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Advances in elastomeric isolators

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ABSTRACT: Seismic hazards remained as a challenge to engineers over ages. In order to reduce loss of life and damage to property due to earthquake, several techniques have been developed among which Seismic Isolation technique using Elastomeric Isolators has gained high acceptance and becoming popular all over the world, due to its simplicity, reliability and overall cost effectiveness. Seismic Isolation with Elastomeric Isolators is done using Lead Rubber Bearing (LRB) or High Damping Rubber Bearing (HDRB). International specification and guidelines have been published which provide thorough overview on the subject and define stringent acceptance standard for the devices through extensive test requirement. This technical paper discusses performance evaluation of the Elastomeric isolators, based on tests carried out both on rubber compound and full scale devices as well as relevance of the tests to simulate and evaluate actual performance of Elastomeric Isolators and estimation of durability and life of the devices.

1 INTRODUCTION

Seismic hazards remained as a challenge to engineers over ages. Even in the modern age of engineering, loss of life and damage to property due to earthquake remains frequent and significant. The very recent Nepal earthquake killed more than 8,800 people and injured more than 23,000. At a general estimate, since 1900, there have been an average of 18 major earthquakes (magnitude 7.0–7.9) and one great earthquake (magnitude 8.0 or greater) per year. A large part of human population live in high seismic zones.

Seismic Base Isolation system, although, a relatively recent technology and in application only since mid-80’s, is one of the most popular and powerful means of earthquake engineering pertaining to the passive structural vibration control technologies. It is meant to enable a building or non-building structure to survive a potentially devastating seismic impact through a proper initial design or subsequent modifications. Seismic isolation differs fundamentally from conventional structural strengthening approach in a manner that it aims at period lengthening and hysteric energy dissipating mechanism. Application of base isolation may also raise a structure's seismic performance as well as its seismic sustainability considerably.

Seismic Isolation technique is gaining acceptance and becoming popular all over the world, due to its simplicity, reliability and overall cost effectiveness. From the records of recent earthquakes, it could be generally established that seismically isolated structures have performed as expected and also corroborated its analytical behaviour with the recorded performance. Among the isolation technique available at the moment, the most popular one is the Elastomeric Isolators. Elastomeric Isolators primarily comprise of two type, viz., Lead Rubber Bearing and High Damping Rubber Bearings. Lead Rubber Bearings (LRB) consist of alternate layers of low damping rubber of limited thickness and vulcanized reinforcement made of thin steel plates and a central lead core while High Damping Rubber Bearings (HDRB) consists of special rubber compound, chemically modified to provide wider hysteresis loop, vulcanised in layers of limited thickness separated with thin steel plates. Both LRB and HDRB, when used as base isolation devices, can provide all basic requirements of base isolation technique i.e., enhance global flexibility of the structure and increase the period of vibration to meet target natural period needed to reduce force response (Fig 1); dissipates energy through optimum hysteresis and control displacement of the structure (Fig 2); re-centres the system when ground motion due to severe earthquake ceases; provides necessary rigidity under low service loads such as wind and also perform under all service loads and slow displacement due to thermal action and secondary effects offering moderately low resistance. (Mendez et al., 2012)

The technology of Elastomeric Isolator has developed significantly during the last three decades and achieved considerable reliability and acceptance. In tandem with the research and development, taken place all over the world in this field, two elaborate guide Specification documents; i) EN 15129-2009 and ii) GSSID by AASHTO-2014, have also been published, which give not only thorough overview on the subject but also define stringent acceptance standard for the devices through extensive test requirements, essential for controlling the performance and durability of such safety devices.

Bridges are ideal candidates for the adoption of base isolation technology due to the facility of installation, inspection and maintenance of isolation devices. Although seismic isolation is an effective technology for improving the seismic performance of a bridge, there are certain limitations on its usage. Seismic isolation improves the performance of a bridge under earthquake loading partially by increasing the fundamental vibration period (Salomon et al., 2009). Thus the vibration period of a bridge is moved away from the high-energy seismic ground period and seismic energy transfer to the structure is minimized (Ruiz Julian et al., 2005). Therefore, the usage of seismic isolation on soft or weak soil conditions, where high period ground motion is dominant, reduces the benefits offered by the technology (Turkington et al., 1989).

The seismic isolation system has a relatively high vibration period compared to a conventional structure. Due to the principle of dynamic resonance, a larger difference between the dynamic vibration frequencies of the isolation system and the superstructure results in a minimized seismic energy transfer to the superstructure. Therefore, seismic isolation is most effective in relatively rigid structural systems and will provide limited benefits for highly flexible bridges. (Mendez et al., 2010)

Another consideration is related to the large deformations that may occur in the seismic base-isolation bearings during a major seismic event, which causes large displacements in a deck (Pan et al., 2005). This may result in an increased possibility of collision between deck and abutments. Damping is crucial to minimize the seismic energy flow to the superstructure and to limit the horizontal displacements of the bearings (Mendez et al., 2008). The lead plug deforms plastically at a predetermined flow stress and thus dissipates energy through hysteretic damping.

2 CHARACTERISTICS AND WORKING PRINCIPLE OF ELSTOMERIC ISOLATORS

Rubber compounds used in Elastomeric Isolators are primarily categorised as low damping rubber (damping < 6% corresponding to 100% shear strain) and high damping rubber (damping > 6% corresponding to 100% shear strain). Selection of shear modulus of the rubber compound has a key role as it determines the shear stiffness of the Isolator and thereby defines the natural frequency of the isolator and thus flexibility of the whole structural system. Rubber compound for Elastomeric Isolators may have a shear modulus within a wide range of 0.3 MPa to 1.5 MPa. At a shear strain of 100%.

Unlike regular elastomeric bearing, which are designed for limiting shear strain of 70%, elastomeric isolators are required to be designed for much higher strain depending upon capacity of the elastomer compound used in manufacturing the isolators. Depending upon the quality of the compound the maximum design shear strain amplitude may be as high as 300%.

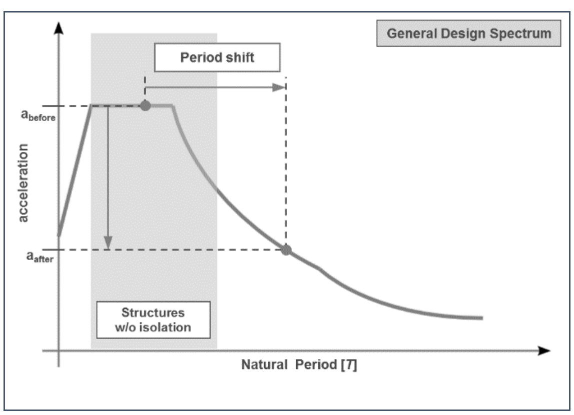

Figure 1. Reduction of accelerations by period shifting

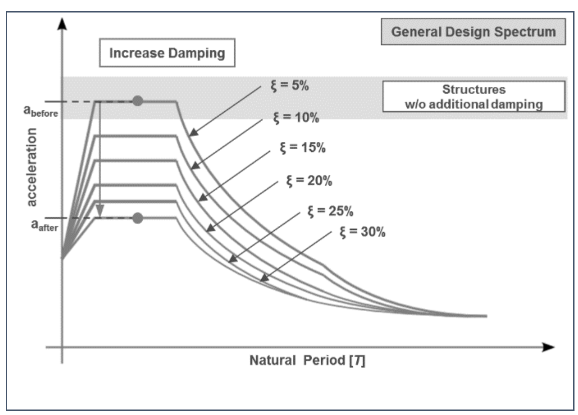

Figure 2. Reduction of accelerations by added damping

2.1 *Lead Rubber Bearing (LRB)*

Many innovative devices and systems are being developed for the purpose of seismic isolation of bridges (Moehle, 1999). One of the most widely adopted isolation system is the lead-rubber bearing (LRB). This type of elastomeric bearing protects the bridge from the destructive effects of earthquake ground motions increasing the structure fundamental period beyond the energy-containing periods of earthquakes and also by dissipation of seismic energy through the additional hysteretic damping due to yielding of the lead plug (DesRoches, 2004). Under normal conditions, LRB bearings behave like regular bearings. The isolation device is characterized by a high initial stiffness provided by the lead plug inserted in the bearing to avoid undesirable displacements under service requirements, wind action and minor earthquakes. However, the shear stiffness decreases favorably for moderate levels of deformation, allowing the isolator to uncouple the bridge from the damaging action of earthquake ground motions (Mendez et al., 2009). Therefore, the seismic damage the structure acquires is drastically minimized through the reduction of the seismic inertial loads (Bessasson, 2004).

LRBs work on the principle of seismic isolation and limit the energy transferred from the ground to the structure in order to protect it. The rubber/steel laminated isolator is designed to carry the weight of the structure and make the post-yield elasticity available. LRBs are normally made from natural rubber (NR). The rubber provides the isolation and the re-centering though its flexibility in shear deformation. The lead core deforms plastically under shear deformations, while dissipating energy through heat. With LRB, it is possible to achieve very high energy dissipation through damping and are used to provide damping up to as high as 30%. It is possible to design LRBs with high initial stiffness and therefore LRB can also be used efficiently as a means of providing high rigidity to control displacements against transient loads like wind actions or traction/ braking in bridge structure in service limit states.

It is fabricated with the rubber vulcanised directly to the top and bottom connection plates. The bearing can also be supplied with additional anchor plates, allowing easier replacement of the bearing.

2.2 *High Damping Rubber Bearing (HDRB)*

HDRB has similar construction as of LRB except that the rubber compound is much different and are specially compounded with chemical modification to provide higher damping. High damping elastomer compound used in HDRB being more viscoelastic in nature under a cyclic load or stress, shows that the resulting deformation lags in time behind the applied load or stress (i.e. shows a phase difference) causing higher energy dissipation through hysteresis producing heat and thereby offers higher damping. Since the rubber compound can provide good amount of damping (about 16%), no additional lead core is required in HDRB. HDRB has comparatively lower initial stiffness than LRB but has better re-centering ability.

3 ANALYTICAL MODEL OF STRUCTURES WITH ELASTOMERIC ISOLATORS

Elastomeric isolators are represented using a number of analytical models. The most simplified method is the equivalent linear model composed of the effective stiffness (K_{eff}) and equivalent damping ratio, applied on a single degree of freedom system i.e., structure which respond predominantly as a single degree of freedom system with no coupling of displacements between any two or three coordinate system and this model can be efficiently analysed by static equivalent method or Single Mode Spectral Method.

The most extensively adopted model for dynamic analysis of seismic isolated structures is the bilinear idealization for the force-displacement hysteretic loop. Due to the simplicity and accuracy to identify the force-displacement relationship of the isolation devices, LRB and as well as HDRB bearing supports can be represented by the bilinear force-displacement hysteresis loop given (Figure 3). The principal parameters that characterize the model are the pre-yield stiffness K_1 and yield force Q_d, corresponding to the combined stiffness of the rubber bearing and the lead plug in case of LRB and high initial stiffness of the rubber compound in case of HDRB, and the post yield stiffness of the rubber K_2.

The system may then be analysed by Multimode Spectral Method or by Non-Linear Time History Analysis Method. This model can adequately address structures in which coupling occurs between displacements in more than one of the three coordinate direction within any of the predominant modes of vibration.

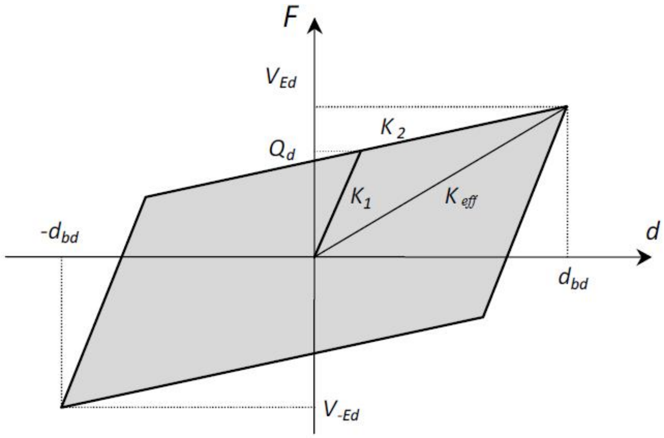

Figure 3. Bilinear analytical model of LRB bearing

4 PERFORMANCE VERIFICATION TESTS

For all isolation systems, it is extremely important to verify the design seismic performance thorough testing of the full scale isolators. For elastomeric isolators, it is also important to verify expected performance of the elastomer compound.

4.1 *Test on Elastomer Compound*

For the elastomer compound to be used in Isolators, mechanical properties like tensile strength and tear resistance are to confirm the general suitability of the elastomer as these properties are not directly related to the performance of Isolators. Elongation at break is however of significant relevance as it defines the ultimate strain at the break point and therefore considered as an important design input for estimating safe performance under extreme strain. Together with the Elongation at break, other mechanical properties, viz., bulk modulus, shear modulus, Young's modulus are also having considerable influence on the performance. Compression set primarily provides a check that the elastomer is adequately vulcanised. Other tests like accelerated ageing and ozone resistance provide a check that suitable antidegradants have been included in the compound to ensure satisfactory performance of the elastomer under standard exposure throughout the design service life (Fig. 4).

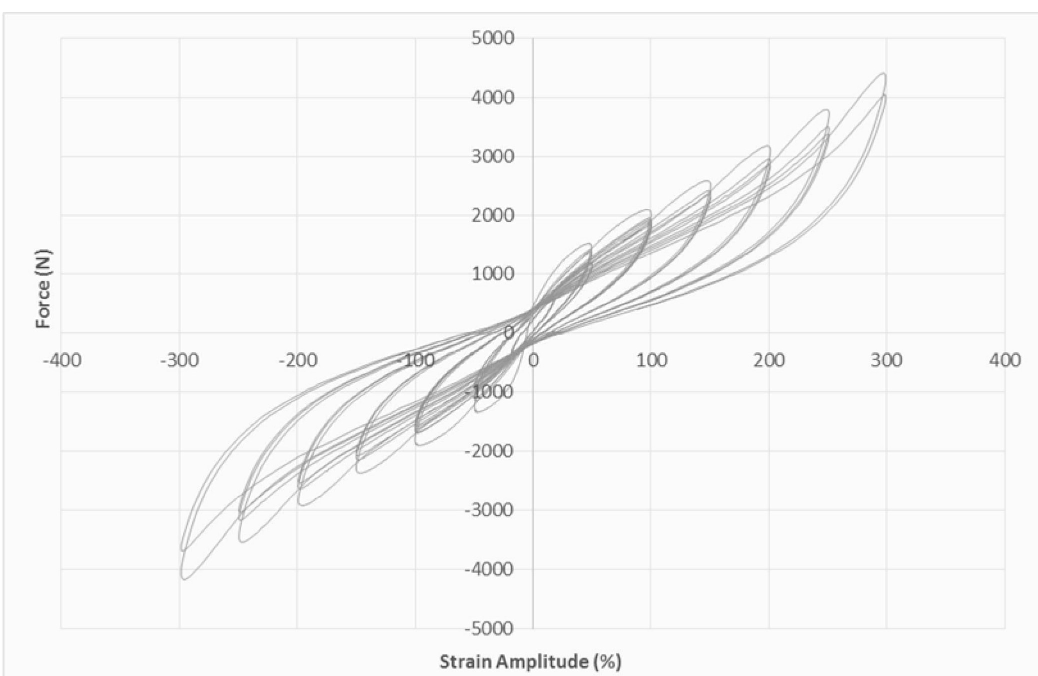

Figure 4. Typical Strain amplitude test data of High Damping Rubber compound

Apart from the evaluation of mechanical properties of the elastomeric compound, dynamic properties of the compounds are also required to be tested. Shear modulus and damping properties are of much importance in case of dynamic actions and require proper estimation through tests. Both of these properties have great influence in defining stiffness for target natural period, controlling displacement and ensuring energy dissipation through hysteresis. Variation of shear modulus and damping are required to be evaluated through dynamic testing of specially moulded samples of elastomer compound for range of strain amplitudes the isolator is expected to perform; range of frequencies, temperature variation, repeated cycling as well as ageing effect. Tests are conducted on sample quadruple test pieces conforming to ISO 4664.

Other important test requirement for elastomeric compound includes, shear bond test to estimate achievable ultimate strain of the rubber before bond failure between steel and rubber in both un-aged and aged condition as well as performance evaluation of the elastomer for low temperature exposure including crystallisation parameters.

4.2 *Test on Full Scale Isolators*

Test protocol for Full-scale Type Tests should include extensive testing to demonstrate that the Isolators perform within defined design limits in compliance with serviceability requirement and provide adequate safety against strength requirement for all possible static and dynamic load and displacement combinations. Test requirement include static load tests viz., Test of Compression Stiffness as well as Maximum Lateral Displacement capacity under maximum and minimum vertical compressive loads.

As elastomeric isolators are normally designed with much higher shear strains, the test for Maximum Lateral Displacement, which is conducted by applying shear strain corresponding to maximum seismic displacement (MCE condition), added with thermal displacement, at a ramp rate between 1% s^{-1} and 100% s^{-1} while maintaining constant compressive vertical load, is quite demanding and gives good insight about the performance of the isolator. Horizontal load corresponding to test displacement is also measured during the test to compare the performance with design value.

Dynamic tests are also to be carried out on full scale samples to evaluate its primary horizontal characteristics viz., shear modulus and damping. These characteristics are required to be evaluated by applying cyclic deformations for a range of strain amplitudes, up to the design displacement at a frequency of 0.5Hz. Shear modulus and damping are also evaluated through repeated cycling test conducted with a strain amplitude corresponding to 100% shear strain or design displacement at a frequency of 0.5 Hz to verify the performance of the elastomer under repeated cycling (Figure 5).

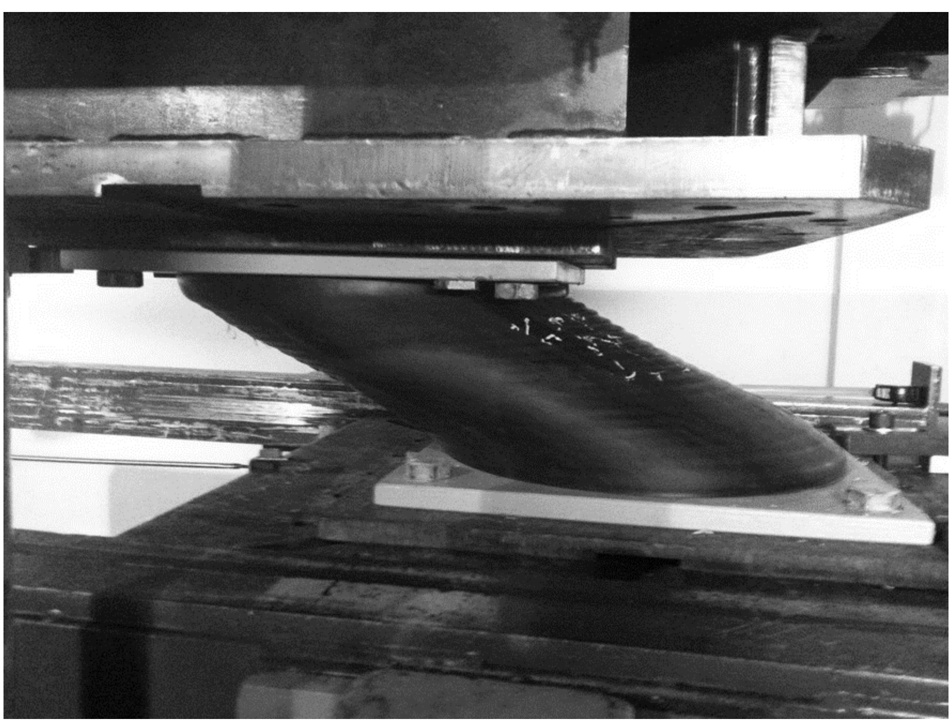

Figure 5. Isolator subjected to more than 300% shear strain and vertical load

Response of the isolators to the Frequency of vibration is another important parameter of the dynamic behaviour of the isolator. Test for frequency is conducted on full scale samples in the order of increasing frequency of 0.1 Hz, 0.5 Hz and 2 Hz or other values spaced similarly depending upon the project requirement.

For instance, currently the European specifications for Anti-Seismic Devices, also called EN 15129, focus on the following tests at full scale samples of isolators:

4.2.1 *Compression capacity tests*

The main objective of this test is to confirm that the elastomeric isolator, in this case the LRB, is able to withstand the maximum vertical load under service conditions. During the testing it is required to carry out a visual inspection in order to ensure that no visible defects are appearing. In the case of the two samples, such maximum vertical load was 3,450 kN and was applied to the isolator for a period of 3 minutes. Before reaching the maximum value, the load is reached during a period of 10 minutes. Fig. 6 shows the isolator equipped with measurement devices in order to evaluate the vertical displacements due to the compression load.

4.2.2 *Compression stiffness*

This test is performed by a loading ramp applied at a constant loading rate which is mainly aim to register static information of the LRB. As for the compression capacity, the load is reached in a period of 10 minutes. For seismic information, this load has to be applied in one second. Once the value of the compression stiffness is recorded, this value will be the base for the performance of the Factory Production Control tests required by the norm. The production units to be tested must show the same value of compression stiffness, with a tolerance of +/- 30%.

4.2.3 *Horizontal characteristics under cyclic deformation*

These test were particularly demanding on the lead rubber bearings, as the whole series of tests represented a total of 18 complete cycles at a frequency of 0.5 Hz and at different shear strains: +/- 5%, +/- 10%, +/- 20%, +/- 50%, +/- 100% and +/- 150% (Fig. 7). In terms of lead rubber bearings, the aim of these tests is to record mainly two values, the horizontal stiffness and the characteristic strength. These values are then compared from cycle to cycle and among shear strains, in order to verify that both dynamic characteristics remain stable during all cyclic tests. The tolerance in the analysis of the horizontal stiffness and characteristic strength is 20% of the design value.

4.2.4 *Horizontal stiffness under one-sided ramp loading*

As for the value recorded during the compression stiffness tests, the horizontal stiffness recoded form this test will serve as a value base for the verification of the Factory Production Control Tests. This test must be performed just after the cyclic test with the closest horizontal displacement.

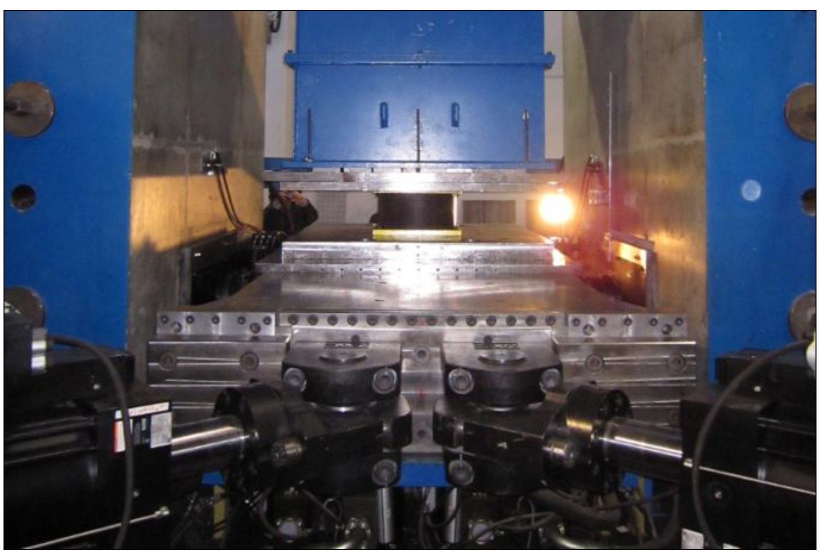

Figure 6. LRB installed at bearing testing machine

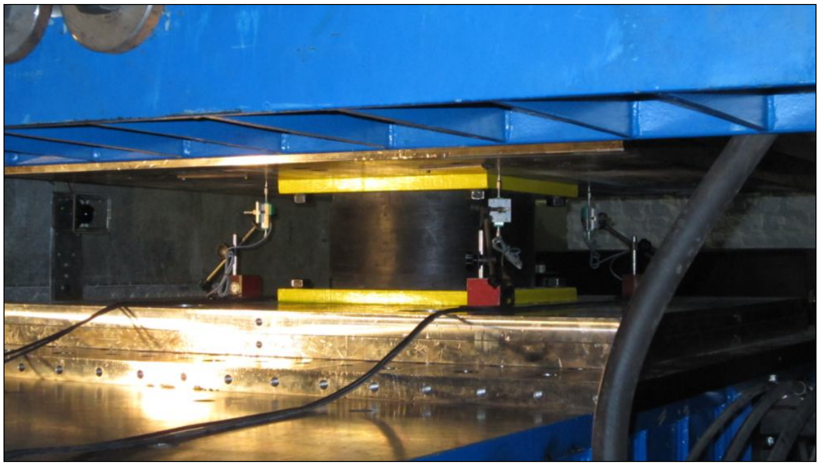

Figure 7. LRB during compression testing

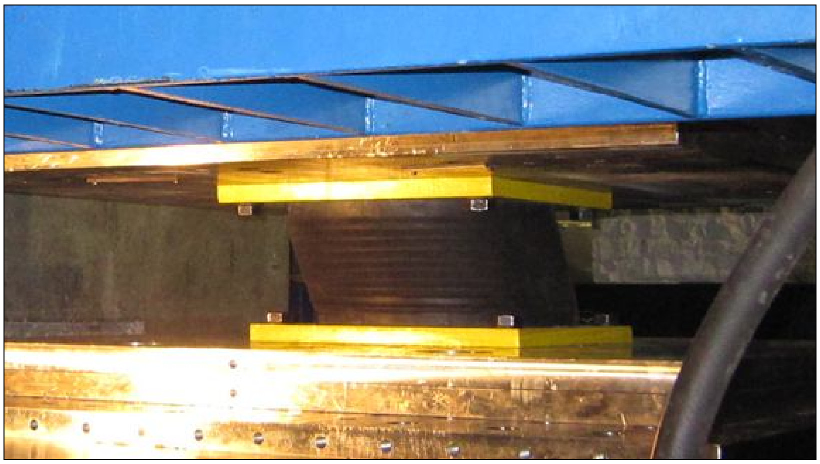

Figure 8. LRB during horizontal cyclic characteristic test

4.2.5 *Variation of horizontal characteristics with frequency*
The main objective of these tests is to evaluate the effect of frequency particularly on the horizontal stiffness and characteristic strength of the isolators. In order to reach a solid evaluation, tests are performed at different frequencies: 0.1, 0.5 and 2.0 Hz. As for the tests for the horizontal characteristics under cyclic deformation, the values will be compared among cycles and frequencies, in order to verify that the influence of the variation of frequency does not lead to variation higher than +/- 20% of the design value.

4.2.6 *Dependence of horizontal characteristics on repeated cycling*
This tests aims to evaluate the effects of the repeated cycling on the horizontal characteristics of the isolator. Same as for the previous tests, the most important parameters to verify are the horizontal stiffness and the characteristic strength. There are basically three parameters that need to be considered in the evaluation of these tests, the first is the ratio between the minimum and the maximum horizontal stiffness measured between the second and tenth cycle. Such Ratio must remain higher than 0.7. This also applies to the value of characteristic strength, where 0.7 is also the minimum acceptable ratio. Additionally, a third consideration includes the horizontal stiffness at the first cycle, which has to be compared with the last cycle. The ratio between the last two values must be higher than 0.6 (Figure 8). Examples of results are shown in Figures 9 and 10.

4.2.7 *Lateral capacity*
The purpose of the horizontal displacement capacity is to verify that the isolator is able to reach the maximum displacement, without showing any sign of damage or defects. Such displacement is an amplified value of the design displacement of the isolator, as this value has to be multiplied by two factors: 1.15 and 1.5. This leads to a significantly large horizontal displacement that has to be maintained for 2 minutes during which visual inspection has to be carried out in order to ensure that there are no signs of failure or cracks wider than 2 mm.

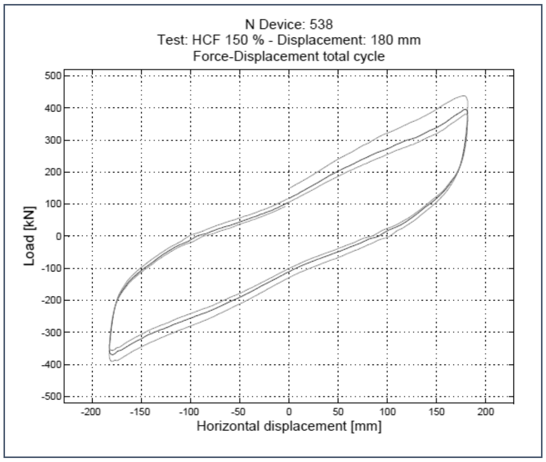

Figure 9. Hysteresis diagram of LRB with 150% strain

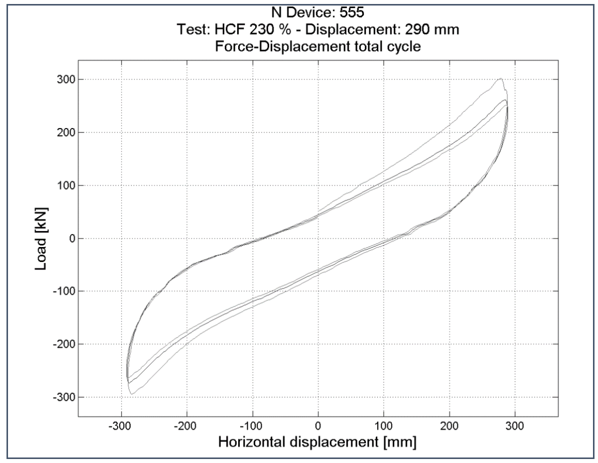

Figure 10. Hysteresis diagram of HDRB with 230% strain amplitude

5 CONCLUSIONS

Elastomeric isolators brings in appropriate solution to structures against seismic hazards. Prudent selection and application of seismic isolators also helps to bring down overall cost of the structures as it helps to avoid direct enhancement in strength of the structure to mitigate seismic hazard by using more material. Over the last few decades there have been considerable advances in this field not only with respect to improved material properties with enhanced performance but also towards analysis of structures integrating the properties of the isolators. The new guide Specification documents added considerable value in ensuring high quality standards of the devices, performance, safety and durability. It is therefore expected that with more and more applications of such devices loss of life and properties due to earthquake can be well achieved.

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