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Seismic Isolation of RC Bridges using Low-Cost High Damping Rubber Bearings

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Abstract

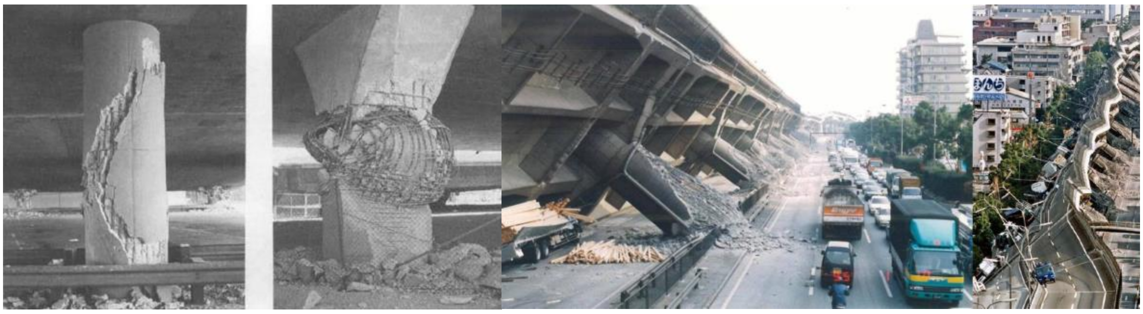
This paper presents a simplified seismic design procedure for the seismic analysis and design of HDRB isolation for reinforced concrete (RC) bridges. Reduced-scale HDRBs were locally fabricated in Pakistan, which were investigated through shake table tests at the Earthquake Engineering Center of UET Peshawar. A natural acceleration time hisotry of 1994 Northridge earthquake was used for multi-levels excitations from 0.10g to 1.0g. The essential mechanical properties of HDRB were obtained; including shear moduli, shear stress-strain relationship and hysteretic response curves. A simplified Bi-Linear hysteretic model was calibated, which was incoproated within the fiber-based nonlinear finite element numerical model of represntative bridge, for nonlinear time history analysis. An exmaple bridge studied for seismic isolation design is presented, which was verified through nonlinear time hisotry analysis procedure using design spectrum compatible natural acceleration time histories. This preliminary research have shown promising behavior of the locally fabricated HDRBs in limiting chord rotation demand on bridge piers, essential for controling damage, under representative design basis earthquakes.

Keywords: Seismic isolation, reinforced concrete bridges, HDRBs, risk mitigation

1. INTRODUCTION:

Bridges are very critical structures and should be designed with great care, which otherwise could result in catastrophic failure, causing human and economic losses. It is not only common to developing countries, but countries with cutting edge technology and research in the field of structural and earthquke engineering are continuously suffering from the damaging earthquakes. For example, the 1989 Loma Prieta, 1971 San Fernando and 1994 Northridge earthquakes in USA and 1995 Kobe earthquake in Japan, among others, where number of important bridges collapsed, or severely damaged, and resulted in huge economic losses (Figure 1). The structural collapse mechanisms of such bridges included; fall of deck, pounding, flexure or shear failure of bridge piers, foundation or soil failure and failure of abutments. Seismic codes worldwide don’t allow the collapse of bridge in any earthquake, thus, design and construction procedures were stipulated over the course of time to safeguard bridges against typical modes of collapse and limit structural damages under seismic actions, through establishment of desired strength hierarchy in the bridge to ensure damage occur where designer intends (Priestley et al., 1996). Further, the bridge should sustain functionality for emergency traffic and repair must be easy, in case a bridge incurs damages duirng an earthquake. In response to this, bridge piers were considered appropriate with the emphasize to design these for adequate inelastic deformation and seismic energy dissipation. Such ductile behavior of bridge piers can be promising in moderate to high seismicity region, however, alternative techniques will be needed to avoid or at least control damages in piers.

Recent studies have focused on the development of design procedures and isolation devices, and their verification through experimental testing (Priestley et al., 1996; Christopoulos and Filiatrault, 2006; Kawashima, 2004; Skinner et al., 1994; Constantinou et al., 2007), which have shown excellent seismic performance in limiting actions on bridge components. Unfortunately, majority of reinforced concrete bridges and flyovers in Pakistan have been provided with non-seismic elastomeric bearings without proper design. Further, the installtion of such bearings is also carriedout without proper care i.e. bridge girders are directly placed on bridge pads without proper connection between pad–pier or bent beam and pad–girder. Shear keys are provided with marginal clearance between girder and keys, that prevent transverse movement of girder, thus, transfer lateral seismic force to bridge piers. The present research focuses on the investigation of low-cost seismic isolation using high damping rubber bearings (HDRBs), locally produced in Pakistan. These HDRBs have been recently installed also in Gulpur Hydropower Project in District Kotli, Azad Jammu Kashmir, which is an area of high seismicity. The present pilot research focus on shake table testing of these HDRBs for seismic qualification and to obtain the essential mechanical properties of low-cost indigenous HDRBs, which can facilaite design of seismic isoaltion for structures.



(a) - 1971 San Fernando, USA (b) - 1995 Kobe, Japan

Figure 1: Critical damages observed in some important bridges in past earthquakes.

2. PILOT RESEARCH BACKGROUND AND SCOPE:

The deck inertial forces generated during transverse seismic excitation are fully transferred to the bridge piers and abutments through structural connections, achieved through monolithic connections or bearings supplemented with shear keys. Depending on the type of bridge (e.g. steel or concrete) and expected loads, the engineer can select among various types of bearings like elastomeric, pot, line rocker and spherical bearings. In case of reinforced concrete bridges and flyovers, to provide comfort to the passing vehicle, elastomeric bearings made of natural or synthetic rubbers are widely used in Pakistan. These bearings are placed between pier and girders to allow translation and rotation movements in the longitudinal direction, however, shear keys are provided between bearings and girders, with a marginal separation, to restrain horizontal translation in the transverse direction but permitting rotation. Depending on the vertical load, the elastomeric bearings may be provided also with thin steel shim plates to avoid bulging of elastomers. Such bearings are ideally used for short span bridges located in low seismicity regions. As the conventional constructions of bridges involving bearings transmit the total inertial force to the supporting components: abutments and piers, which can incur severe damages under extreme seismic actions. This can be catastrophic in case of deficient bridges where low quality construction materials (low strength concrete and low quality re-bars) are coupled with poor quality of reinforcement detailing, as commonly observed in the existing bridge stock of Pakistan (Ali, 2009). Alternatively, this seismic action on supporting components can be reduced by permitting horizontal translation of bridge deck, yet, within the allowable deformation limit. An economical solution is to modify the design and materials of existing laminated rubber bearings; by altering the geometry, selected based on appropriate design for seismic loads, and using high damping rubber bearing (HDRB) materials instead of ordinary elastomers. Elastomers exhibiting damping in excess of 6 precent can be regarded as HDRBs (EN 15129). In this regard, the Rainbow Rubber Industry in Karachi was contacted to produce indigenous high damping rubber bearings, which were tested at the Earthquake Engineering Center of UET Peshawar, in order to retrieve their essential mechanical properties for facilitating seismic analysis and design of bearing isolations for bridges. The following sections describe the initial findings from this pilot research conducted on the indigenously produced HDRBs

3. SHAKE TABLE TESTS ON INDIGENOUS HDRBs:

3.1 Test model, instrumentation and loading protocols:

The test model comprised of a wide-deep beam with a superimposed load of 1.20 tonne, resulting in a total weight of 3.66 tonne, which was acting as a simply supported beam (Figure 2). Bearings of cross-sectional area 135 mm x 135 mm and height 90 mm were provided at both the ends. These bearings were resisting a vertical stress of about 2.00 MPa, considering the limit state displacement, which can be experienced in short-span bridges subjected to lower gravity loads. The bearings were provided with 30 thin steel shim plates (1 mm), dividing the total bearing height into 31 layers of rubber of about 2.00 mm thickness. This gave shape factor “S” of bearing of about 16. The bearings were provided with steel plates both at the top and bottom to facilitate connectivity. For testing, the bearings were mounted on the shake-table and fully secured through anchor bolts. The beam was also attached to the bearing through anchor bolts. The test model was instrumented with displacement transducers and accelerometers both at the top and bottom, in order to record the seismic input and model response under each test run. The test model was subjected to acceleration time history of 1994 Northridge earthquake, scaled to multi-levels of excitation from 0.10g to 1.0g in order to retrieve the full response of bearings. The data obtained under each test run was processed for the required baseline correction and filtering, in order to derive lateral force-displacement hysteretic response of bearings under seismic excitations.

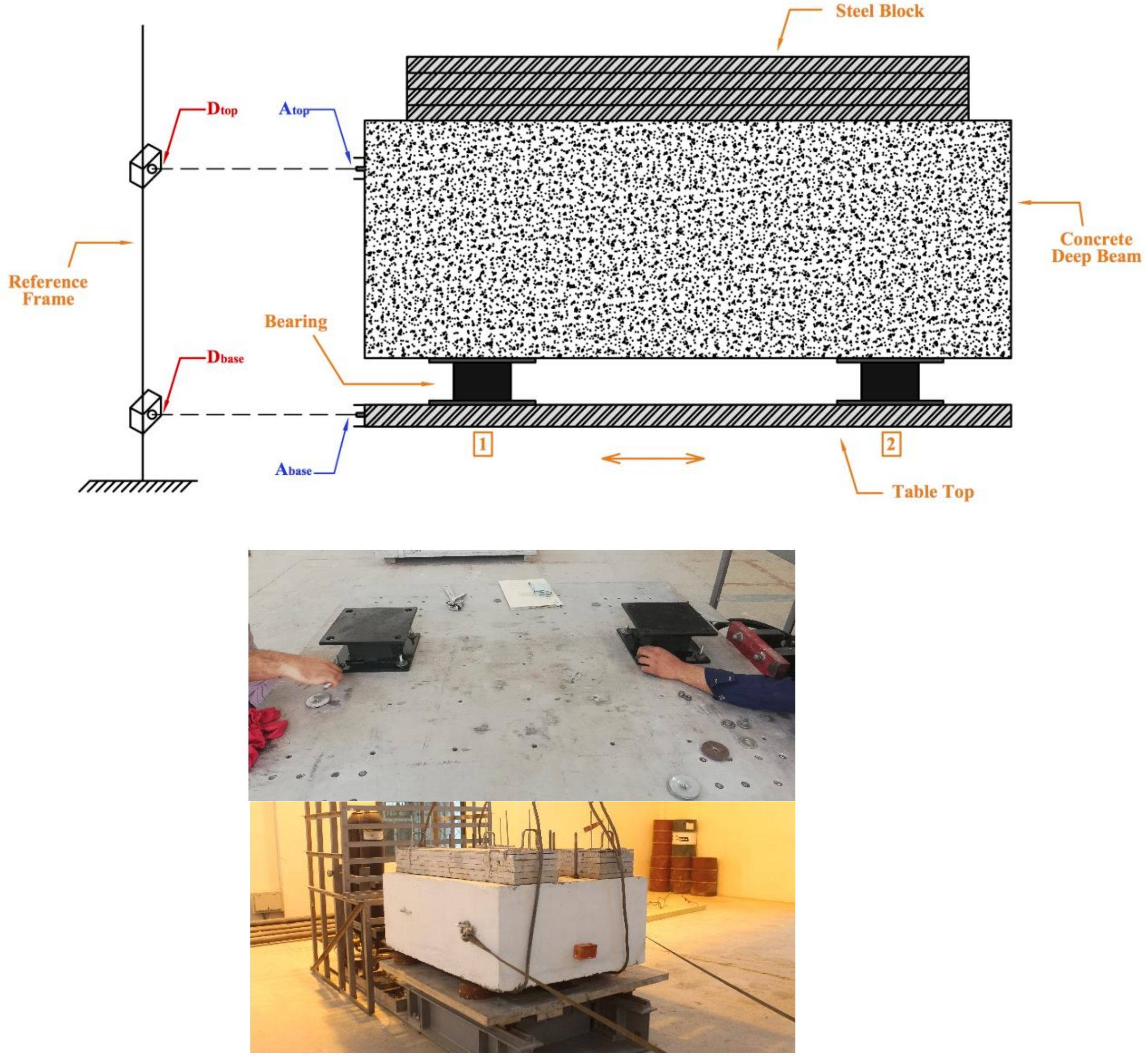
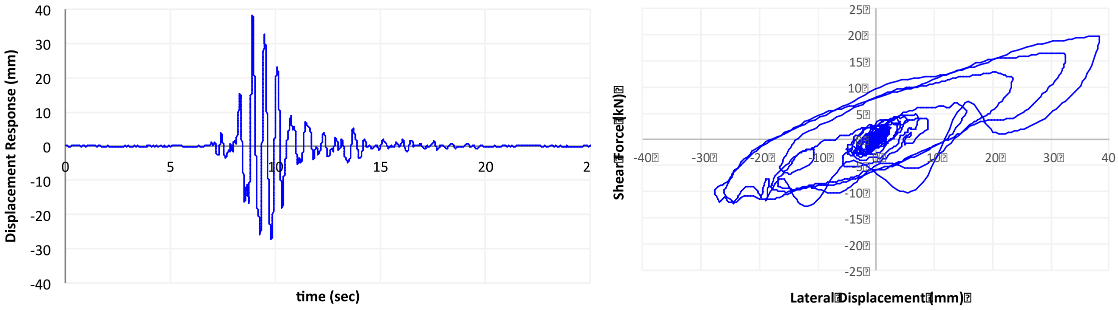


Figure 2: Experimental test model.

3.2 Observed behavior and seismic response:

The bearings under low intensity shaking were not observed with any apprecial deformation. However, the bearing exhibited signficant lateral deformation, and even rocking, under extreme shaking. Rocking of bearing was experienced due to the low-vertical stress, nevertheless, the bearings avoided overturning and were still able to recover their lateral deformation. Figure 3 shows the displacement response and force-displacement hysteretic response of the tested model under extreme level shaking (1.0g). Despite the extreme level shaking, the bearing was able to control lateral displacement demand, which was due to the high damping exhbited by the bearings. This can be evidenced also from the force-displacement response of the test model (Figure 3b).



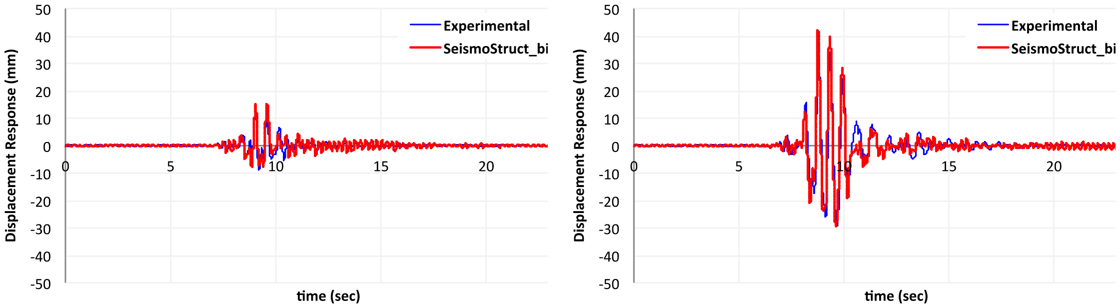
(a) – Displacement Response (b) – Hysteretic Behavior

Figure 3: Response of bearings under shake-table test with extreme shaking 1.0g.

4. VERIFICATION OF HDRBs ISOLATION FOR RC BRIDGE:

4.1 Nonlinear modelling of HDRBs:

The Bi-Linear hysteretic model available in SeismoStruct was adopted, which was calibrated with the observed experimental data. The calibration involved calculating the yield force, yield stiffness and post-yield stiffness of the numerical hysteretic model. These parameters were obtained through regression analysis performed on data obtained experimentally. The calibrated numerical hysteretic model was tested against each run, which has shown excellent performance in predicting the displacement time history response of test model (Figure 4).



(a) – Displacement Response, 0.50g (b) – Displacement Response, 1.0g

Figure 4: Comparison of numerically predicted-to-experimental displacement response

4.2 Selection, Scaling and Matching of Accelerograms:

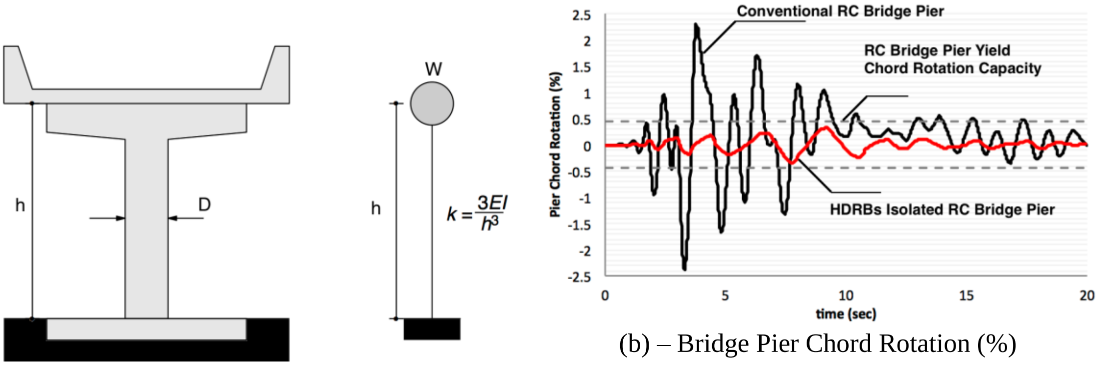
A suite of 07 acceleration time histories, compatible with the regional tectonics, were obtained from the PEER strong ground motions data base. These accelerograms were scaled and matched to the seismic design spectrum specified in the Building Code of

Pakistan (BCP-SP 2007) for highest seismic zone i.e. Zone 4, for type D “Stiff Soil”. SeismoMatch program of SeismoSoft (2016) was used for scaling and matching of accelerograms. The matched accelerograms, simulating the design basis earthquakes, were used for the nonlinear time history analysis of an example bridge.

4.3 Pier Chord Rotation under Design Basis Earthquakes:

An example bridge with single cantilever pier of 4 m height and diameter 1.50 m, supporting superstructure with total weight of 190 kN/m, was considered for seismic analysis in transverse direction (Figure 5a). The pier is considered with longitudinal reinforcement of 1%, which gives lateral yield strength of pier F_y = 1715 kN. The initial yield stiffness of pier is 967 kN/cm, resulting in the initial time period of 0.56 sec for bridge pier in transverse direction. The bridge was analysed through nonlinear time history analysis procedure, using accelerogram of 1971 San Fernando earthquake, scaled and matched to seismic design spectrum. Figure 5b shows the pier chord rotation demand, with a maximum observed chord rotation of 2.40% and ductility (ratio of maximum displacement demand to yield displacement capacity) of 5.40. This chord rotation demand is clearly a larger demand for bridge pier having construction deficiencies.

Initial design of HDRBs was carried out for target period of 3.0 sec, to obtain the geometric dimensions (length, width and height) of required bearings. A total of four bearings were considered on the top of pier; two bearings supporting girder on either side. The initial design was verified through nonlinear time history analysis procedure; checking the displacement demand to remain within the allowable displacement capacity of HDRBs. The final design suggested four HDRBs with dimensions 700 mm x 700 mm and height of 470 mm. The bearing need to be reinforced with a total of 36 steel shim plates having 4 mm thickness. The isolated bridge was observed with maximum chord rotation of 0.35%, hence, the bridge pier was responding elastically (Figure 5b).



(b) – Bridge Pier Chord Rotation (%)

(a) – Example Bridge, Cantilever Pier

Figure 5: Nonlinear time history analysis of example cantiliver bridge pier, under design basis earthquake. Max. chord rotation of 2.40% and ductility of 5.40 were observed for conventional pier while chord rotation of 0.35% was observed for isolated bridge.

4. CONCLUSIONS:

The folliwng conclusions were drawn on the basis of research conducted on low-cost indigenous HDRBs, designed and fabricated locally in Pakistan:

- The HDRBs exhibited significant viscous damping of about 16%, which helped the test model to control lateral displacement demand.
- The Bi-Linear numerical hysteretic model calibrated with the experimental

data has shown excellent performance in predicting the displacement response of test model.

- Nonlinear time history analysis performed on Example Bridge has shown promising behavior of HDRBs in controlling pier damage under design basis earthquakes. A reduction of more than 80 percent was observed in the pier chord rotation demand.

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