Hybrid Testing of Bridge Structures Supported on Elastomeric Bearings

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SUMMARY:
The results of hybrid tests performed on a multi-span RC bridge are presented. The bridge, typical example of bridges employing only plain, elastomeric, low damping isolation devices, is sub-structured for testing purposes: the isolators are physically tested while the response of the remaining structure is simulated numerically. Hybrid testing is performed quasi-statically and - to account for the actual influence of real-time loading on the properties of the isolation devices - a pre-testing phase is carried out in which isolators are strained dynamically at different velocity levels to determine the relation of the real-time response to that during static conditions. Following this phase of characterization, pairs of isolators in a back-to-back (parallel) configuration are tested with the hybrid method, with on-line modification of the measured restoring forces based on the results of the pre-test campaign. The experimental program revealed that the specific type of elastomeric bearings used in the srudy do not comply to current code provisions as they rupture at deformation levels considerably lower than the code-prescribed ones.

Keywords: hybrid testing, elastomeric bearings, seismic isolation

1. INTRODUCTION

Seismic isolation of bridges aims at lengthening the fundamental period of the system to reduce force and strength demands, adding often energy dissipation to reduce further the force demands and limit the increase in displacement demands brought about by the longer period. Flexible or sliding bearings are normally sufficient for the period lengthening. Viscous dampers, elasto-plastic devices or high damping bearings provide the additional energy dissipation. There is no consensus yet on whether lengthening of the period is sufficient or additional energy dissipation is required.

The present study focuses on the first strategy of seismic protection of bridge structures via period lengthening with the use of low damping elastomeric bearings. The main interest lies in the experimental investigation of the response of such structures and the associated testing techniques. The experimental technique used is the hybrid (pseudo-dynamic, PsD) testing of the idealized structural model of the bridge with the addition of a force-correction step accounting for the effect of loading rate on the behaviour of the isolation devices.

Owing to their large size bridges do not lend themselves to seismic testing at full or even realistic scale. Their seismic response has been studied experimentally either via cyclic testing of single piers, or through shake table tests on scaled models (Casirati et al., 1996; Correal et al., 2007). The development of hybrid techniques based on sub-structuring, combining pseudo-dynamic physical testing of part of the system with – linear or nonlinear – mathematical simulation of the rest, has made possible testing of bridges at nearly full scale (Pinto et al., 1996; Pinto et al., 2004; Spencer et al., 2006; Johnson et al., 2006). So far in studies of this type physical testing has been limited to the piers, while simulating the deck and any bearings numerically. On the other hand, in experimental work to-date isolation devices or systems have been tested individually, mainly under imposed cyclic displacement histories. In this study attention is exclusively focused on the physically tested isolation system that belongs to a bridge subjected to seismic ground motions.

2. MODELLING AND EXPERIMENTAL SETUP

2.1. Prototype structure

The prototype bridge used as reference for the experimental program is a 12-span highway bridge at the valley of river Nestos in northern Greece. The bridge is part of recently completed Egnatia highway (E-90). The piers are located on average 38 m apart and their net height (from valley ground level up to the cap beam) is approximately 5.8 m. The cross section of all the piers is identical and constant along their longitudinal axis (height). On the top of each pier lies a 2.6 m high transverse cap beam that serves as support for the deck. Each deck span consists of five simply supported, precast, prestressed concrete girders, topped by an in-situ cast concrete slab. Each girder is supported at both ends by plain elastomeric pads and, additionally, each end of the central girder of a span is connected to the cap beam with a pair of viscoelastic dampers – one in the longitudinal and one in the transverse direction. The foundation of the bridge consists of pile groups reaching as far as the underlying bedrock.

2.2. Hybrid model

The size of the studied bridge renders the construction of a full-scale (or even a realistic scaled) model impossible. Nevertheless, the fact that the superstructure (deck) and the piers are expected to exhibit elastic behaviour during a seismic event makes the use of the substructuring method appropriate. More specifically the bridge is discretized into an experimental substructure comprising the isolation system (elastomeric bearings) and a numerical substructure consisting of the piers and the deck. Taking advantage of the symmetry of the prototype bridge in the longitudinal and the transverse direction, each span can be modelled as a two-degree-of-freedom (2-DOF) system where the first degree of freedom corresponds to the horizontal displacement of the top of the pier and the second degree of freedom corresponds to the horizontal displacement of the deck. Assuming that the piers are fixed at the level of the top of the piles' cap, the stiffness of the pier, its mass, as well as the mass of the deck correspond to the 10 bearings that support the deck girders on the cap beam of the pier. The deck itself is modelled as a rigid mass. The stiffness and mass properties for the real structure (per 10 bearings) and for the numerical substructure (per pair of bearings) are summarized in Table 1.

Table 1. Properties of the prototype structure and of the corresponding numerical model

Model Parameter	Per 10 bearings (prototype)	Per pair of bearings (numerical model)
Pier stiffness (longitudinal) K_{xx}	2200 MN/m	440 MN/m
Pier stiffness (transverse) K_{yy}	13600 MN/m	2720 MN/m
Deck mass	917000 kg	183400 kg
Pier mass	430300 kg	58200 kg (effective)

The bearings used during testing are low-damping rubber bearings manufactured by ALGA (Type NB4 with an external diameter of 350 mm). Each bearing consists of 7 layers of rubber with a layer thickness of 11 mm and 6 steel shim plates with a thickness of 6 mm each. The total height of the bearing - including the external connection plates - is 181 mm, while the total rubber height is 77 mm. The theoretical horizontal stiffness for each bearing (with the assumption of rubber shear modulus G = 0.99 MPa) is K_H = 1237 kN/m.

2.3. Experimental setup

The experimental substructure consists of a pair of bearings placed in a "back-to-back" (parallel configuration. The relative displacement of the isolation system (i.e. the algebraic difference of the deck and pier displacements) is calculated by the pseudodynamic algorithm and physically imposed on the bearings at each step by means of a servohydraulic actuator (MTS, 500 kN force capacity, 50 cm stroke, 1500 lt/min servovalve). The measured reaction force is fed back to the algorithm and the solution proceeds to the next step. Simultaneously, a constant vertical load of 900 kN that corresponds to the deck's mass is imposed to the pair of bearings using a set of six hydraulic jacks. A schematic of the experimental setup is presented in Figure 1 while a close-up view of the pair of bearings is illustrated in Figure 2.

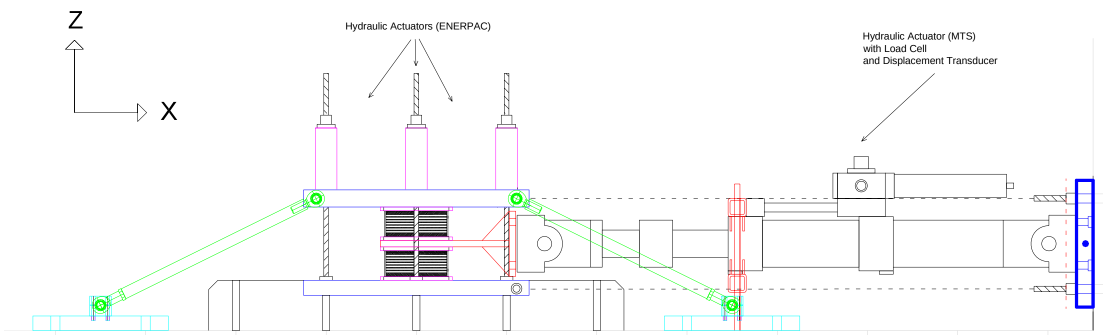

Figure 1. Schematic of the experimental setup

Figure 2. Photo of a pair of elastomeric bearings in parallel testing configuration

3. EXPERIMENTAL PROGRAM AND RESULTS

Two main categories of tests were executed within the context of the experimental program. The first category are the characterization tests that are necessary for determining the mechanical properties of the bearings at different rates of deformation and for calculating the strain rate correction parameters to be used at subsequent pseudodynamic (PsD) testing for each pair of bearings. The second category are the PsD tests that simulate the response of the numerical substructure and the experimental substructure for a given ground acceleration input.

3.1. Strain-rate effect compensation

Seismic isolators (in this case, elastomeric bearings) are devices whose behaviour varies significantly according to the rate of applied strain. Since pseudodynamic tests are normally performed at a "dilated" time scale (i.e. slower than in real-world conditions), it is necessary to devise a procedure so that at every test step the restoring force of the isolators is corrected so that it corresponds to the actual restoring force that would have been measured had the test been executed at real-time speed.

The continuous pseudodynamic algorithm used for the tests is embedded in the controller of the ELSA-PSD test system (Zapico and Molina, 2008a & 2008b): a number of *N* points are interpolated between two successive points of the input acceleration record with the equation of motion being solved *N* times at a frequency equal to the internal clock frequency of the controller (500 Hz or 2ms time step), taking *N* measurements of the restoring force and executing *N* substeps for each step of the acceleration record. If ΔT is the time increment of the acceleration record, Δt is the internal sampling time increment of the controller and *N* is the chosen by the user number of substeps, the time scaling factor is: $\lambda = \left(N \cdot \Delta t\right) / \Delta T$.

In order to obtain correction factors for compensating for the low strain rates of pseudodynamic tests with respect to real-time tests, one must resort to a series of strain-rate characterization tests during which the isolators are subjected to a predefined (usually harmonic) displacement history including a desired frequency band. The dominant frequency of the displacement history should be close to the first eigenfrequency of the structure. Also, the achieved level of strain should be similar to that expected during the subsequent pseudodynamic test. The characterization test is run successively at multiple "speeds" corresponding to different values of the time scaling factor λ, starting with λ = 1 (real-time) and proceeding with lower rates (λ = 10, λ = 100 etc.). Eventually a set of force vs. displacement curves is obtained, such as the ones presented in Figure 3. From the loops it is evident that the response of the elastomeric bearings varies according to test speed with a consistent tendency for less stiff response as speed (and strain rate) drops.

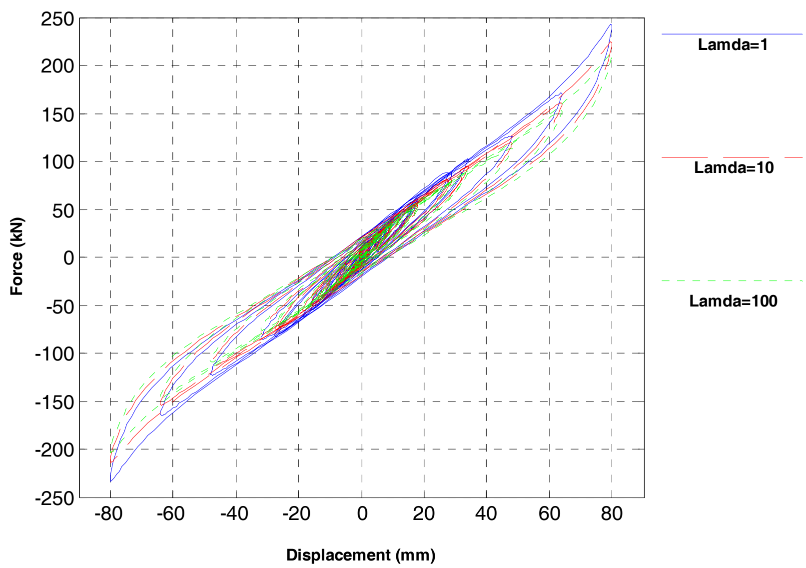

Figure 3. Uncorrected force vs. displacement loops from characterization test (CH14) for different values of time scaling factor λ (Lamda)

A force correction procedure proposed by Magonette et al. (1998) and Molina et al. (2002) and modified by Palios et. al (2007) has been implemented in the ELSA-PSD testing algorithm (Zapico & Molina, 2008a). The basic assumption of the strain-rate compensation procedure is that the correction of the measured force at the isolator (for a specific value of the time scaling factor λ) is used in the algorithm after adding a force term which is a function of the measured force, displacement, force rate and displacement rate (speed). This can be expressed as follows

$$F_{SRAdd} = F_0 \cdot F_{meas} + D_0 \cdot u_{meas} + F_1 \cdot \dot{F}_{meas} + D_1 \cdot \dot{u}_{meas} \quad (1)$$

where F_{SRAdd} is the additional force term that compensates for the strain-rate effects which is added to the measured restoring force and the sum being fed back to the PsD algorithm; F_{meas}, u_{meas}, $\dot{F}_{meas}$, $\dot{u}_{meas}$ are the measured restoring force, the measured displacement, the first time derivative of the force and the first time derivative of the displacement (i.e. speed); F_0, D_0, F_1, D_1 are parameters that need to be determined.

The parameters' determination procedure is basically a least squares regression technique where the "slow" loops (i.e. those obtained for $\lambda = 10$ or $\lambda = 100$) are transformed by the addition of a strain-rate force term according to Eqn. 1 so that they match the "real-time" loop obtained for $\lambda = 1$ (Tsitos and Bousias, 2012). The result of the correction procedure is illustrated in Figure 4, where the corrected loops obtained for $\lambda = 10$ or $\lambda = 100$ are almost identical with the "real-time" loop. The calculated parameters for the test series presented in Figure 3 and Figure 4 are summarized in Table 2.

It is emphasized that the correction factors must be always calculated for the specific strain-rate sensitive device just before PsD testing and, in the case of elastomeric bearings, are dependent on previous loading history. They are not globally valid and their values depend on the displacement history selected for the characterization tests (i.e. on strain levels and rates included therein). Thus, the input displacement history should be carefully selected, so as to match the predicted PsD response in terms of strain level and frequency content.

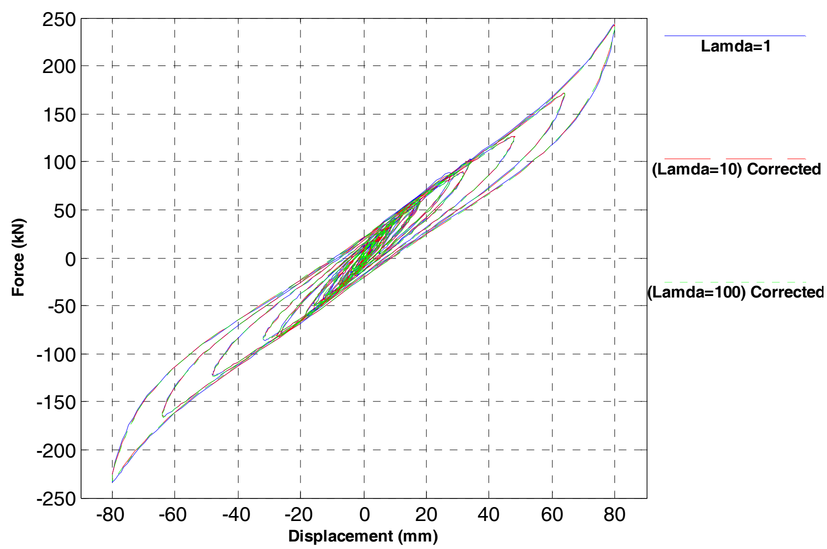

Figure 4. Corrected force vs. displacement loops from characterization test (CH14)

Table 2. Calculated parameters from characterization test

Chatecterization test CH14		
Correction Parameter	**λ = 10 (4 param.)**	**λ = 100 (4 param.)**
F_0	0.1768	0.2518
F_1	-0.0036	-0.0031
D_0	-0.264	-0.2896
D_1	0.0027	0.0018

3.2. Pseudodynamic tests

The earthquake input used for the pseudodynamic tests is an artificial accelerogram which was obtained by modifying a real record from the April 15, 1979 Montenegro earthquake, so that its spectrum matches the design spectrum of Eurocode 8 (CEN, 2004) for soil type C. The acceleration time history has a maximum value of 11.28 m/s^2 and consists of 1500 points with a time discretization of 0.01 s, adding up to a total prototype time duration of 15 s.

The pseudodynamic tests were performed with a time scaling factor $\lambda = 10$ (i.e. 10 times slower than the prototype time) and a force correction procedure was used, as explained in Section 3.1. The numerical substructure is the two degree-of-freedom simplified model presented in Section 2.2. The experimental substructure is the pair of elastomeric isolators and the applied (by the actuator) displacement corresponds to the relative displacement of the two DOF's (i.e. the displacement of the isolation system). Two pairs of isolators were used for the pseudodynamic testing. Prior to the PsD tests, each pair was subjected to a characterization test series for the determination of the force correction parameters. It is noted that the PsD tests were run with scaled-down acceleration input with a factor of 25% maximum, as it was not expected that the specific type of elastomeric bearings would withstand higher intensities. The main focus of the testing program was to verify the ability to perform fast, large amplitude characterization tests, in order to determine force correction parameters for subsequent use in PsD testing. The speed selected for the pseudodynamic tests (λ = 10) is approximately one order of magnitude faster than that used in similar testing of rate-dependent systems (see Molina et al., 2002, Bousias et al., 2005).

Representative results of a pseudodynamic (PD10) test are presented from Figure 5 to Figure 8. In this test the maximum achieved seismic input intensity was approximately 20% *g* before bearing failure occurred. The response histories of the measured restoring force (load cell), the additional strain-rate correction force and the total computed corrected force are plotted in Figure 5. The bearing measured force vs. strain loops (for a single bearing – not the pair) are presented in Figure 6. The top bearing failed at a strain level equal to 145% at prototype time 12.2 s but it did not disintegrate (local un-bonding of rubber from shim plate), which permitted the completion of the test. The loops are obviously pinched at shear strain levels above 100%. The displacement response histories of the two degrees of freedom (pier and deck) are illustrated in Figure 7. Finally, a photograph depicting the deformed state of the bearings during test PD10 is presented in Figure 8. Note that the bottom bearing of the pair has already started failing, as can be seen from the small tear in the cover rubber layer on the right-hand side.

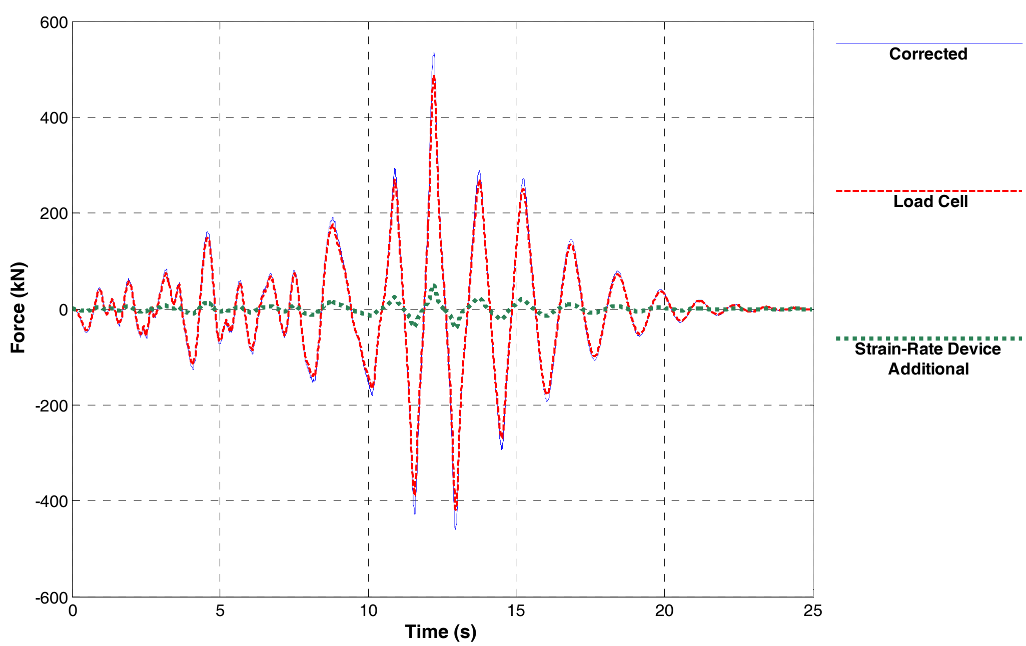

Figure 5. Total corrected force (blue solid line), load cell measured force (red dashed line) and additional strain-rate compensation force (green dotted line) time-histories (PsD test PD10)

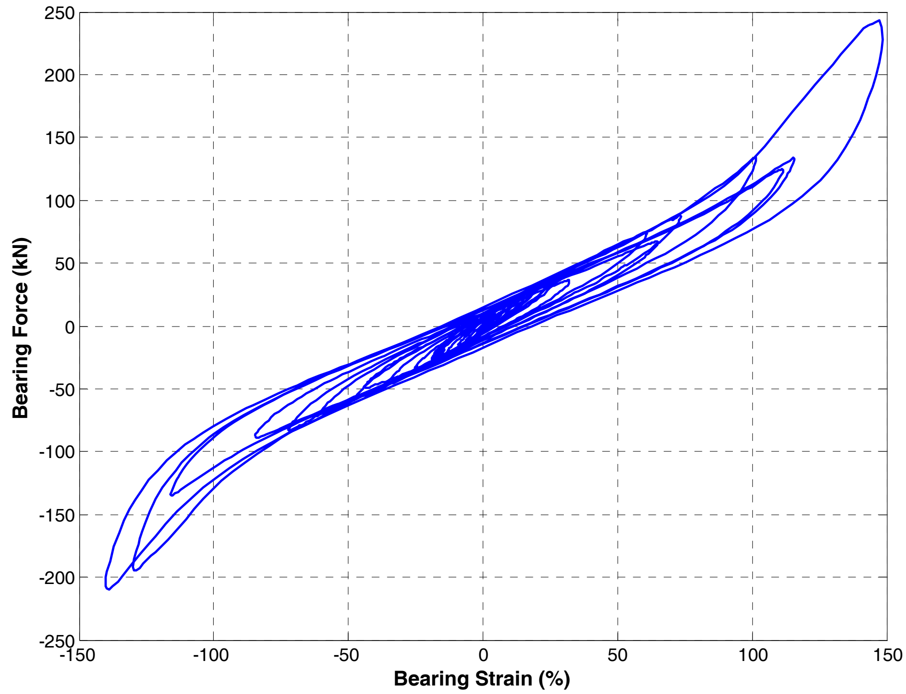

Figure 6. Bearing force vs. bearing strain loops (PsD test PD10)

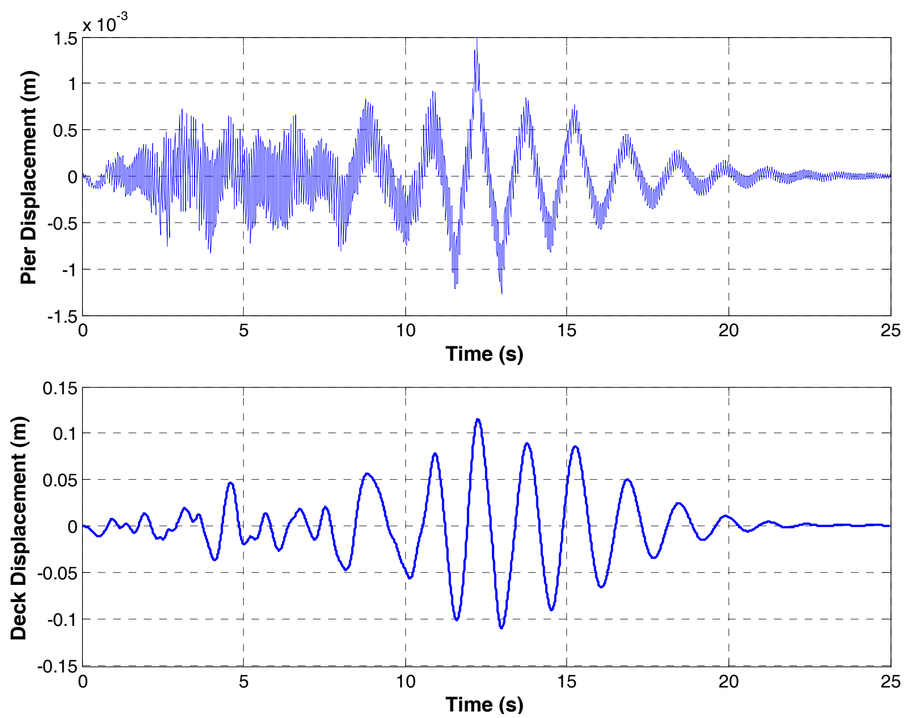

Figure 7. Pier and deck displacement response histories (PsD test PD10)

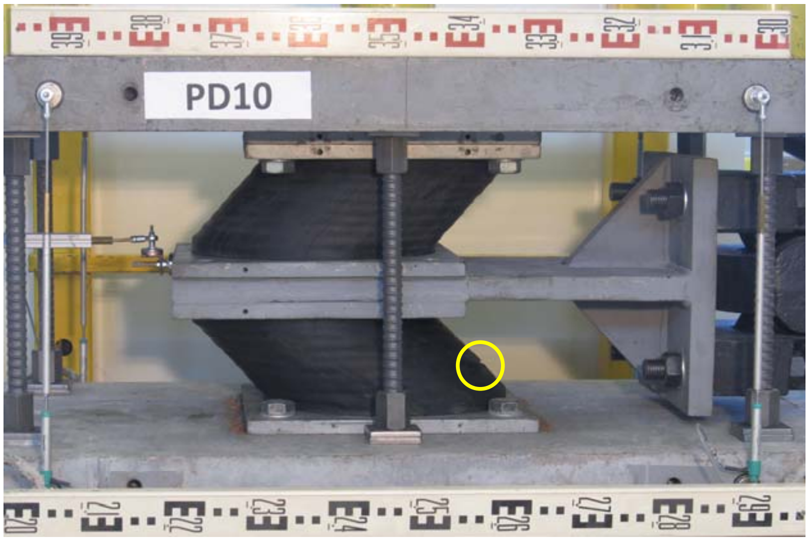

Figure 8. Deformed bearings at failure – note the damage in the yellow circle (PsD test PD10)

In order to validate the force correction procedure presented in Section 3.1, preliminary PsD tests were run with an accelerogram intensity of 7.5% g for two values of the time scaling factor: λ = 100 ("slow" tests) and λ = 10 ("fast" tests). A four-parameter online force correction scheme was applied in all cases, as has already been explained. A characteristic comparative result from those tests is presented in Figure 9 in the form of force vs. displacement plots from two pseudodynamic tests ("slow" test PD01 and "fast" PD04). The set of correction parameters used in each of the aforementioned tests was different and had previously been obtained through a characterization test series. From the loop plots in Figure 9 it can be observed that the response of the isolation system is practically identical for both tests.

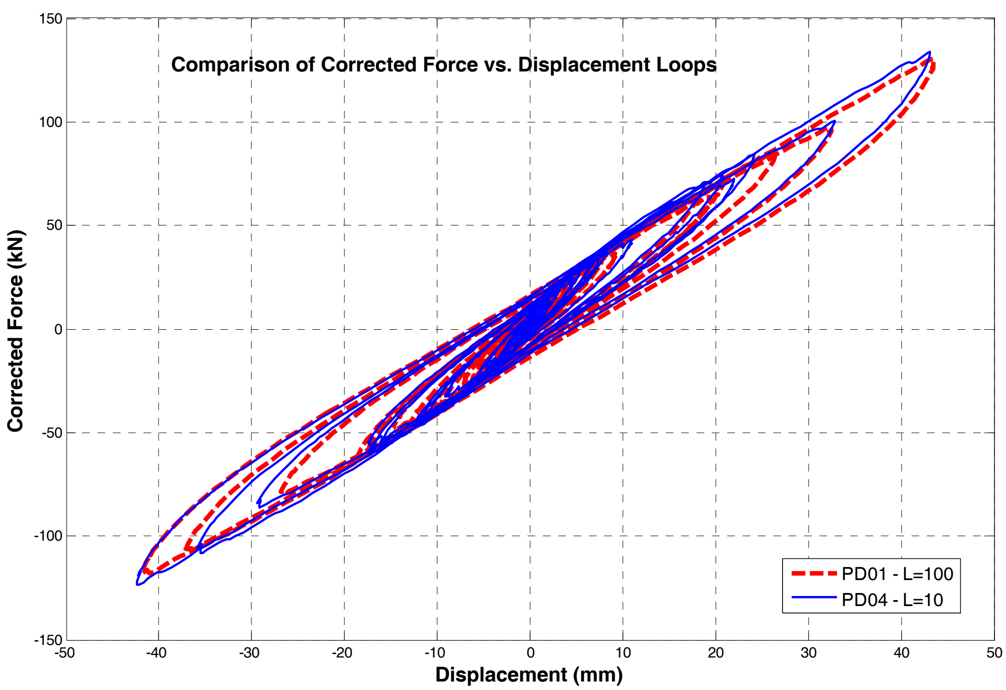

Figure 9. Comparison of corrected restoring force vs. displacement loops between "slow" PsD test PD01 (λ =100) and "fast" PsD test PD04 (λ = 10)

4. CONCLUSIONS

An experimental setup was constructed enabling the execution of high velocity and high strain characterization tests on elastomeric bearings. The characterization tests were used for determining force correction parameters in order to compensate for the strain-rate effect in slower than real-time pseudodynamic (PsD) tests. The force correction parameters were calculated on the basis of a least squares regression method, in which force vs. displacement loops obtained from “slow” tests were fitted to “real-time” loops. It was found that the force correction parameters differ for each pair of bearings and, in order to accurately represent the intended response, should be evaluated immediately prior to the respective PsD test and at comparable strain levels and frequencies with those to be developed during the actual PsD test.

The calculated parameters were used in a series of PsD tests that demonstrated the ability to use a time scaling factor equal to 10, which is at least an order of magnitude faster than similar previous tests. In terms of performance of the isolation system, it was concluded that the tested configuration which employed only low damping elastomeric bearings was inadequate per se for the seismic protection of the bridge structure, as failure - for seismic input with peak ground acceleration ranging from 20% of *g* to 25% *g* - occurred at shear strain around 150% which is lower than that prescribed by current codes of practice.

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