and located anywhere on the floor or specific rooms – instead of isolating single equipment or the entire building. To investigate the mechanical behavior of bi-directional spring units used as isolators in a kind of such isolated floor systems, three types of characterization tests were conducted - from spring components alone to the complete spring unit in its implemented configuration. The test results show that the behavior of the springs and spring units is stable when subjected to cyclic repeated motions, and is not sensitive to the velocity of motion. The hysteretic behavior of the spring units was found to be unconventional, with bilinear and different ascending (loading) and descending (unloading) branches. All these results provide the foundation to develop a physical model for engineers to better understand the behavior of such kind of bi-directional spring units and the corresponding isolated floor system.

Introduction

Extensive research has been conducted in the past decades to develop and implement technologies (such as lead-elastomer bearings and friction pendulum bearings) for the seismic base isolation of buildings (e.g., Naeim and Kelly 1999, Fenz and Constantinou 2008, to name a few). In recent years, there has been a growing interest in isolating only the specific equipment or specific floors of buildings. Isolating equipment rather than entire buildings can be challenging to some types of isolation devices due to the relatively low mass supported by the isolators. Various systems have been developed to isolate equipment, such as ball-in-cone isolators (Kemeny and Szidarovszky 1995, Kasalanati et al. 1997, to name a few) and another system studied by Fathali and Filiatrault (2007). These isolation systems generally focused on the response of the equipment isolated.

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Floor isolation systems have been implemented in Japan for over 15 years. Complex mechanisms are used (Arima et al., 1997) to provide three-dimensional isolation by using gravity based systems (suspension mechanisms) or linear spring based systems (coil springs or rubber units used for restoration force), with viscous dampers or lead plugs used for damping. Kaneko et al. (1995) report that a floor isolated system in Kansai area worked effectively during the 1995 Hyogoken-Nanbu Earthquake.

In the US, isolated floor systems are gaining interest in various applications to protect nonstructural components that can be moved and located anywhere on the floor or specific rooms – instead of isolating single equipment or the entire building. One such type of system uses a special kind of bi-directional spring units to provide stiffness, damping and self-centering capabilities to the isolated floor. This system is a physical substitute of a raised floor (or a computer access floor) and is designed to protect the contents in computer data centers with minimal intrusion of retrofit. To investigate the force-displacement behavior of these unique bi-directional spring units, characterization tests were conducted on the springs alone as well as on the overall spring units. This paper focuses on these characterization tests.

Description of Bi-directional Spring Unit

An image of the bi-directional spring unit and a conceptual sketch of its application in isolated floor system are shown in Figs. 1a and 1b. The isolated floor is supported on casters (rollers), which provide the vertical load transfer with unimpeded horizontal movement in any direction. A steel cable connects the isolated floor and the bi-directional spring unit, which is mounted on (or attached to) the non-isolated ground/floor. Owing to the placement of the spring under the isolated floor, any horizontal movement of the isolated floor results in vertical pull of the cable, which causes extension in the spring. The extension of the spring provides the restoring force for the isolated floor. Fig. 2 compares the input motion applied on the shake table (representative of what the contents of a non-isolated floor would experience) with the motion of the isolated floor. As seen here, the isolated floor reduces the accelerations by 50% to 75%, demonstrating effective behavior of the system. [For more details on this, see Cui & Bruneau (2009).]

The steel cable that connects the isolated floor and the spring passes through a bushing. The main purpose of this bushing is to provide smooth curvature from a horizontal spring to the vertical contact with the isolated floor. The bushing is capable of accommodating 180° rotation of the cable in vertical plane and 360° rotation in horizontal plane. The surface of this bushing is the revolution of a semi-circle around an external axis parallel to the diameter as shown in Fig. 1c. The sliding of the cable on the bushing results in significant damping, which is discussed in detail in the later sections. Another bushing at the underside of the isolated floor accommodates rotations up to 90° vertically and 360° horizontally, thus allowing the isolated floor to move horizontally without bending the cable at connection point. Note that there is no sliding between this bushing and the steel cable (due to the fixed vertical connection point). The surface of this bushing is a revolution of a quarter-circle around an external axis as shown in Fig. 1d. Looking from above, the bushing surface looks like the inside surface of the flare of a "trumpet". The bushing in the spring unit (where sliding occurs) is made of brass, and the one on the isolated floor (where no sliding occurs) is made of steel.

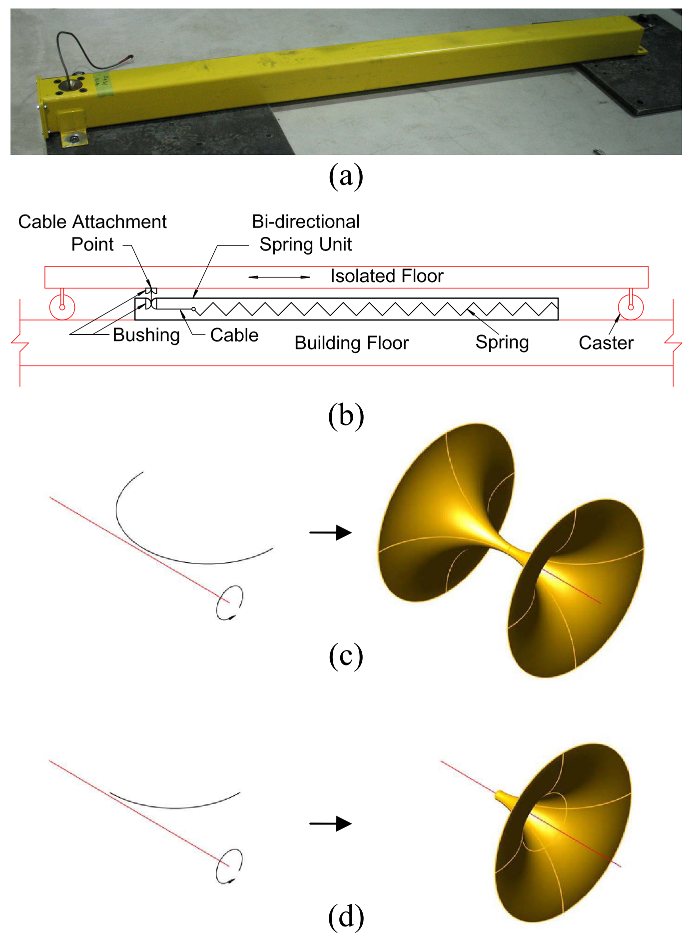

Figure 1. Bi-directional spring unit: (a) overview; (b) application in isolated floor system; (c) revolution of semi-circle, and; (d) revolution of quarter-circle.

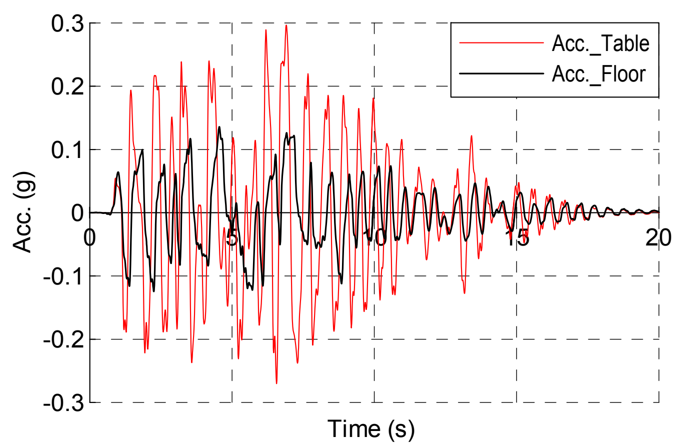

Figure 2. Performance of the isolated floor system: comparison of shake table accelerations (input) and accelerations on top of the isolated floor.

Characterization Tests

Specimen Setup and Instrumentation

Three types of tests were conducted to determine the force-displacement relationship of the spring unit as a complete component, as well as that of its internal individual spring, namely:

- Test Series 1: axial tests of individual springs left within the tube, without threading the cable through the bushing of the spring unit, to investigate the behavior of the spring alone;
- Test Series 2: axial tests of individual springs taken out of the tube but resting on a steel channel at the same height level corresponding to the bottom surface of the tube in Test Series 1, to capture the behavior of the spring alone and compare results with those from Test Series 1, in an attempt to quantify friction between the spring and the tube. Under this new setup, the spring could be openly seen, unlike the Test Series 1 tests where the spring was hidden by the tube;
- Test Series 3: tests of complete spring unit assembly, in same configuration as implemented in the corresponding isolated floor system.

Results from Test Series 1 and 2 showed that the spring, sagging downward due to its self-weight, was always in contact with the bottom of the tube during its motion. This friction results in a small hysteresis as described in the Results section. Note that for Test Series 1 and 2, the spring, load cell and actuator were aligned on the same axis.

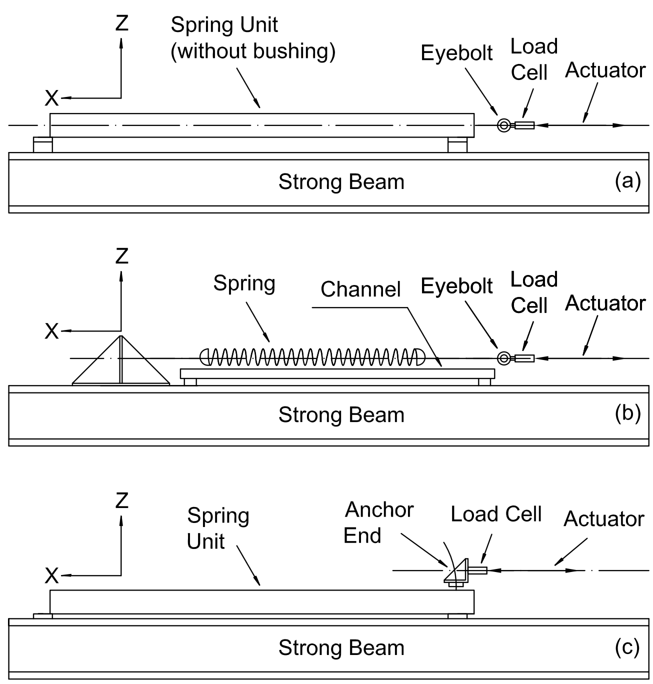

Figure 3. Specimen configurations: (a) test Series 1; (b) test Series 2, and; (c) test Series 3.

The specimen setup for Test Series 1 to 3 is shown in Fig. 3. Note that for Test Series 3, to simulate the working conditions of the spring units as they are installed in the complete isolated floor system, an anchor end was manufactured to hold the spring cable. A bushing was welded to the bottom plate of the anchor end to simulate the bushing on the isolated floor shown in Fig. 1b. In the specimen setup for this series of tests shown in Fig. 3c, note that the central lines of the load cell and the actuator shaft were different from that of the spring unit by a distance of 20 mm (0.783 in) to simulate the working condition of the spring unit in complete isolated floor system.

Input Program

To check whether the behavior of the individual spring and spring unit is sensitive to cyclic repeated motions and velocity, sinusoidal displacement input of ten cycles with different frequencies were used during these characterization tests. Sinusoidal displacement signals of amplitude of 254 mm and 203 mm at a frequency of 0.05 Hz and 0.2 Hz, respectively, were used. For those amplitudes of the sinusoidal signals, the velocity at each point of the 0.2 Hz sine wave was 3.2 times that of the corresponding 0.05 Hz wave.

Some seismic floor displacement inputs were also adopted as inputs to test the bi-directional spring units. These are relative displacement histories between the isolated floor and the base floor recorded during the tests of an isolated floor system using this kind of bi-directional spring units. They are called 2Acc31wo, 3Acc31wo, B107050, and B207050, and are considered to reflect a representative range of floor response histories, as shown in Fig. 4.

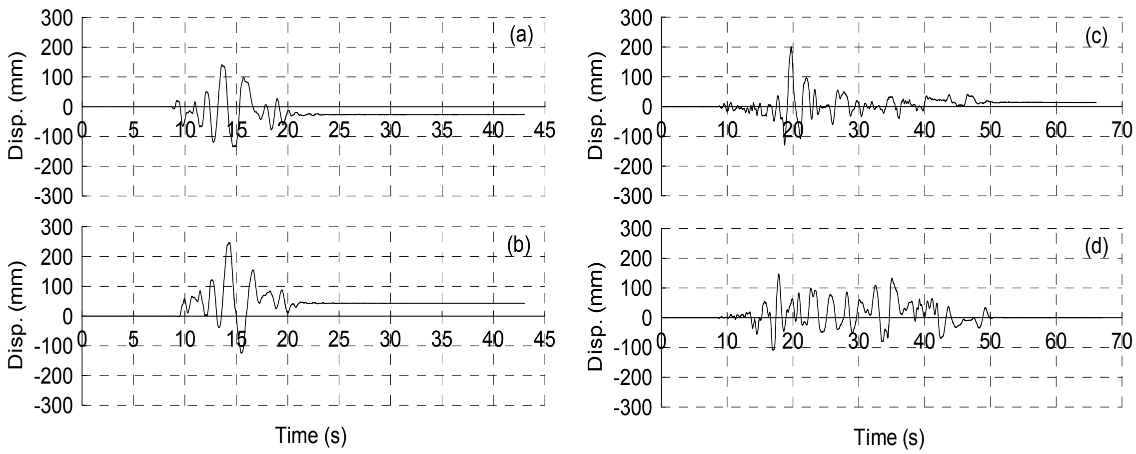

Figure 4. Seismic displacement histories: (a) 2Acc31wo; (b) 3Acc31wo; (c) B107050, and; (d) B207050.

Half-sinusoidal input was used for Test Series 1 and 2 because the spring is tested alone in these and can only be pulled. For the same reasons, the seismic floor displacement histories were not used for these two test series. For Test Series 3, the complete "pull" and "push" parts of the sinusoidal signals and the seismic displacement records were used.

Test Protocol

Bi-directional spring units can be built with internal springs having different stiffnesses to meet the design needs of the isolated floor systems. Springs with two different nominal stiffnesses were considered as part of the current test program. Also, to investigate consistency between nominal (specified) and actual stiffness within a group, *two* springs with nominal stiffness of 2627 N/m (15 lb/in), and *two* springs with nominal stiffness of 1313 N/m (7.5 lb/in) were tested. A total of 36 tests were conducted on the spring units for the three series of tests. The names of tests were chosen per the following nomenclature:

- Names for sinusoidal inputs consist of *five* parts from left to right: 1) Signal frequency (0.05 Hz is expressed as "05", and 0.2 Hz as "2"), 2) Pretension, noted as null ("0") or 51 mm (2 inches expressed as "2"), 3) Nominal spring stiffness (15 lb/in is expressed as "15" and 7.5 lb/in as "07"), 4) Presence of the tube, noted as with ("w") or without ("wo"), and 5) Presence of the bushing noted as with ("w") or without ("wo").

  For example, "05150wowo" means test for a 0.05 Hz sinusoidal input signal, for a spring of 2627 N/m (15 lb/in) nominal stiffness spring, without pretension, and without tube and bushing on (i.e. Test Series 2). For Test Series 1 and 2, only one spring of each nominal stiffness was tested. For Test Series 3, two springs of each nominal stiffness were assembled and tested sequentially to check the repeatability of the behavior of the spring units. In Test Series 3, there is an extra "2" at the end of the names of the tests to denote that the second spring of same nominal stiffness was used.
- Names of tests using seismic floor displacement record inputs are constructed using seismic displacement record input name, followed by the same conversion indicated above for the nominal spring stiffness, the pretension condition (null or 51 mm), and whether the tests was conducted with or without tube, and with or without bushing.

Results of Test Series 1 and 2

Figs. 5 and 6 show the results of the spring tests without pretension and with 51 mm (2 in) pretension when subjected to different frequency sinusoidal motions, respectively. Note that parts (a) and (b) in each of these figures are not in the same vertical axes scale. As shown in these figures, the behavior of the individual spring is stable under cyclic repeated motions. Also, note that the force-displacement loops corresponding to different frequency sinusoidal motions agree well with each other, demonstrating that the behavior of the springs is not sensitive to motion frequency/velocity. In addition, note that the results from Test Series 1 (spring in the tube, no bushing) and those from Test Series 2 (spring on steel channel, no bushing) overlay perfectly on top of each other, confirming that the configurations of Test Series 1 and 2 are actually identical.

From Fig. 5a, note that for the 2627 N/m (15 lb/in) nominal stiffness spring without any pretension, the behavior is bilinear with a small offset at the beginning, or trilinear if a small linear segment is used to model the offset. The first phase of behavior is relatively soft when the displacement is less than about 6 mm (0.25 in), then much stiffer until a displacement of about 51 mm (2 in), after which elongation proceeds per a lower linear stiffness of about 2428 N/m (13.9 lb/in). Note that the springs are designated with this secondary stiffness (specified values of 15 lb/in and tested value of 13.9 lb/in in this case). From Fig. 5b, it is found for the 1313 N/m (7.5 lb/in) nominal stiffness spring without any pretension that the behavior is bilinear. After a displacement of about 10 mm (0.4 in), the spring starts to elongate with a linear stiffness of about 1525 N/m (8.7 lb/in). When the springs were pre-tensioned by 51 mm (2 in) before starting the tests, as shown in Fig. 6, the curves plotted starting from zero displacement were linear. These pre-tensioned curves corresponded to the data that would be read from the curves shown in Fig. 5 if starting to read the curves from a point that is 51 mm (2 in) right of the ordinate axis. Fig. 5 and Fig. 6 also show that each of the force-displacement curves obtained for the spring components exhibit some small hysteresis around the mean force line. This hysteresis is likely attributed to the friction between the spring and the tube in Test Series 1 and between the spring and the steel channel in Test Series 2, the value of which is around 18 N (4 lb).

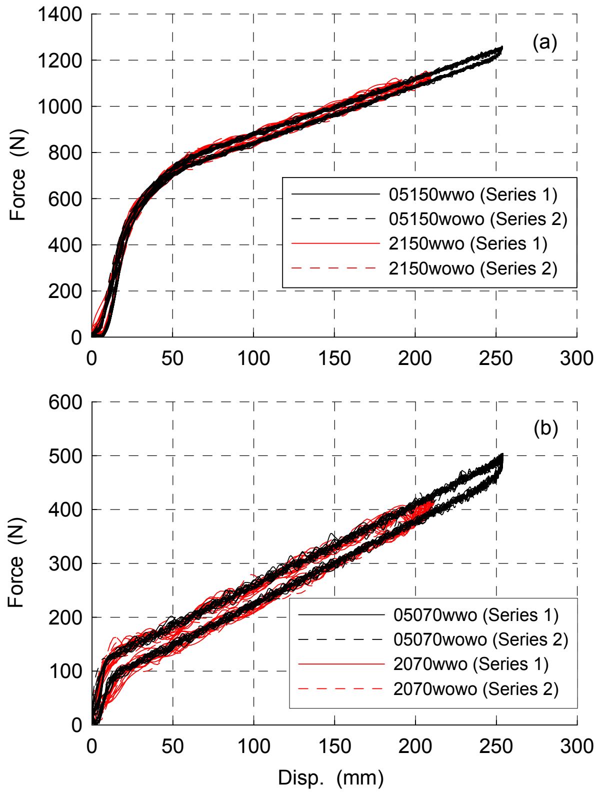

Figure 5. Results of Test Series 1 and 2 – spring tests without pretension: (a) 2627 N/m spring, and; (b) 1313 N/m spring.

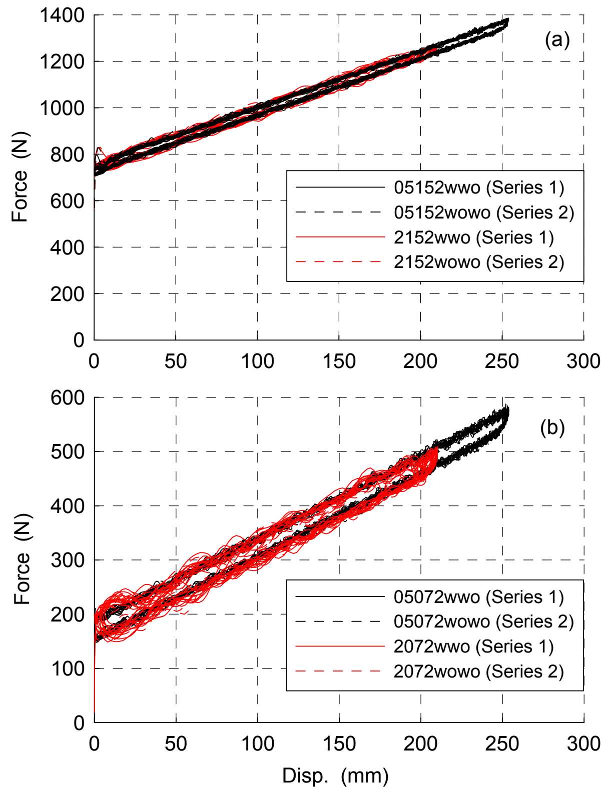

Figure 6. Results of Test Series 1 and 2– spring tests with 51 mm pretension: (a) 2627 N/m spring, and; (b) 1313 N/m spring.

Results of Test Series 3

Complete spring units were tested without and with pretension, for sinusoidal motions and earthquake displacement records. Fig. 7 shows the results of complete spring unit tests without any pretension. The results of tests with 51 mm (2 in) pretension are illustrated in Fig. 8. Note that parts (a) and (b) in each of these figures are not in the same vertical axes scale. From these figures, note that the force-displacement loops, when subjected to cyclic sinusoidal motions, agree well with each other from test to test and that the behavior of the spring unit is stable under cyclic repeated motion. Further, the behavior of the spring units is also stable with respect to the frequencies/velocities of motions. Fig. 8 also demonstrates that the behavior of the spring unit subjected to seismic displacement records coincide well with the corresponding ones subjected to sinusoidal signals, which again confirms that the hysteretic behavior of the spring units is stable and not sensitive to displacement history. Figs. 7 and 8 also show consistency in the force-displacement loops for both spring units with same nominal stiffness. However, the shape of the hysteretic loop itself is unconventional. The lateral force (F)-lateral displacement (D) curve goes up bilinearly when loading, drops vertically on load reversal, and goes down a different bilinear path when unloading. The F-D curve transitions to a linear stiffness for the loading and unloading branches at a displacement of 76 mm (3 in) for the system with 2627 N/m (15 lb/in) spring and 30 mm (1.2 in) for the system with 1313 N/m (7.5 lb/in) spring. However, the unloading slopes are different from the loading slopes.

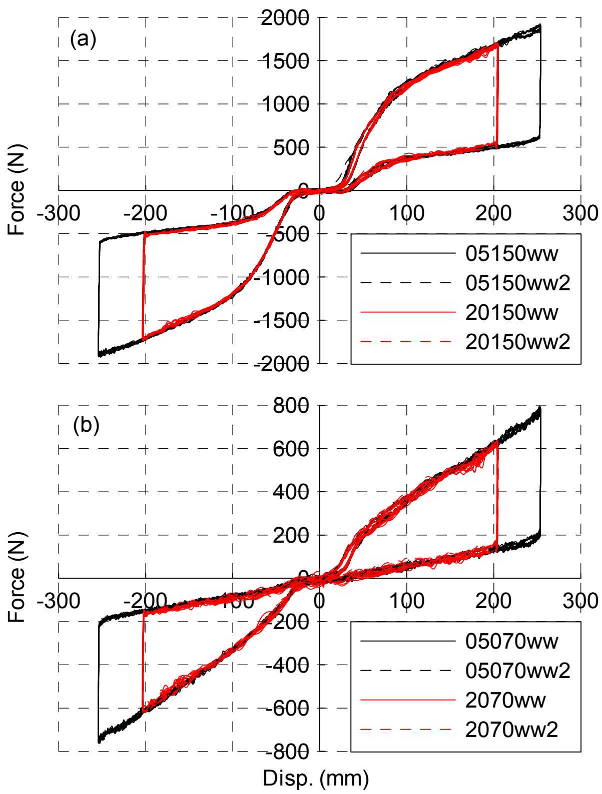

Figure 7. Results of Test Series 3 – spring unit tests without pretension: (a)2627 N/m spring unit, and; (b) 1313 N/m spring unit.

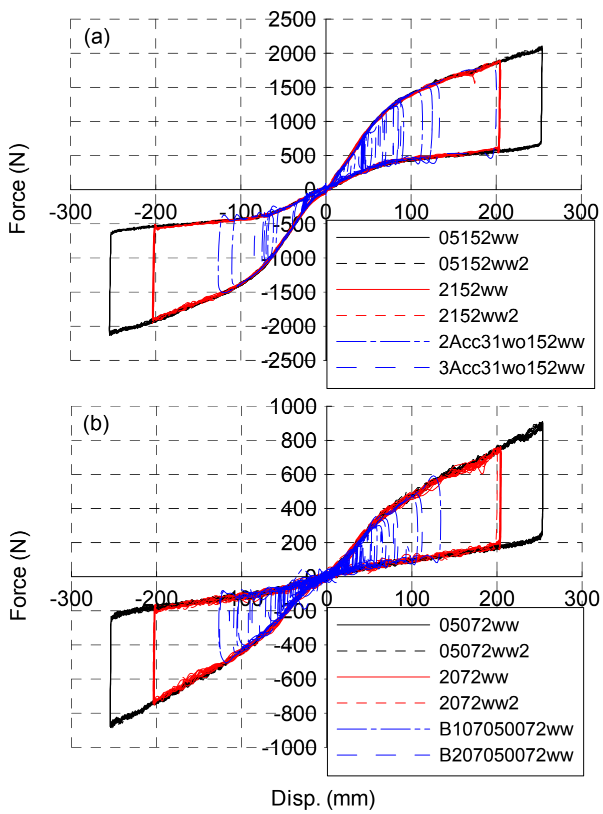

Figure 8. Results of Test Series 3 – spring unit tests with 51 mm pretension: (a) 2627 N/m spring unit, and; (b) 1313 N/m spring unit.

Conclusions

To investigate the behavior of the individual springs and the complete bi-directional spring units used as isolators in a kind of isolated floor system, three series of characterization tests were conducted: from single springs to complete spring units. The test results show that the behavior of the springs and the spring units is stable when subjected to cyclic repeated motions, and is not sensitive to motion velocity. The hysteretic behavior of the spring units was found to be unconventional with bilinear and different ascending (loading) and descending (unloading) branches. These results build the foundation to develop a physical model for engineers to better understand the behavior of such kind of bi-directional spring units and the corresponding isolated floor systems.

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