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EXPERIMENTAL TESTING OF A NEW HYSTERETIC DAMPER FOR BASE ISOLATED BRIDGES

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ABSTRACT

An experimental procedure was developed to implement a simplified design method of supplemental dampers for isolated highway bridges. For seismically base-isolated bridges subjected to an earthquake, the principal modes of the structure are in the isolation level which effectively lessens the seismic base shear conveyed from the superstructure to the substructure. However, this also has the effect of increasing superstructure displacement. To control the deformation of the isolators, supplemental energy dissipating devices can be introduced into the isolation system. This may nevertheless increase the total structure base shear and the merit of adding dampers has to be evaluated properly. In this paper a new type of steel hysteretic damper is proposed and tested in combination with an elastomeric isolator using displacement controlled cyclic tests. This very simple and economic damper was designed using a simplified method presented in earlier works. First, having characterized the response of an elastomeric isolation bearing used in a real structure, a simple and economic hysteretic damper was designed in accordance with the simplified method. In the next step, the designed damper in parallel with an elastomeric isolation bearing was tested by a unidirectional displacement-controlled quasi static method. Results show that this new type of damper could be used in combination with isolators to control superstructure displacement and substructure base shear.

Keywords: isolated highway bridge, damping device, quasi-static test, seismic design

1. INTRODUCTION

In order to reduce substructure loadings in bridges subjected to significant earthquake activity, base isolation is being used more and more. Golzan and Legeron (2010) showed that isolation systems for small to medium span bridges can be very effective to reduce substructure loading. Isolated highway bridges under certain extreme loadings such as seismic and wind loads may undergo large displacements which might lessen the interest for the use of isolation for certain cases. Such large seismic displacements may impose using expansion joints with high initial and maintenance costs.

In this regard, adding dampers to the isolated structure can be used as a method to modify the response of the structure. Since the dampers are often sacrificial members in a structure, it is important to design elements that are economic. Such devices, nonetheless, can increase seismic loads in certain cases (Jangid and Kelly, 2001). There are several types of dampers that have been developed by researchers and manufacturers for building and bridges. Metallic hysteretic dampers among all are simpler in fabrication and more economic with lower initial and maintenance costs. These types of dampers dissipate earthquake energy at designated places in a structure by yielding of metallic elements with hysteretic behavior. (Moreschi and Singh, 2003)

Steel dampers as one special category of such dampers have been reported and demonstrated efficient in the reduction of damage due to earthquake on bridge structures where there is significant deformation demands. (Chen et al., 2001; Maleki &Bagheri, 2010)

So far several such devices have been developed tested by researchers. Cyclic tests of U shape hysteretic dampers under diverse strain velocities and temperature have been conducted by Suzuki et al. (2005). These tests presented a stable hysteretic response, even for high deformations in two perpendicular horizontal directions. To reduce the seismic demands of low or medium rise structures, Oh et al. (2012) tested U shape hysteretic dampers in base isolation systems. The test results for these dampers in combination with laminated rubber bearings also showed a stable hysteretic response at large displacement levels. Pan et al. (2014) developed a new type of triangular steel dampers for bridges with large ultimate deformation which allows large displacement through a vertical free mechanism and decreases the earthquake responses of bridges to a great extent. This damper shows a stable hysteretic performance under cyclic loading and has great capacity in dissipating seismic energy.

In this paper a new type of steel hysteretic damper is proposed and tested in combination with an elastomeric isolator using displacement controlled cyclic tests. This very simple and economic damper was designed using a simplified method presented earlier (Golzan et al., 2015). The dampers were tested with a sinusoidal loading at different frequencies and amplitudes, and the effect of multiple cycles on the behaviour of the damper was evaluated.

The basis of the design method as presented in Golzan et al. (2015) is to establish a relationship between effective stiffness, K_{eff} and damping reduction factor, B, of the bridge with the desired reduction in displacement, φ, and increase in base shear, ε, of the base isolated bridge before and after adding dampers. The principal governing equations of the method are:

[1] $$\frac{T_{e_1}}{T_{e_2}} = \frac{B_2}{B_1} = [(1-\varphi)(1+\varepsilon)]^{-\frac{1}{2}}$$

[2] $$\frac{K_{eff_2}}{K_{eff_1}} = \left(\frac{T_{e_1}}{T_{e_2}}\right)^2 = \frac{1+\varepsilon}{1-\varphi}$$

Where T_e is the natural period of the bridge and indices 1& 2 indicate the property before and after adding dampers. The method then allows calculating the stiffness and damping required for the added damper in order to reach the target reduction in displacement and variation in base shear.

2. EXPERIMENTAL SETUP

The test setup consists of vertical and horizontal loading systems; the rollers sliding surface; the instruments to measure displacements and; the control systems. (Figure 1)

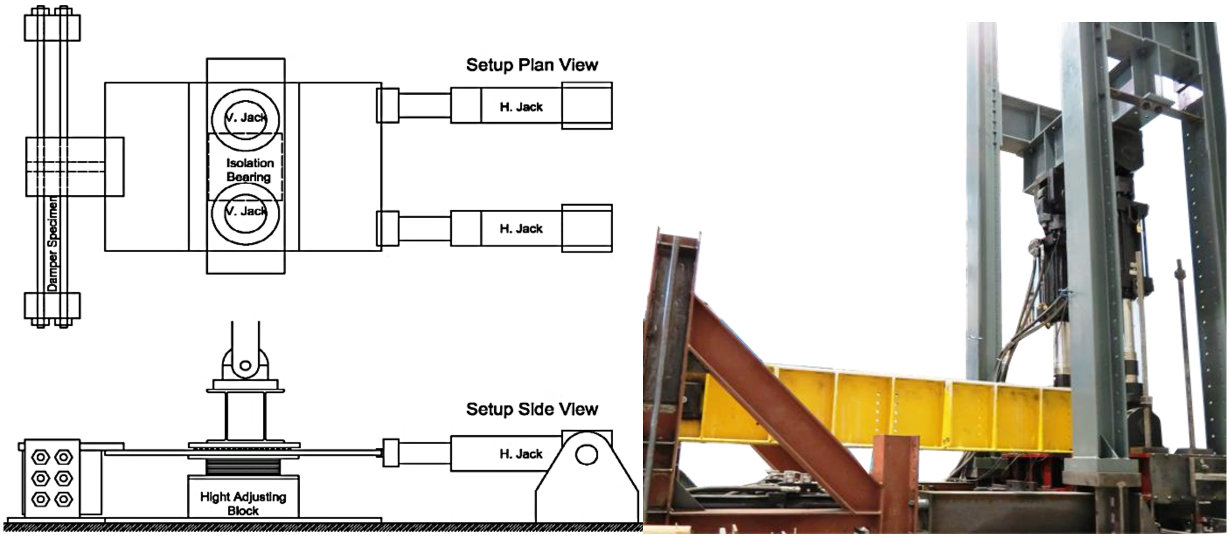


Figure 1: Test set up

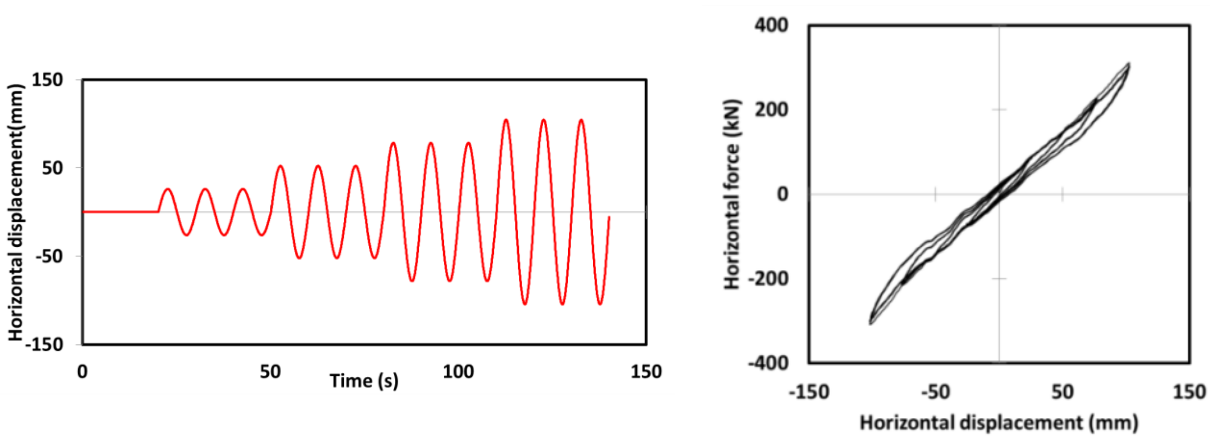
The test setup was designed for characterization test of individual isolators. The horizontal load is applied by a pair of servo-controlled hydraulic jacks of a nominal capacity of 250kN. The upper plate of the isolation bearing is bounded to the horizontal jacks by the mobile plate, whereas the lower plate of the isolation bearing is fixed to the ground plate. The applied horizontal load is displacement controlled and is measured directly by the jacks applying the load. In the characterization phase of the isolation bearing, the damper is not installed in its place so that the whole horizontal force is carried by the bearing.

The required decoupling and sliding surface between the upper plate and the vertical load system is accomplished by a set of parallel rollers fixed in a steel frame. The resistance in displacement of clean rollers under a vertical load of 900kN applied by two servo-controlled jacks that are fixed to the overhead frame is about 0.7% of the vertical load. The horizontal displacements are measured by diverse devices. The extension of the two horizontal jacks establishes the main measure of the horizontal displacement. A supplementary extension to the setup provides a place for the installation of the damper as will be discussed in the next section. The horizontal displacement of the middle of the damper specimen, relative to the end blocks where the damper is anchored, is measured by a laser sensor.

3. ISOLATOR BEARING CHARACTERIZATION

The isolation bearing in this study has been designed for a vertical load 900kN, a base shear of 302kN and a maximum displacement of 103mm. To investigate the control potential damages on the isolator, characterization tests were performed on the isolation bearing first before testing with dampers and second as a control series after testing with dampers. No significant change was noticed in the behavior of the isolator after all tests.

The characterization test on the bearing was performed using a progressive sinusoidal loading (Figure 2) as specified by CSA S6 (2006).



(a) (b)

Figure 2: Loading of the bearing (a) and Hysteretic behavior of the isolation bearing at different levels (b)

Testing the bearing at different displacements, the bearing was characterized for a range of displacement up to its design displacement. Based on this characterization, some constituting laws of the isolator were drawn to constitute an approximate bilinear model of the bearing in the design of the damper. The effective stiffness and the equivalent damping ratio of the isolator at design displacement are 2940kN/m and 0.045 respectively. The test condition simulates an isolator on a bridge with a very stiff substructure (Base of the lab) that can be assumed infinitely rigid. Considering the design vertical load of 900kN on the isolator, the natural period of the system is equal to 1.1s.

4. HYSTERETIC DAMPER DESIGN

Having the characteristics of the isolation bearing for the seismic design of a bridge, a supplementary element can be introduced to the structure to add damping to the system and reduce displacement. In the design of this steel hysteretic damper that is designed to work with the isolator, attempt has been made to keep it as simple and economic as possible.

Design in this paper is based on an equilibrated displacement for the combination of the damper and the isolation system assuming that no force increase takes place in the combination. The gravity loads are completely supported by the isolator and lateral loading is resisted by both the isolator and the damper.

This damper consists of several fixed end steel bars aligned horizontally (Figure 3) that dissipate the energy of a vibration by plastic hinge mechanisms at both ends and mid-length of the bars. The response of the superstructure to earthquake in terms of exerted force is applied to the damper bars through an articulation which assures the yielding of the bars in bending only and not in torsion. The number of bars and their lengths as well as the steel grade can determine to what extent the displacement demand will be attended by this design method. The choice of several bars is useful for distributing the end moments on a larger surface. Since steel dampers have a relatively large initial stiffness before yielding of the material, they add to the overall stiffness of the structure, which will reduce low amplitude vibrations induced by any weaker horizontal loads other than strong seismic and wind loads.

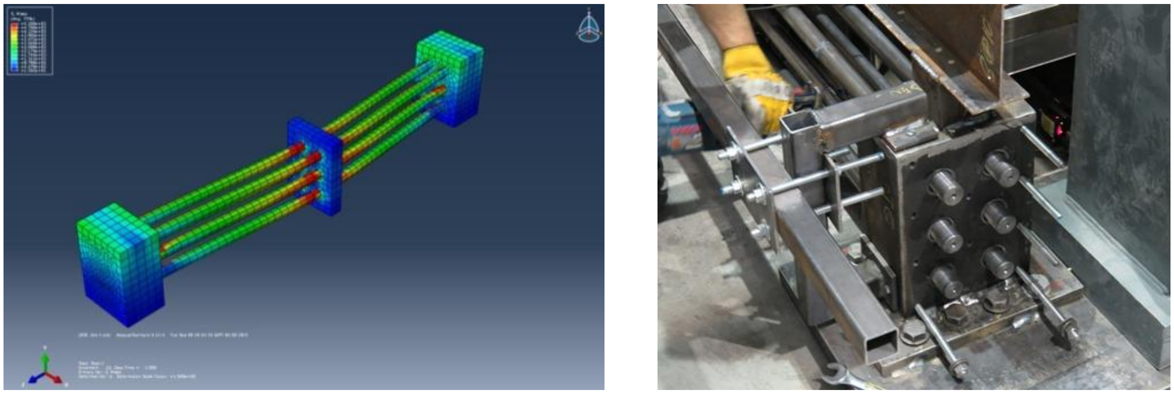


Figure 3: Damper specimen and its end fixation

Hwang et al., (1996) proposed that to obtain the effective stiffness K_{eff} and equivalent damping of a hysteretic system ξ_{eq}, three parameters of elastic stiffness (K_{el}), post yield stiffness ratio ($\alpha = K_{el} / K_{pl}$) and ductility ratio ($\mu = D/D_y$) could be taken as variables and set to desirable values. Equation 3 shows the value of effective stiffness in a bilinear hysteresis model and Eq. 4 shows the equivalent damping in the same model. These equations were formulated for isolators, but they can also be applied for the evaluation of damper properties.

[3] $$K_e = \frac{1+\alpha(\mu-1)}{\mu} k_{el}$$

[4] $$\xi_e = \frac{2(1-\alpha)(1-\frac{1}{\mu})}{\pi[1+\alpha(\mu-1)]}$$

Since the damper is aligned in parallel with the isolator, the effective stiffness is simply given by the sum of the isolator and damper stiffness, and the equivalent damping of the combination can be calculated from:

[5] $$\xi_2 = \frac{K_i}{K_i+K_d}\xi_i + \frac{K_d}{K_i+K_d}\xi_d$$

Geometry of the bars can be determined assuming the behavior of the combined system at the desired designated displacement. Practical considerations such as: steel grade; length, cross section details and number of bars and; accessibility and location where the damper will be installed need to be taken into account in the design of the damper.

In the first place in the design, it is assumed that the displacement of the system reduces by 50% while the developed force remains the same.

Having initial effective stiffness of the isolator equal to 2940 kN/m and its equivalent damping ratio equal to 0.045, from Eq.1 and Eq.2 the target effective stiffness for the combination is calculated to be 5880 kN/m with an equivalent damping ratio equal to 0.08. By subtracting isolator's effective stiffness from the secondary effective stiffness the damper's effective stiffness is calculated to be 2940kN/m and from Eq.5 its equivalent damping ratio is equal to 0.14.

The steel grade to be used for the damper is supposed hot rolled steel with yield strength of 350MPa. The post yield stiffness ratio was assumed approximately equal to 0.3 which would be verified by the tests. Ductility ratio ($\mu = D/D_y$) and elastic stiffness K_{el} remain to be identified such that the effective stiffness and the equivalent damping of the designed damper are set equal to Kd, and ξd based on the bi-linear model presented in Equations 3 and 4. With D already defined with the target variation in displacement φ equals to 52mm (50% of 103mm), the elastic stiffness K_{el} and the elastic displacement D_y can be related to the geometry of the damper using Equations 6 and 7.

[6] $$K_{el} = \frac{3n\pi d^4 E}{l^3}$$

[7] $D_y = \frac{F_y.l^2}{12E.d}$

Where, n is the number of steel bars, l is the length of the bars, d is the diameter of the bars, E is the modulus of elasticity (equal to 200 GPa) and F_y is the yield strength of the material. The number of bars n needs to be assumed in order to solve for the diameter and length of the bars, In this case, the use of six bars was found to give practical bar sizes for the available test setup and isolator. For the damper composed of six bars, the diameter and length of bars were found respectively equal to 36mm and 1352mm. For practical reasons, it was decided to use bars of 38mm (1.5 inches) diameter and the 1500mm length.

For the specimen, two coupons (Figure 4) were tested according to ASTM E8 / E8M - 15a (2015) standard test methods for tension testing of metallic materials to determine the steel mechanical properties. The actual yield strength of the damper was found to be 371MPa which would give from Eq. 7 a yield displacement equal to 9mm.

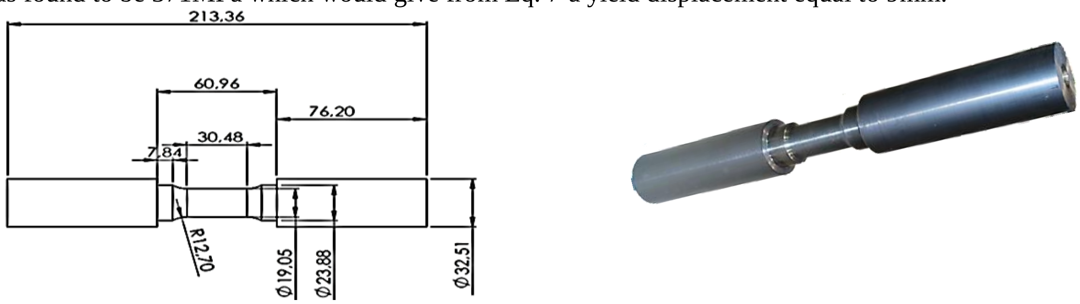
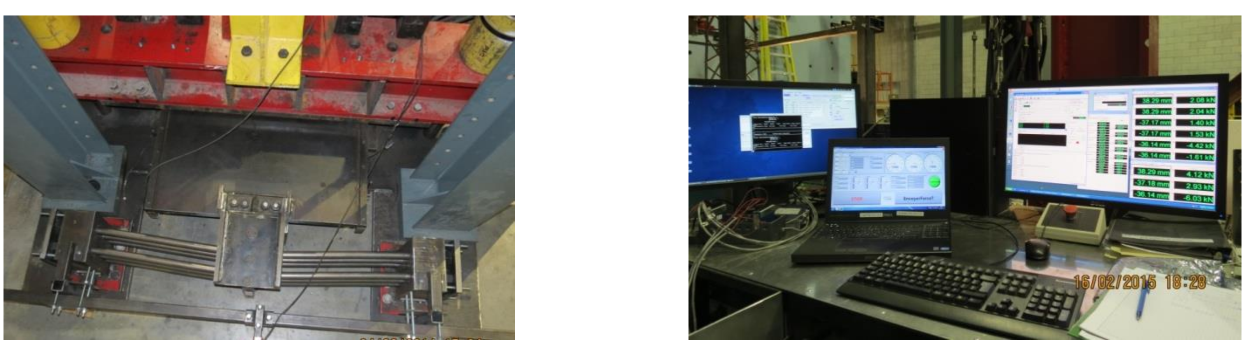


Figure 4: Coupon dimensions (mm)

Given the actual geometry and yield strength of the bars and employing Eq.3 and Eq.4, the effective stiffness and equivalent damping ratio of each component and the combined system can be recalculated. Then, the ratio of target to initial damping reduction factor B_2/B_1 is calculated to be 1.53 and the ratio of target to initial stiffness $K_{eff2}/K_{eff1}$is calculated to be 2.03. This yields a reduction of 54% in displacement and also a reduction of 7% in the force of the total system. Therefore, based on the simplified method the final displacement of the combined system will be equal to 47mm and its final force will be equal to 284kN.

5. DISPLACEMENT CONTROLLED CYCLIC TESTS

Displacement controlled cyclic loading has been performed on the specimen named HR1. As shown in Figure 5a the bars are confined between two end blocks fixed to the laboratory base ground. The force of the jacks is applied in the middle by an articulated plate. The data are acquired by the loading system and the control system (Figure 5b) to apply a cyclic displacement controlled load to the specimen.



(a) (b)

Figure 5. Plan view of the installed damper (a) Control system (b)

Frequency of loading and number of cycles were two parameters to be verified during the tests. A frequency of 0.17 Hz was used in general for displacement controlled cyclic tests, but tests were also performed at 0.5 Hz. The effect of loading frequency on the results of displacement controlled cyclic testing was found to be negligible. This can be shown in Figure 6.

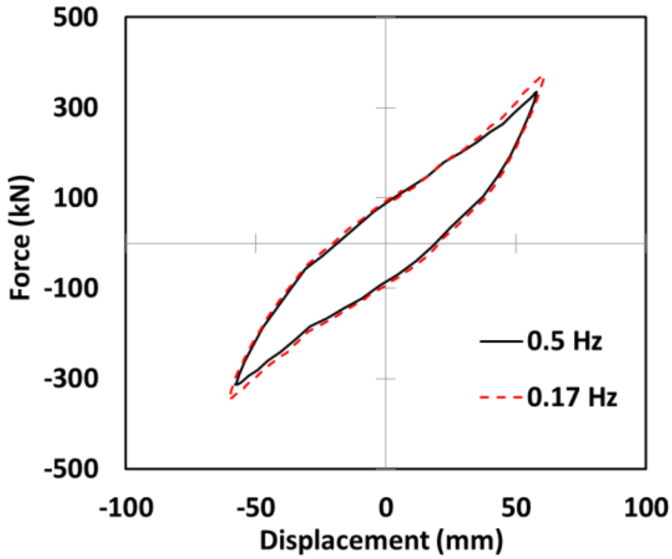


Figure 6: Comparing the hysteresis with two different frequencies of HR1

At designated loading frequencies, three amplitudes were chosen based on the calculations that were applied on the system at three cycles each. At the end of the tests on the specimen at its maximum displacement, tests of 100-150 cycles were performed to verify the effect of loading damage and heat generation in the bars due to the plastic hinge mechanism. Tests results confirm the deterioration of the specimens around 10% due to warming and also damaging of the material during the consecutive 100 loading cycles (Figure 7). After these cycles, the system was let to cool down. Another series of 140 cycles was then performed to verify if there is any gain in the force after cooling. Test results show a gain of 5% of force after cooling. Likewise, throughout the 140 cycles, the force further reduces by around 10%.

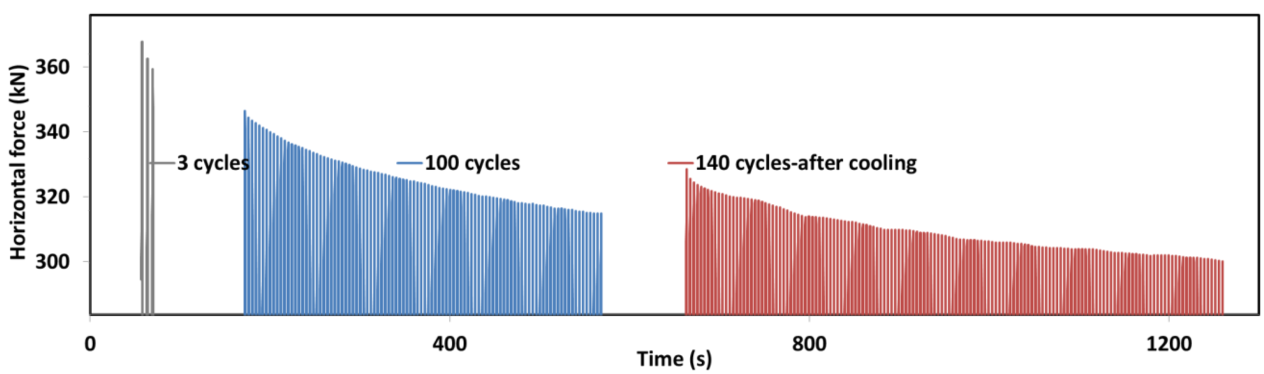


Figure 7: Force decrease of isolator and damper after 240 cycles of 0.25 Hz at 50mm

To match approximately the final displacement of 52mm (50% reduction), the specimen was tested at three amplitudes with the lowest amplitude corresponding approximately to the yield displacement (9mm) and two other displacement amplitudes of 50, and 60 mm. Three cycles at each displacement amplitude were performed consecutively as shown in the loading force and hysteretic curves of Figure 8 for the specimens in comparison with the isolator alone.

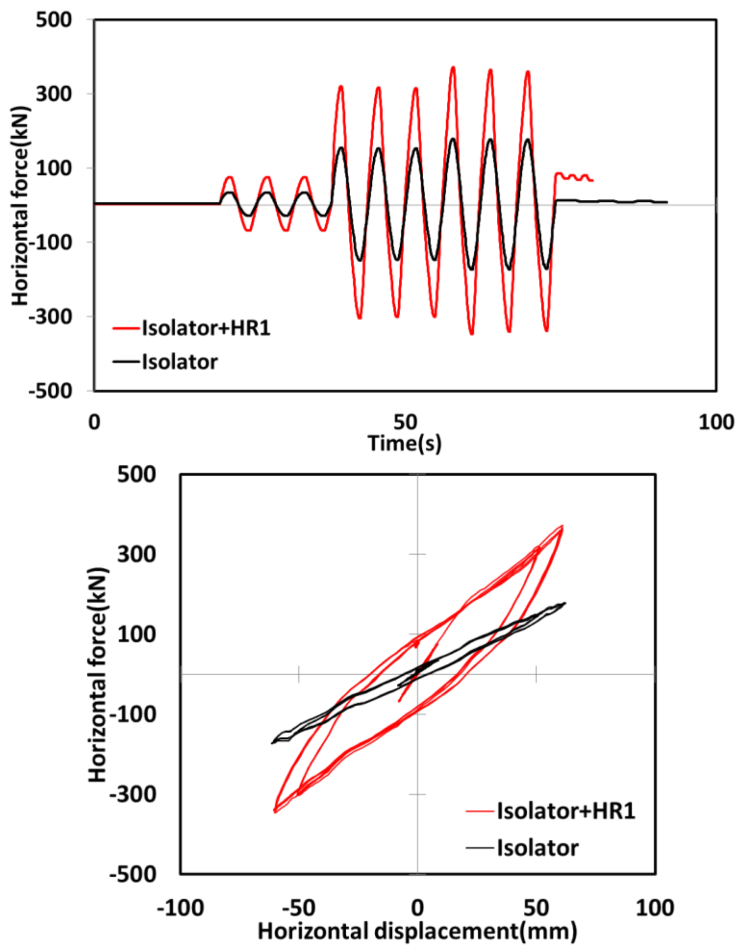


Figure 8: Comparison of the Isolator and HR1 vs. Isolator alone

The resulted force in the tests at the equilibrated displacement found from simplified method shows 297kN which has little difference from the force obtained from the simplified method equal to 284kN. The force values from the test correspond with the first cycle of the test and the force in the other cycles tend to be less. The attained ductility ratio of the specimen at its maximum design displacement is 5.2 and from the tests it is found that the post yield stiffness ratio of the specimen is 0.27. A comparison has been made between the isolation bearing and its combination with the specimen in Figure 9. The figure also shows a comparison between the test results and the simplified method.

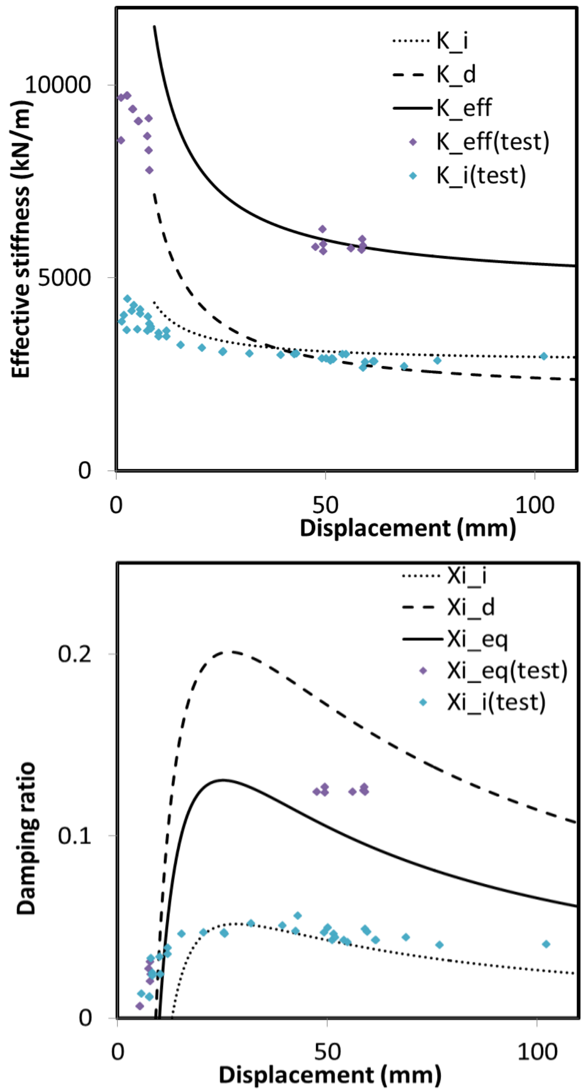


Figure 9: Effective stiffness and equivalent damping ratio of Isolator, damper and combined system in various displacements

6. DISCUSSION AND CONCLUSION

This paper discusses the design of a simple, easy-to-replace and economic hysteretic damper for highway bridges that act as a fuse in case of large displacements and base shears from earthquakes. The damper has been designed following the simplified method developed in earlier works. The damper was fabricated from hot rolled mild steel to work in parallel with an isolation bearing with known responses in force and displacement. It was tested under displacement controlled cyclic loading.

The main conclusions are as follows:

1. The designed damper following the simplified method with added stiffness and damping to a structure shows to be able to control displacement and base shear as required.
2. The elements of the damper are designed to be horizontal so that the vertical movements of the deck of the bridge cannot affect its functionality. This composition also permits to choose a desired length and cross section for the damper elements. Finally, the three point plastic hinge mechanism in the proposed damper offers a greater capacity for the elements to dissipate earthquake energy.

3. Displacement controlled cyclic test results in a good level of damping and stiffness as expected by the design method.
4. The developed damper in this study can be one suggestion out of many as a simple means to rehabilitate isolated highway bridges structures. Other types of dampers with different mechanisms in damping are to be evaluated.

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