EXPERIMENTAL STUDY OF BRIDGE SEISMIC ISOLATION SYSTEMS WITH OR WITHOUT SUPPLEMENTAL ENERGY

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ABSTRACT :

The seismic response of isolated bridges is studied experimentally for three different isolation systems which provide, separately or in combination, lengthening of the period and additional energy dissipation. A multi-span highway bridge is subjected to hybrid (sub-structured pseudodynamic) testing, with on-line correction of the measured restoring forces for the velocity-dependent properties of the isolation devices. Common (low damping) elastomeric bearings, lead-rubber bearings (LRBs) and elastomeric bearings coupled with magneto-inductive dissipation devices were tested at several levels of excitation. A broad parametric experimental study was conducted regarding the influence of certain parameters such as the mass of the deck and the level of ground motion. The elastomeric bearings did not satisfy the design requirement of 200% strain at ultimate, but displayed a somewhat higher damping ratio than anticipated. The LRBs provided effective bridge protection reaching almost a strain level of 175% at ultimate and an effective damping ratio of 16%. The combination of elastomeric bearings with a magneto-inductive damper proved to be extremely efficient in containing the response and protecting both the bridge and the bearings.

KEYWORDS: Bridges, hybrid testing, isolation devices, seismic isolation, sub-structuring

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, while viscous dampers, elasto-plastic devices or high damping bearings often provide the desired energy dissipation. There is no consensus yet on whether lengthening of the period may sometimes be sufficient or whether additional energy dissipation is essential. To contribute to this question with additional information, an experimental programme was carried out on the seismic response of bridges on flexible bearings, with or without energy dissipation. Attention is exclusively focused on the physically tested isolation and dissipation system belonging in a bridge. The influence of certain variables (pier stiffness, deck mass, input acceleration level) on the response of the isolated bridge and the performance of the isolation devices is studied by hybrid pseudodynamic testing. Those cases where failure of the device took place but the test was carried out to the end regardless, give the opportunity to evaluate the effect of such an event on the subsequent response.

2. EXPERIMENTAL PROGRAM

2.1 Specimen description and experimental setup

The testing program used as reference an actual 12-span highway bridge (Fig. 1). Piers are 5.8 m-high, their cross-section consists of a rectangular central part 4.0m in the transverse direction by 2.5m in the longitudinal, with two semicircular ends, 2.5m in diameter. For each carriageway the deck consists of five 38m-long prestressed T-girders at 3m spacing, simply-supported at the piers. The superstructure is supported at the abutments and the piers on common (low damping) elastomeric bearings. Viscous dampers are employed between the top of the pier and the central beam of each span in the longitudinal and transverse directions.

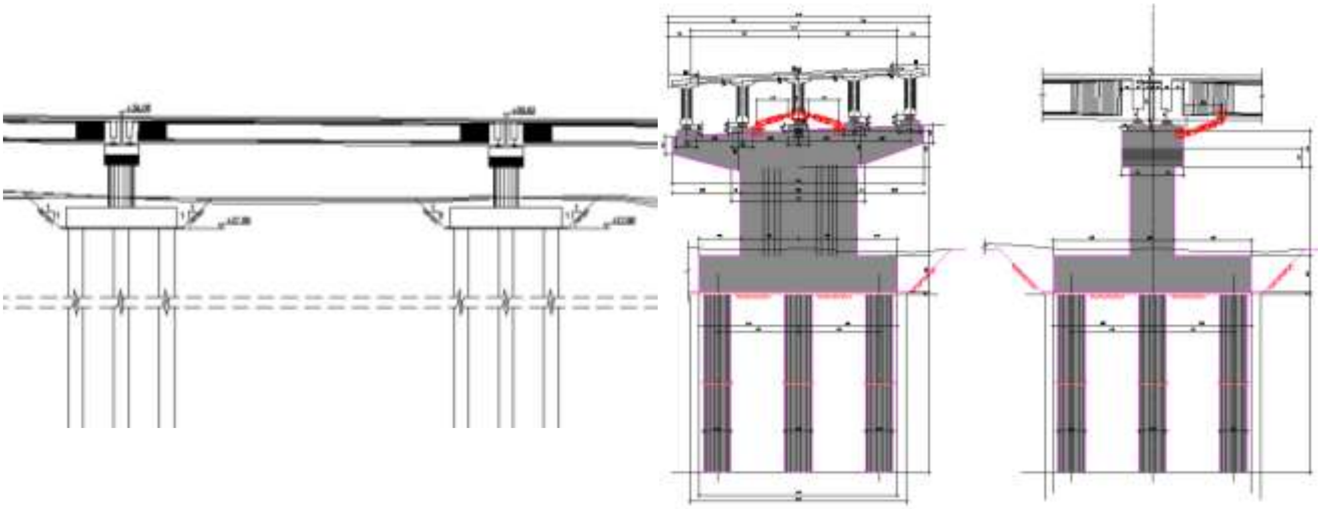

Figure 1 Bridge layout: typical span (left), piers and deck support in the transverse and longitudinal direction

Figure 2 Elastomeric bearing (left) and magneto-inductive energy dissipation device (right) used in the tests.

Hybrid testing in the longitudinal bridge direction used two different types of bearings (Fig. 2): a) 350mm-dia. low-damping elastomeric bearings with seven 11mm-thick rubber layers (77mm total effective thickness), 8mm-thick steel plates in-between and two external steel plates (total height of 181mm); b) 300mm-dia. Lead Rubber Bearings (LRB), with ten 8mm-thick rubber layers and a 30mm-dia. lead core for energy dissipation. A velocity-dependent magneto-inductive energy dissipation device with 250kN force and 250mm displacement capacity .n device has been used in some tests together with the elastomeric bearings.

In the present hybrid tests the bridge is modelled as a two degree-of-freedom (DoF) system. Piers are modelled analytically as elastic throughout the response. The deck is taken rigid. Non-linear response is considered to be limited to the isolation and energy dissipation systems, which are the only physically tested components. In the pseudodynamic method the equations of motion of the full (in this case two-DoF) system are solved numerically at each step of the test on the basis of the measured restoring forces, to determine the displacement increment to be imposed at the next step. Structures with constant viscous damping may be tested at slow displacement rates with hybrid techniques without ambiguities. By contrast, if rubber bearings or other isolation devices are tested at slow rates, the effect of the rate-dependency of their properties should be accounted for. To this end, a special procedure proposed by Molina et al. (1998) has been modified by Palios et al. (2007): a series of sinusoidal cycles are applied to the device at a variety of testing frequencies. The reference test, at the fastest testing rate, takes place at the fundamental frequency of the structure ($\lambda = 1$, λ being the time-dilatation factor, i.e. the ratio of the testing time-step to that of the input accelerogram). The other tests of the series use as input the same displacement history as the reference test, but at slower rates (λ =3, 10, 30, 75, 100). Due to the strain rate effect, the restoring force, F, corresponding to given displacement, u, is taken to depend on λ as:

$$F(\lambda_o) = f_o(\lambda)F(\lambda) + d_o(\lambda)u(\lambda) + f_1(\lambda)\dot{F}(\lambda) + d_1(\lambda)\dot{u}(\lambda) \tag{2.1}$$

where $F(\lambda), u(\lambda), \dot{F}(\lambda), \dot{u}(\lambda)$ are the measured force, displacement, force rate and velocity at a test with slower strain rate λ. Factors $f_o(\lambda), d_o(\lambda), f_1(\lambda), d_1(\lambda)$ are determined via a least-squares fitting of the test results at the two different strain rates. For example, with λ_o=1 and units in kN, mm, the respective correction factors for elastomeric bearings tested at λ=3 or λ =100 are:

- $f_o(3) = 1.0781$, $d_o(3) = 0.0049$, $f_1(3) = -0.1385$, $d_1(3) = -0.0207$, and,
- $f_o(100) = 1.2004$, $d_o(100) = 0.0041$, $f_1(100) = -0.1135$, $d_1(100) = -0.019$,

respectively, showing the relative importance of the various factors. The effectiveness of the method is shown in Fig. 3 presenting the respective force-displacement loops before (left) and after (right) applying the proposed method. The hybrid pseudodynamic tests presented here have been carried out with a time scaling factor (duration of pseudodynamic test to that of the ground motion) λ = 75, correcting internally the restoring force according to the force-correction factors established as above.

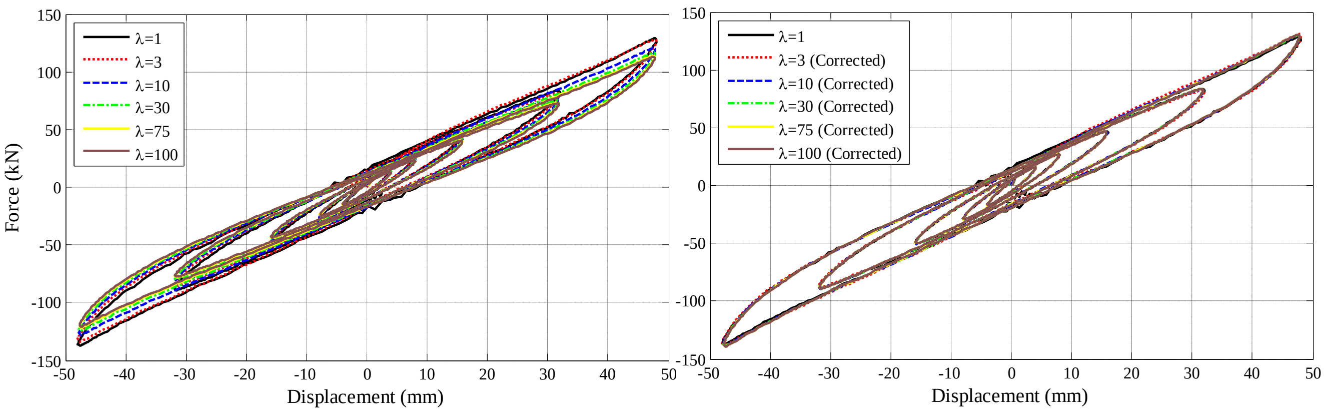

Figure 3 Force-displacement loops of elastomeric bearings at different testing rates, before (left) and after correction (right).

Figure 4 Experimental set-up for testing: elastomeric bearings (left), elastomeric bearings combined with magneto-inductive device (right)

LRBs or elastomeric bearings were tested in a back-to-back configuration (Fig. 4). The energy dissipation device was connected to the steel plate in-between the two back-to-back bearings (Fig. 4, right). A load cell between the device and the steel plate between the bearings recorded the fraction of the force imposed on the magneto-inductive device; the rest (total force measured by the actuator load cell minus that taken by the device) goes to the two bearings. A constant axial force of 900kN was applied on the top plate of the setup by six jacks.

A 20sec-long ground motion fitting the Eurocode 8 spectrum for Soil C (stiff soil) was applied.

In each testing series employing different type of devices parametric tests were carried out with parameters: (i) the Peak Ground Acceleration (PGA) of the applied ground motion, (ii) the mass of the deck and (iii) the stiffness of the piers, (the two later parameters analytically treated). The base case has the actual longitudinal pier stiffness (K=2200 MN/m), the actual deck mass (M=917000 kg) and effective mass of pier (430300 kg) tributary to the two bearings being tested.

2.2 Low damping elastomeric bearings

In this series of tests the ground motion is scaled to a PGA of 0.075g, 0.15g, 0.20g and 0.25g. Measured response increased about proportionally to the PGA (Fig. 5). The bearings failed during the 0.25g test at a shear strain in the elastomer between 110% and 190%. In tests where the shear strain exceeded 100%, a nonlinear increase in stiffness (hardening) was observed (Fig. 6) and the rubber exhibited significant lateral expansion.

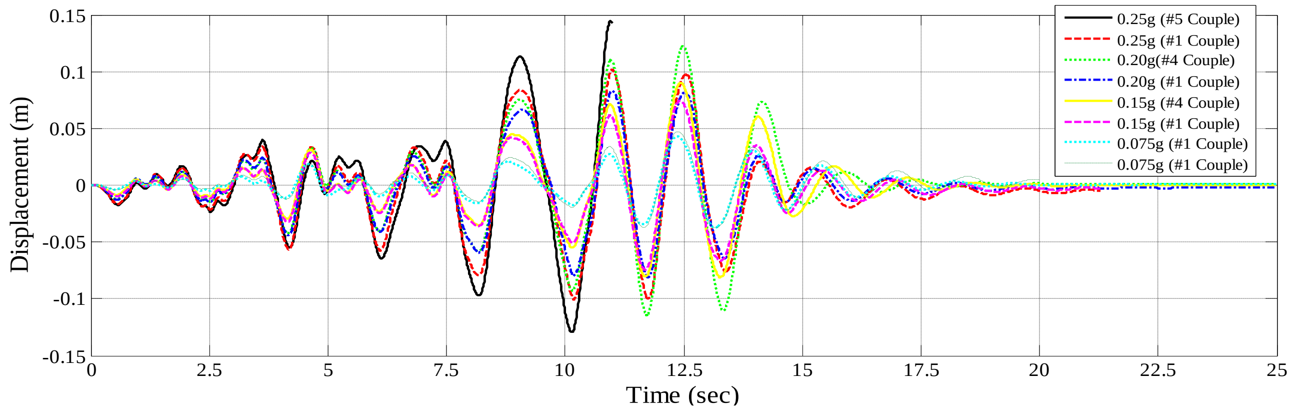

Figure 5 Response of deck on elastomeric bearings alone for different PGA levels

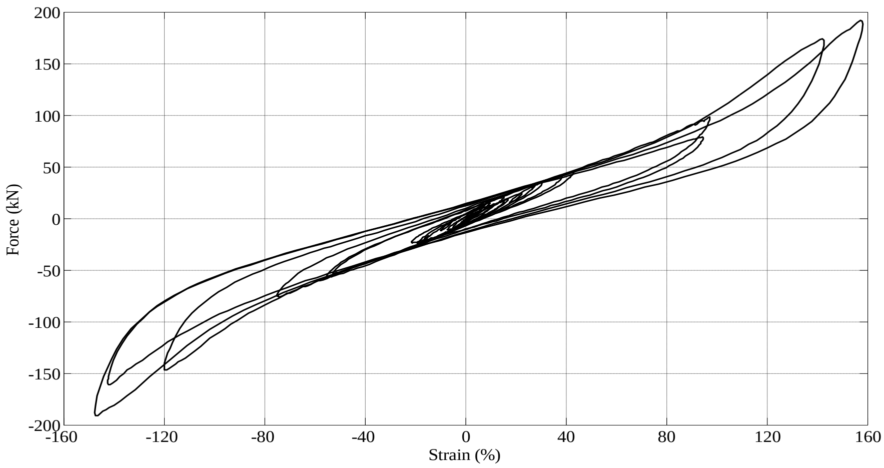

Figure 6 Force-deformation response of elastomeric bearings tested at a PGA of 0.20g

The effect of the deck mass was studied by doubling or halving its base value (Fig. 7). The increase in response displacement when the mass is doubled led to bearing failure even at a PGA of 0.20g (Fig. 7, top).

To examine the effect of bearing delamination on the subsequent response, a test at 0.25g PGA was carried out with the numerically assigned stiffness of the pier equal to one-tenth the basic (actual) stiffness, to increase the displacement response. Fig. 8 depicts the response of the bearings, for both the basic case of pier stiffness and for one-tenth that value, showing that failure of certain bearings may not necessarily increase significantly the displacement response.

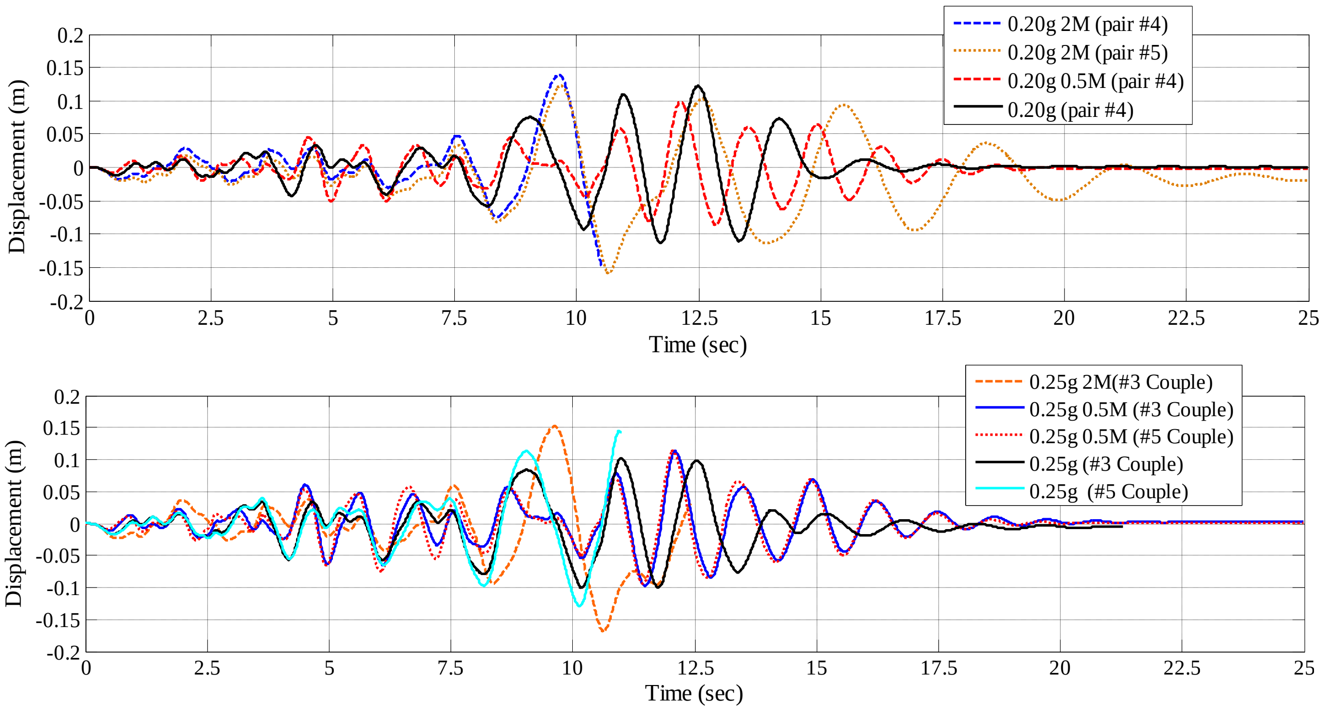

Figure 7 Effect of deck mass on response of deck on elastomeric pads at a PGA of 0.2g (top) or 0.25g (bottom)

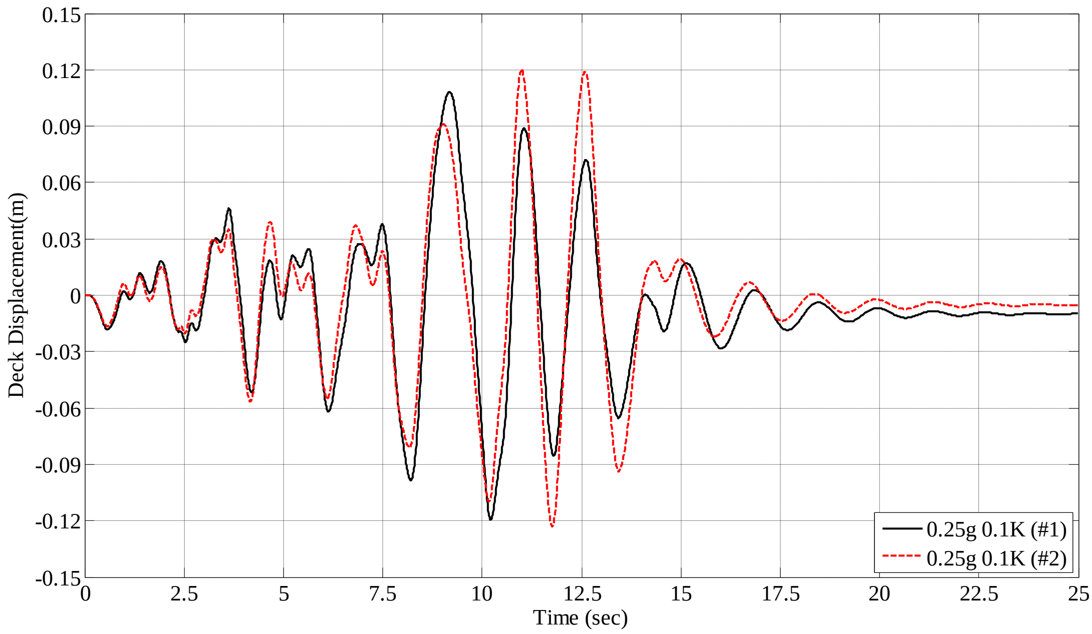

Figure 8 Force-displacement loops of elastomeric bearings for a PGA of 0.25g

Pairs of elastomeric bearings that did not fail were often used in a follow-up test under a larger PGA, to see their sensitivity to prior loading. Previous testing at lower or similar strain levels was not found to markedly affect the response (i.e., “scragging” was not significant).

The secant stiffness of the bearings to the peak of each half-cycle and an equivalent viscous damping ratio (i.e., the hysteretic energy dissipation in the half-cycle divided by the product of the peak displacement and peak force of the half-cycle times π) were determined from the measured force-displacement loops. Fig. 9 (left) shows that the stiffness stays practically constant after the shear strain in the elastomer exceeds 20%. The low strain stiffness corresponds to the shear modulus value of 1MPa given for the rubber. The equivalent viscous damping is well above the default value of 5% used in design, especially at low shear strains (Fig. 9, right).

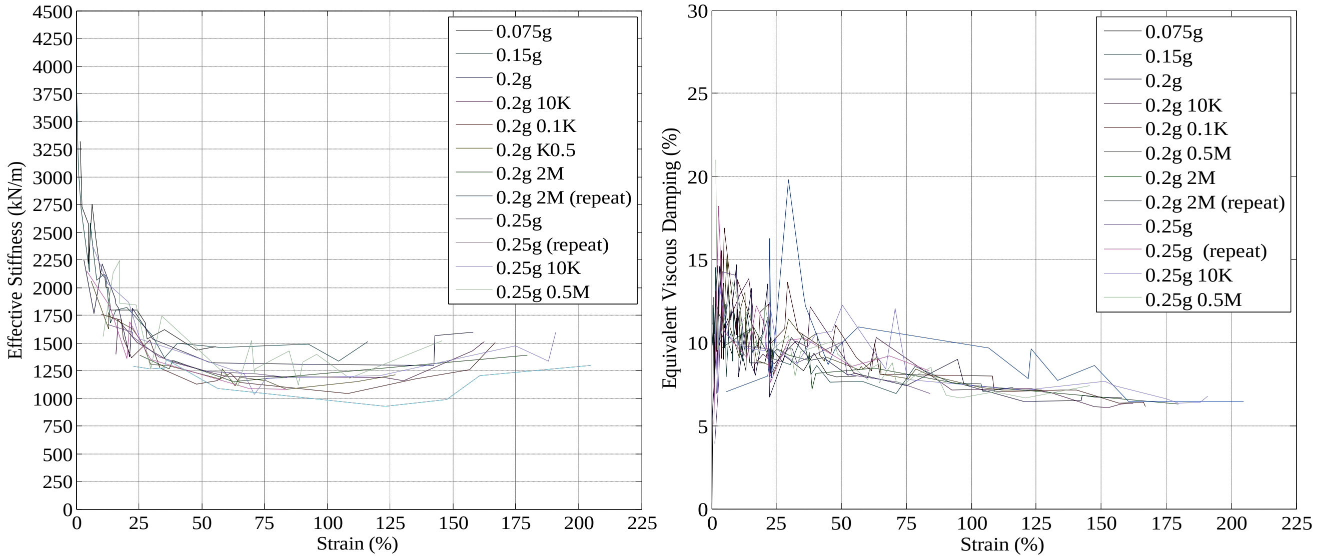

Figure 9 Secant stiffness of bearing to peak displacement (left) and effective viscous damping (right) in all pseudodynamic tests employing elastomeric bearings

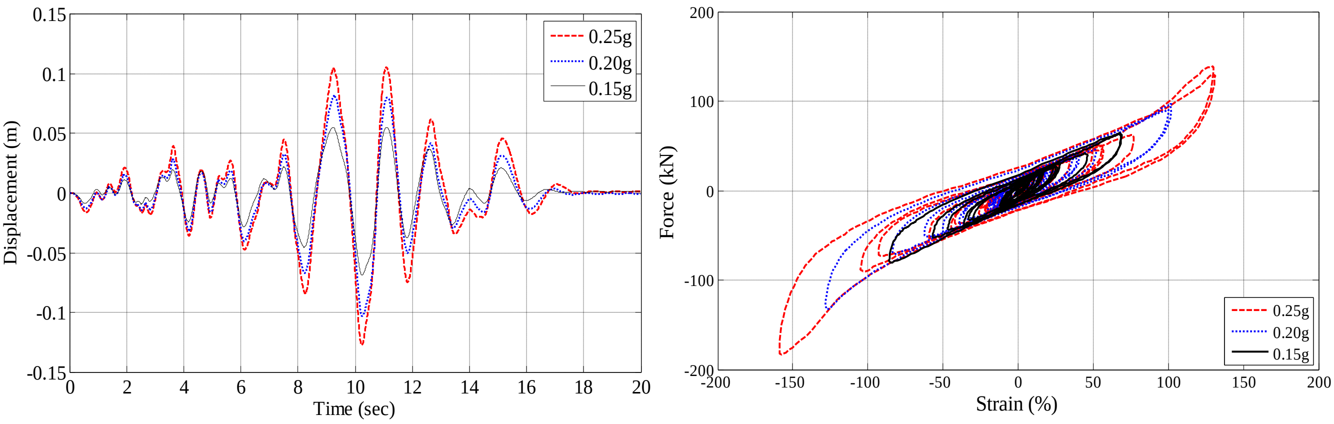

Figure 10 Effect of PGA level on the deck-on-LRBs displacement (left) and on the LRB force-strain loops (right)

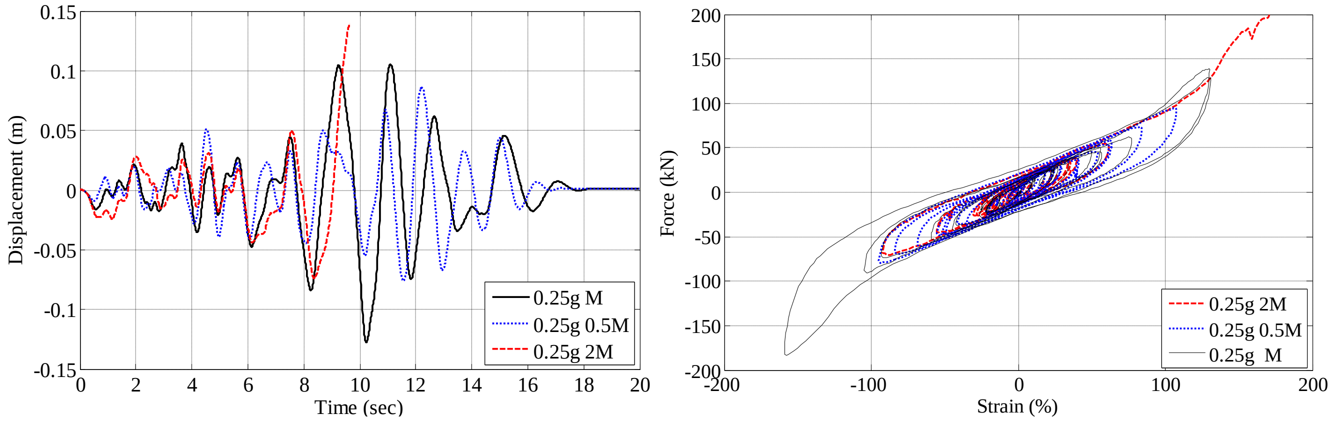

Figure 11 Effect of deck mass on deck displacement (left) and the force-strain response (right) of bridges on LRBs

2.3 Lead Rubber Bearings

In the tests with the LRBs the ground motion was scaled to a PGA of 0.15g, 0.20g or 0.25g. Owing to the energy dissipation in the lead core (the effective viscous damping ratio derived from the force-displacement loops is about 16%), the deck displacements (Fig. 10, left) were much lower than in the bridge on elastomeric pads under the same ground motion. The parametric studies confirmed the marked effect of the deck mass found for elastomeric bearings. Doubling the mass over the base case led to failure of the LRBs at a shear strain of 170% under the 0.25g PGA motion (Fig. 11).

2.4 Low damping elastomeric bearings with magneto-inductive damper

The pseudodynamic tests of the bridge with elastomeric bearings combined with a magneto-inductive damper were carried out for PGA levels from 0.075g to 0.60g. They were preceded by a series of characterization tests on the dissipation devices under different loading rates (Fig. 12).

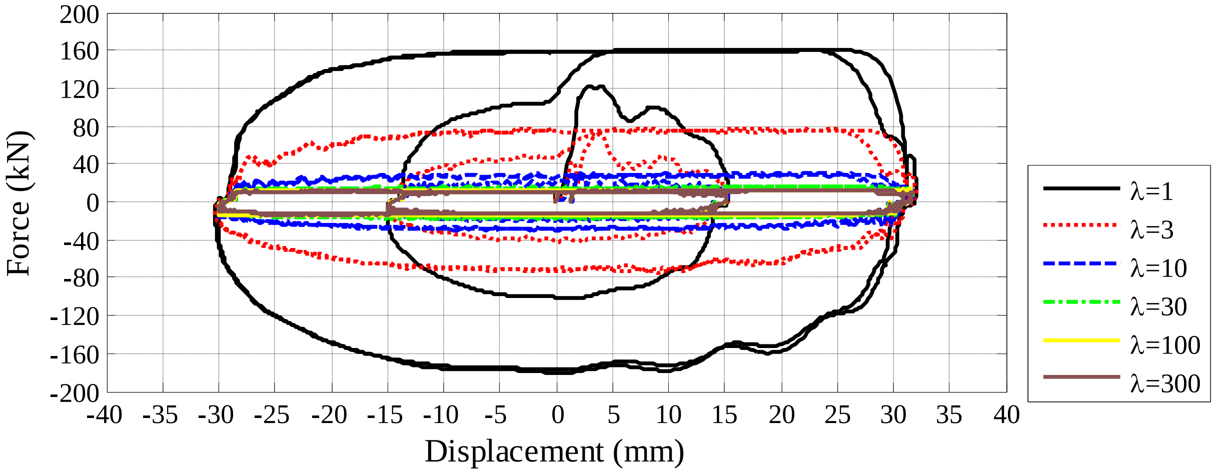

Figure 12 Representative response of magneto-inductive dissipation device under different loading rates (λ =1 ÷ 300)

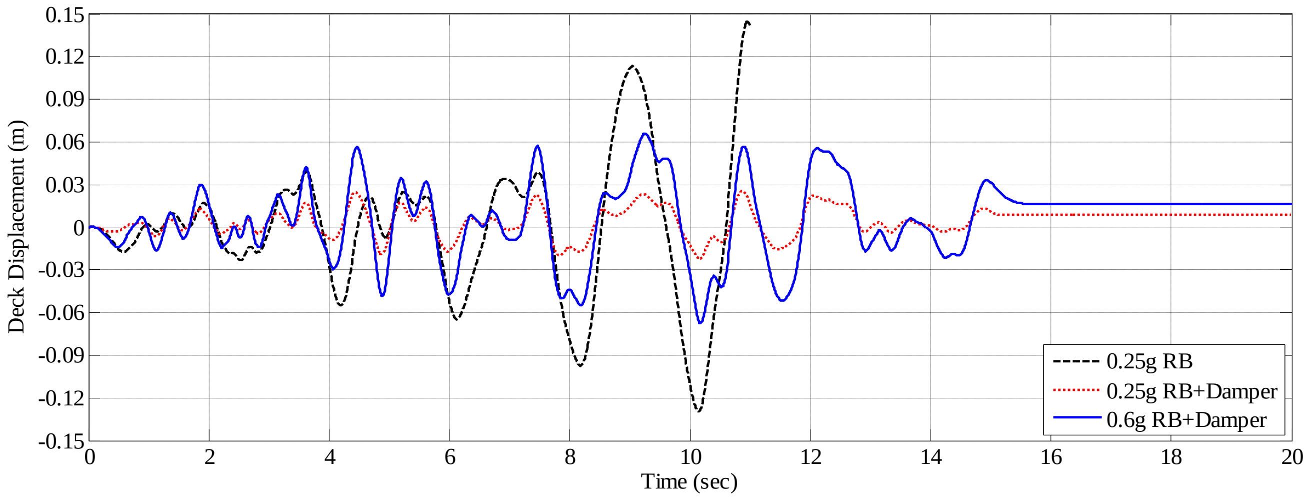

Figure 13 Deck displacements in a bridge on elastomeric pads alone under 0.25g PGA motion (dotted line) and with elastomeric pads and magneto-inductive damper at PGA of 0.25g (broken line) or 0.60g (continuous line).

In the hybrid tests carried out of bridges on elastomeric bearings with magneto-inductive dissipation device, no damage whatsoever took place even under the 0.60g PGA. Peak shear strains of the bearings increased from 15% at a 0.075g PGA to 120% at the PGA of 0.6g. Fig. 13 contrasts the response to the 0.25g PGA motion of a deck on just elastomeric bearings that failed at a strain of 150% (dotted line), to that in the (same) bridge with added magneto-inductive dissipation devices. The reduction of displacements effected by the device for the same PGA level (broken line) is dramatic. Thanks to the device, the elastomeric bearings escape failure even at a PGA of 0.60g (continuous line). Witness, though, the permanent offset at the end of each test, in the order of one-third of peak response, to be contrasted with the almost full recentring achieved with the LRBs or the elastomeric pads alone. The elasticity of the bearing cannot fully recentre the isolation system, as the force in the dissipation device is much larger than in the bearings (especially if the response velocity is high) and governs the response.

An overall equivalent damping ratio of a linear system may be estimated from the area of the force-displacement loops of the global response, representing the energy dissipated by the entire non-linear system. Depending on the level of excitation this estimate is around 50-60% of critical damping, i.e., close to that of a rigid-perfectly plastic isolator.

3. CONCLUSIONS

Hybrid tests with sub-structuring (pseudodynamic physical testing of certain components combined with mathematical modeling of the rest of the simulated system) have been carried out on a seismically isolated bridge, including strain rate compensation. Laminated elastomeric pads, alone or with supplemental energy dissipation, or Lead Rubber Bearings (LRBs) were used as isolation devices.

Despite their higher than expected damping (about 8%) low damping elastomeric pads used alone led to large displacements at the pier-deck interface and failed at fairly low shear strains (about 150%, lower than their design target of 200%). Notwithstanding failure of one of the two bearings, tests carried out to the end show no noticeable effect of this failure on the response displacements.

LRBs have shown an effective damping ratio in the order of 16% of critical. They failed at higher shear strain than the low-damping elasomeric bearings (170%), but still below the design target of 200%.

Magneto-inductive dampers used in combination to low damping elastomeric pads proved very effective for the reduction of the response to levels quite safe for the elastomeric bearings, even at PGA levels of 0.60g.

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