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DYNAMIC AND PSEUDODYNAMIC RESPONSES IN A TWO-STOREY BUILDING RETROFITTED WITH RATE-SENSITIVE RUBBER DISSIPATORS

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SUMMARY

Pseudodynamic testing is currently a well-developed and reliable technique that many times constitutes the only alternative for the seismic testing of large-size specimens. However, although the pseudodynamic technique is applicable to many types of structures or substructures made of usual building materials, some concerns still exist for materials showing a considerable strain-rate effect. High-damping rubber devices, which can be used as isolators or dissipators, do exhibit a strong strain-rate effect which can rise differences of up to 45% between the dynamic and the quasistatic stress in the device. Nevertheless, from the analysis of this phenomenon for the specific material, a simple model can be identified which is able to reconstruct the dynamic force by knowing the quasistatic one and the ratio of speeds between the real dynamic event and the pseudodynamic test. Once this correction is on-line introduced into the pseudodynamic integration of the response, the results of the test for structures containing this kind of materials can almost be as reliable as for conventional (non strain-rate sensitive) ones. The developed pseudodynamic testing technique has been successfully applied to the seismic assessment of a full-size two-storey reinforced-concrete structure retrofitted with high-damping rubber dissipators. Additionally, a small-amplitude real-dynamic random test was done in order to check the accuracy of the developed pseudodynamic technique.

INTRODUCTION

Within the frame of the BRITE EURAM collaborative project REEDS dedicated to the improvement of energy dissipation devices, a reinforced concrete building retrofitted with high-damping rubber dissipators has been seismically tested at the ELSA laboratory of the Joint Research Centre of the European Commission. For such a large specimen, the shaking table test was not feasible and also the pseudodynamic (PsD) method might in principle present some difficulties due to the strain-rate-effect (SRE) in the rubber devices. Usually, for common building materials, the errors due to the SRE introduced by a PsD test may be disregarded since they are less important than the existing variability from specimen to specimen [Gutierrez et al, 1993]. However, for elastomeric devices, a decrease of testing speed of two or three orders of magnitude --as is usual for a PsD test-- may introduce considerable changes in the stress-strain behaviour, especially for filled rubber [Kelly, 1993]. These changes may be described as a proportional loss of force susceptible of on-line correction within the PsD method [Molina et al, 1996] as was successfully implemented in the tests described in this paper.

STRAIN-RATE-EFFECT CHARACTERISATION

Characterisation test of the dissipator devices

The dissipator devices used for the tests were produced by TARRC. They consisted of a 7 mm-deep layer of high-damping rubber glued between two steel plates in the form of a sandwich. Thus, the parallel sliding of one plate with respect to the other implies a shear deformation into the rubber layer. The design strain for these devices was of 100%, which corresponded to 7 mm of relative displacement between the plates.

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In order to characterise the cyclic behaviour of the dissipators, one couple of them was tested by setting one onto the other. The internal two plates were fixed to each other and to a servocontrolled hydraulic piston, while the external two plates of the set were anchored to a reaction block. A high-resolution optical transducer was installed to measure the deformation at the dissipator level. This testing set-up allowed imposing prescribed displacement histories at different speeds, while the required force was measured through the load cell provided with the piston.

The performed characterisation test consisted of the imposition of sinusoidal cycles of different decreasing amplitudes (7.5, 6.0, 4.5, 3.0 and 1.5 mm) at a frequency of 1 Hz (at the original reference speed) and followed by a random history with significant frequency content up to 4 Hz. As shown in Figure 1, the first amplitude (7.5 mm) was repeated four times in order to obtain an stabilised behaviour before starting the decreasing amplitude series. This history of displacement was executed at the original reference speed (λ=1) and then at speeds λ=3, 10, 30,100 and 300 times slower in order to analyse the effect of the strain rate on the measured force.

Equivalent stiffness and damping

At every speed, for each one of the sinusoidal cycles, linear equivalent stiffness and damping parameters were calculated. To this purpose, from the corresponding force-displacement cycle, an equivalent linear viscoelastic elliptic loop was identified by doing the following operations:

- The absorbed energy E_{abs} was computed by performing the integral of the force by the differential displacement.
- At every point, an equivalent damping force was defined as the point in an ellipse with the horizontal diameter equal to the displacement range of the cycle and an area equal to the absorbed energy.
- At every point, an equivalent elastic force was defined as the difference between the measured force and the previously defined equivalent damping force.
- To the loop of the so defined elastic force with respect to the displacement, a linear regression was applied and the equivalent stiffness *k* was defined as the corresponding slope.
- The equivalent linear viscous damping ratio was computed as $\zeta = \dfrac{E_{abs}}{4\pi \dfrac{kD^2}{2}}$ where D is the displacement amplitude.

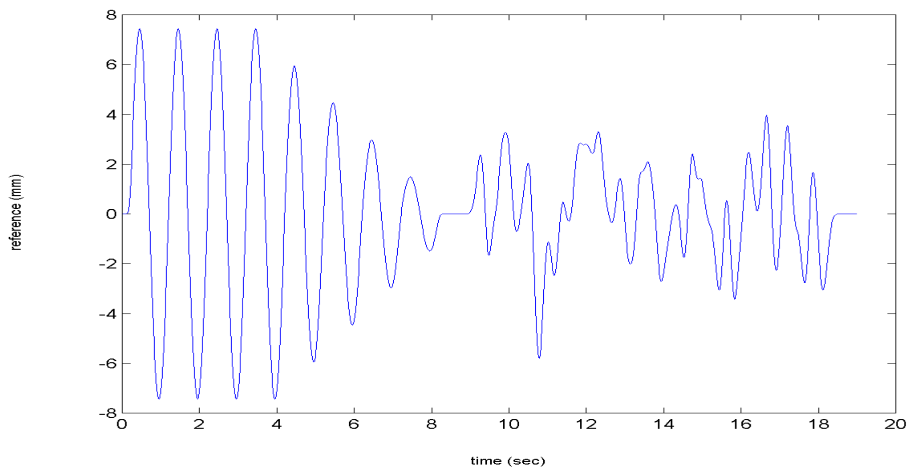


Figure 1. History of imposed displacement for the strain-rate-effect characterization test.

The obtained values for the equivalent stiffness are plotted in Figure 2 as a function of the time scale λ and for every displacement amplitude. It can be seen how the apparent stiffness diminishes considerably for the slow tests with this type of rubber. The same figure also shows that for the smaller amplitudes the stiffness grows rapidly, while for the larger amplitudes the value of the stiffness is more stable diminishing up to a point (around 100% of deformation) after which it starts to grow slowly.

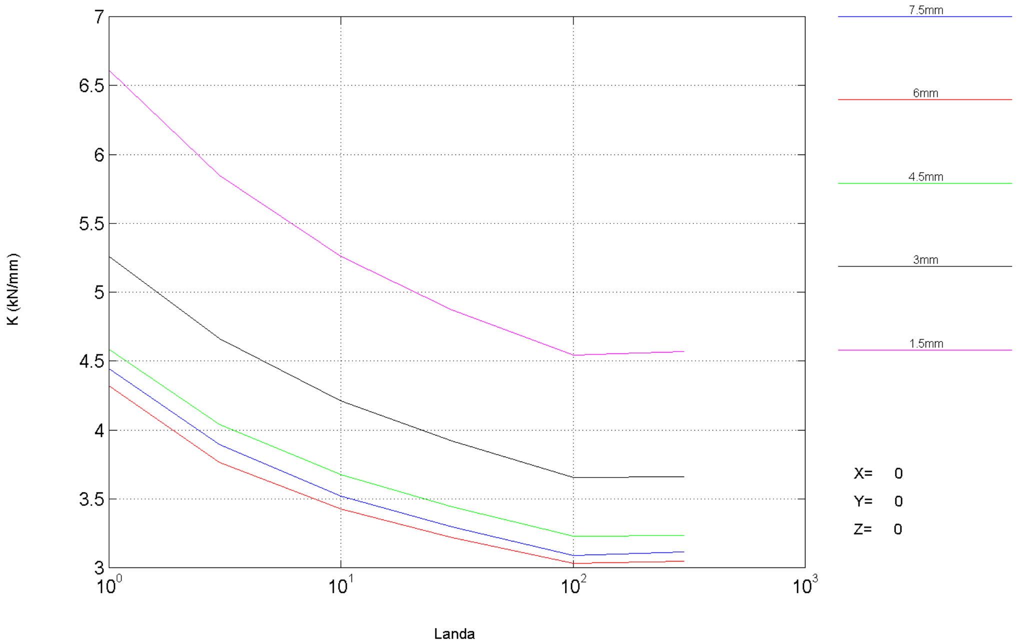


Figure 2. Equivalent stiffness as a function of the test time scale (Landa) and the displacement amplitude.

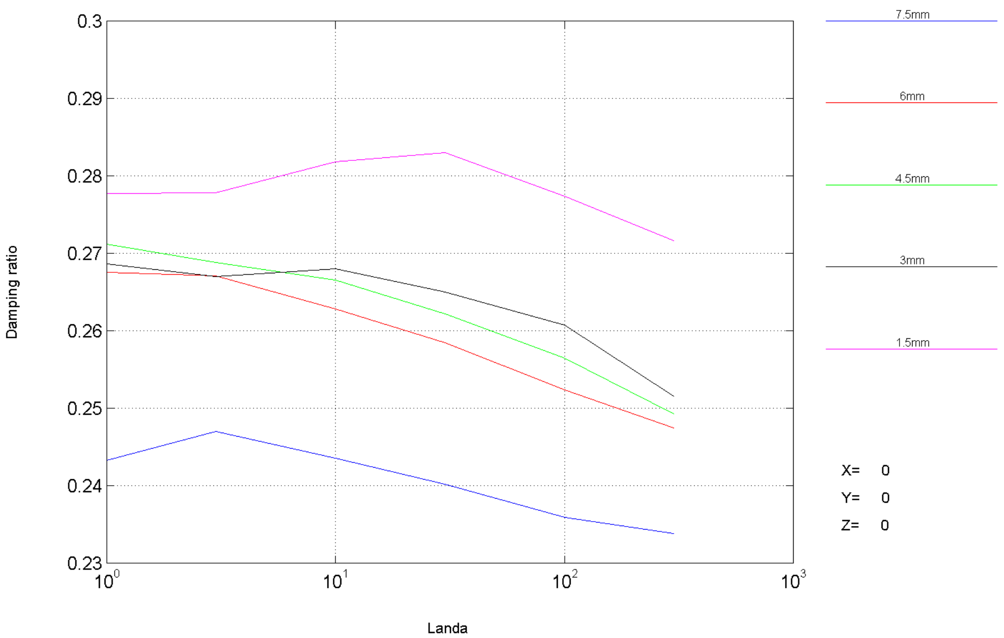


Figure 3. Equivalent damping as a function of the test time scale (Landa) and the displacement amplitude.

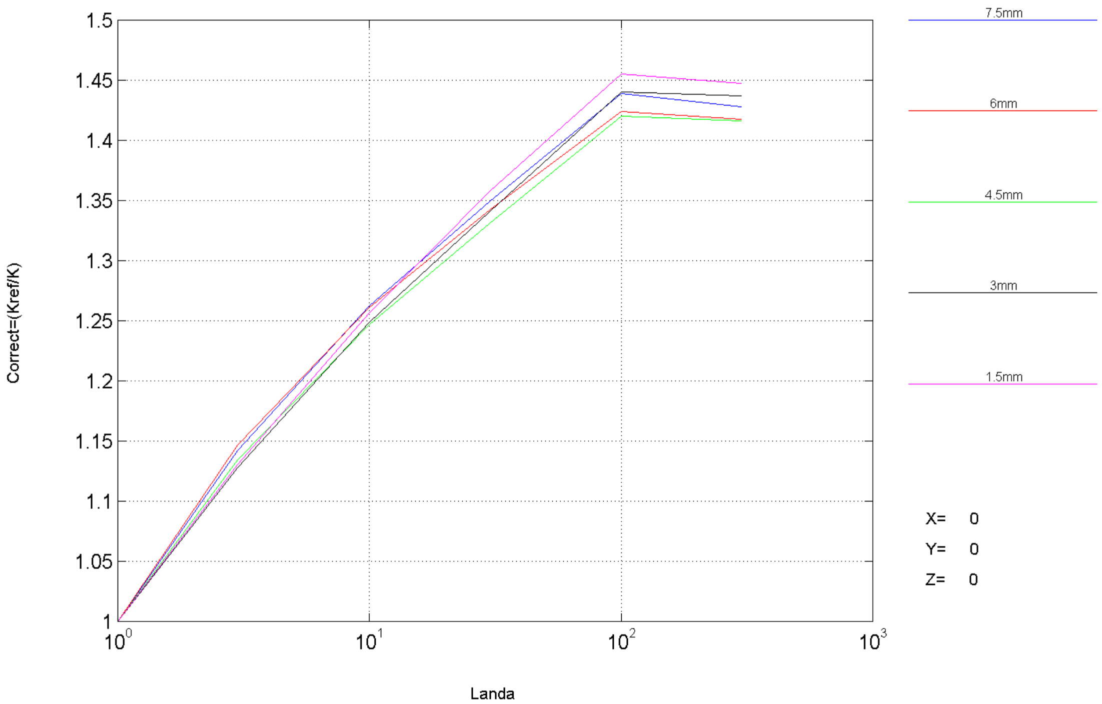


Figure 4. Force correction factor as a function of the test time scale (Landa) and the displacement amplitude.

On the other hand, the obtained values of the equivalent viscous damping are rather independent on the testing speed and only slightly dependent on the displacement amplitude as shown in Figure 3.

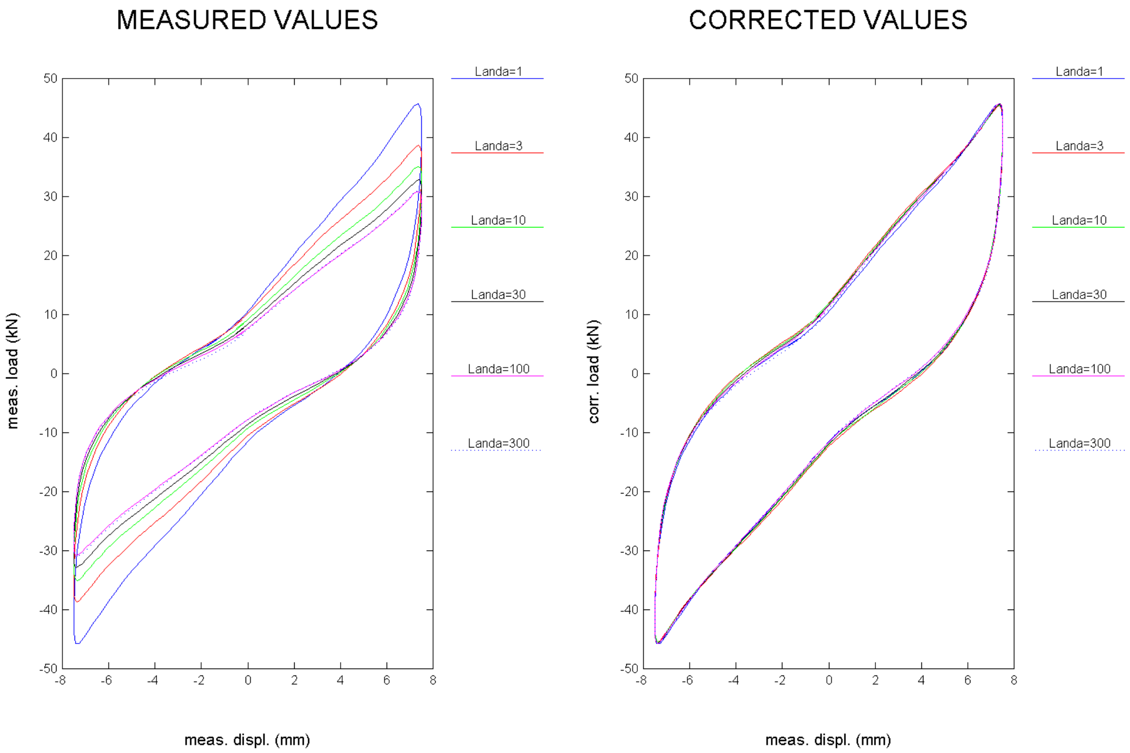
Correction of the strain rate effect

From the results shown in the previous section, the speed of the tests seems to modify the apparent stiffness of the force-displacement loop without altering the damping. This effect is the same that would be obtained by scaling the force values by a multiplication factor. To see what the values of such a factor could be, in Figure 4, the quotient between the stiffness at the reference speed (λ=1) and the stiffness at other testing speeds has been plotted. This quotient C_λ can be understood as a correction factor that allows approximating the force at the reference speed $F_{\lambda=1}$ by the measured load at a different testing speed F_λ in the way:

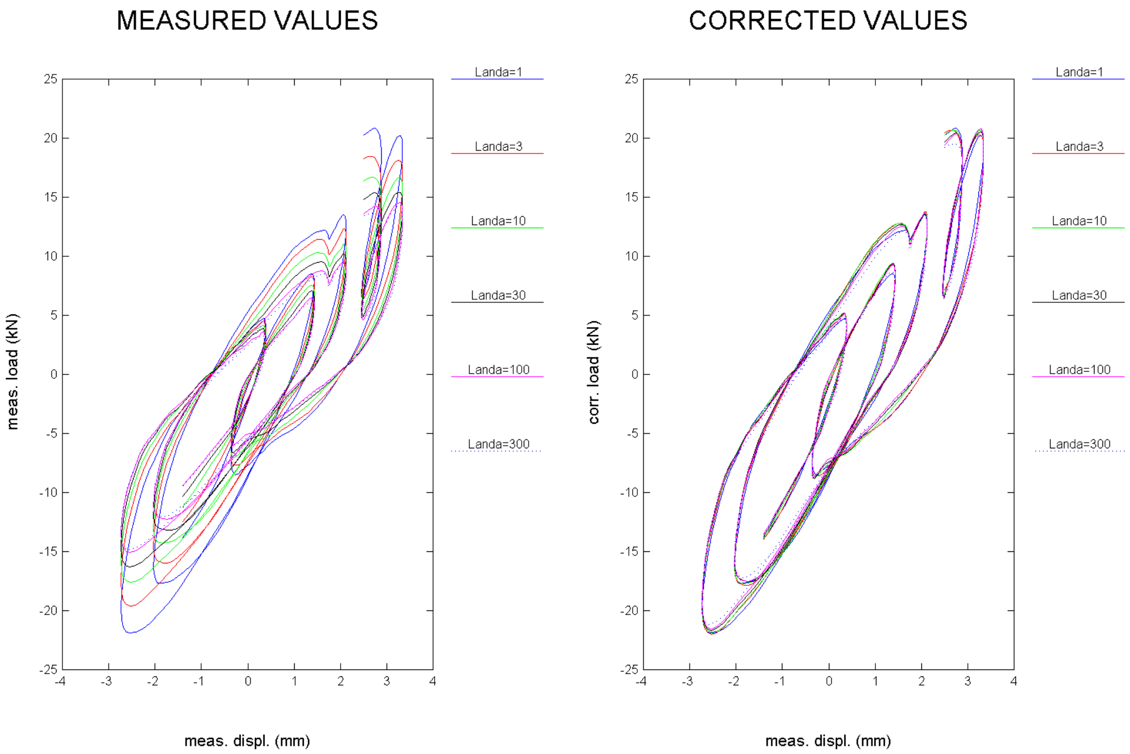
$$F_{\lambda=1} = C_\lambda F_\lambda$$

As shown in Figure 4, for the tested material, this correction factor C_λ depends on the testing time scale, but not significantly on the deformation amplitude.

In this way, the forces at real speed can be approximated by the forces measured at low testing speeds and multiplied by the appropriate correcting factor as extracted from Figure 4 by taking the mean of the different curves. For example, in Figure 5, the form of the force-displacement cycles is shown for the measured and for the corrected forces. Particularly, Figure 5a refers to a single amplitude of the sinusoidal part of the characterisation test, while Figure 5b refers to a piece of the random part of the test. This figures show that the effect of the strain rate can be as important as of a 45% of difference in force for the lowest testing speed. However, they also show that by using the proposed correcting technique, the forces measured at low speed tests can accurately reproduce the real speed ones.



a) single sinusoidal cycle



b) detail of random displacement

Figure 5. Comparison of measured loads at different time scale factors (Landa) without and with application of the correction technique.

TESTING METHOD

Pseudodynamic Method

The PsD testing technique is based on modelling the system by a discrete equation of motion

$$\mathbf{ma} + \mathbf{cv} + \mathbf{r}(\mathbf{d}) = \mathbf{p}(t) \qquad \textbf{(1)}$$

where **m** is the mass matrix, **c** is the viscous damping matrix, **a**, **v**, **d** and **p** are respectively the vectors of acceleration, velocity, displacement and external load, which are functions of time *t*, and **r** is the vector of restoring forces, which is a non-linear function of the displacements. Within this model, **m**, **c** and **p**(*t*) are data, while **r**(**d**) is directly measured on line. Typically, the viscous damping matrix **c** is considered null in a PsD test. Usually, an explicit integration scheme is used by which, at every step, the computed displacement is quasistatically imposed to the specimen and the required forces are simultaneously measured. By using many actuators of the required capacity, the method can be applied to test large structures with clear advantages with respect to a shaking table test [Donea et al, 1996, Molina et al, 2000].

Fast continuous PsD testing

In a classic PsD test every integration time step takes typically at least one second of time which allows to impose the ramp of incremental displacements, wait for the stabilisation of the system before the forces are measured and compute the next displacement. However, in a fast continuous PsD test, as currently implemented at the ELSA laboratory [Magonette et al, 1998], every integration time step takes just 2 ms, which is also the sampling period of the closed-loop controllers of the actuators. Within that time lapse, the same CPU which is in charge for the control algorithm reads the force, integrates one step in the equation of motion and corrects the target according to the new computed displacement. The accelerogram history is subdivided in very small time increments (10 μs, for example) so that the displacement increments can be appropriately followed by the pistons in just 2 ms. Thus, for a large specimen a typical test time scale of λ=2ms/10 μs=200 can be reached which could mean around ten times faster and still much more accurate results than a classic PsD test performed with the same hardware.

Compensation of the strain-rate effect

For materials with significant SRE as the high-damping rubber dissipators discussed in this paper, the advantage of the continuos PsD technique is double because, firstly, the test is faster which reduces the SRE and, secondly, the ramp and hold phases at every step become diffused in a continuos movement which avoids the stress relaxation within each step and the difficult matter of the selection of the stabilisation time before measuring the force.

Since the speed of the testing equipment is nevertheless limited by the required accuracy, the duration of the test is usually from 100 to 300 longer than the original duration of the event. However, the important SRE existing in the rubber devices at this testing speed can be minimised by using the compensating strategy proposed herein. If, for example, the current testing speed is λ=200, the corresponding correction factor for the forces at the dissipator level is 1.45 (see Figure 4). That is, instead of using in the integration algorithm the restoring forces measured at the pistons, these are modified by a correction term which is built from the local measure of the force at every rubber device, multiplied by 1.45-1=0.45, and assembled all of them into a restoring force vector for the structure.

TESTS ON THE TWO-STOREY BUILDING

Building specimen

The test structure was designed by BOUYGUES and consisted of a two-storey two-bay (10 by 4, 5.4 m high) reinforced concrete building that was fixed to the floor of the ELSA laboratory. The tests were conducted in the longitudinal horizontal direction and at every bay in this direction the frames had been retrofitted with a couple of the described rubber dissipators which were attached through K braces so as to deform with the inter-storey drift [Dumolin et al, 1998]. Those braces were instrumented with strain gages, which allowed measuring the load at every dissipator set. The measure of this force was necessary for applying the mentioned compensation strategy for the SRE within the PsD method.

Seismic pseudodynamic tests

For the pseudodynamic tests on the structure, one degree of freedom of longitudinal horizontal displacement was assigned to each one of the two floors. The described testing methodology was implemented including the correction of the dissipator forces in order to compensate for the SRE. The design earthquake was applied both to the building retrofitted with the dissipator devices and to the bare structure afterwards. The attained displacements were of 15 and 66 mm at the second floor for the respective configurations. More details about the efficiency of the adopted retrofitting system are given in the references [Taucer et al, 1999].

Random burst validation test

In order to validate the implemented PsD testing method and the effectiveness of the SRE compensation strategy, a small real dynamic test was run in the specimen and afterwards pseudodynamically reproduced. The dynamic test was done using the same loading system as for the PsD tests, which has the advantage of avoiding the use of different set-ups.

Since the servovalves of the hydraulic pistons used for the PsD test have a limited speed, the excitation provided at high frequencies is very low. Also, due to the large mass of the model, the control error at those frequencies is high, which means that the structure can be excited dynamically but the effective input load history is known only after the test. Nevertheless, these apparent limitations are not an obstacle for creating a documented dynamic event on the specimen, which can afterwards be pseudodynamically reproduced.

For the dynamic random burst test, the same force target was introduced at the four pistons acting on the specimen. It consisted of one of the accelerograms used for the seismic tests but run at real speed and multiplied by a scaling factor that was selected by experimental trial and error so that appropriate measurable displacement amplitude was obtained. After this test, the recorded measured forces at the load cells of the pistons were taken as the excitation force histories (right hand side in equation (1)) for the PsD test. The mass used for this PsD test was an estimate of the real mass of the specimen and not the design mass which had been used for the seismic tests for the design earthquake. As for the seismic tests described in the previous section, the PsD test was run at a speed λ=200 times slower than the dynamic test. According to Figure 4, the appropriate correction factor for the forces at the dissipators was 1.45. In fact the PsD test was run twice: the first time using such correction factor while the second one without any correction. The history of the obtained displacements at the two floors is shown in Figure 6. There the displacements of the dynamic test are compared with the ones of both PsD tests clearly showing that the PsD test with correction of the dissipator forces reproduced quite well the dynamic results, while the PsD test without correction resulted in too large displacements.

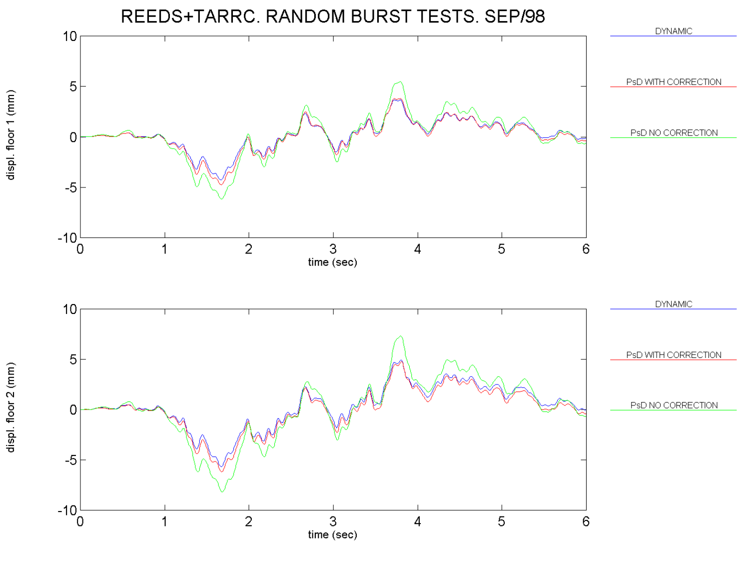


Figure 6. Comparison of the response displacements during the dynamic (blue) and the PsD (red and green lines) random burst tests.

CONCLUSIONS

The results of the dynamic and PsD tests described in this paper show that:

- The developed PsD technique is capable to accurately reproduce real dynamic events.

- The implemented correction of the forces at the rubber devices is necessary in order not to overestimate the response displacements.

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