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Validation of the pseudo-dynamic method to test large scale models of base isolated structures

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ABSTRACT

The research related to seismic risk reduction led, in the last years, to the development of various innovative anti-seismic mechanisms which cover different applications. The efficacy of these devices has been proved by some applications, as shown during the earthquake of Northridge in California, but a systematic use of this technology is made difficult by the absence of design standards. A standard procedure for the Pseudo-Dynamic testing of large scale models of base-isolated structures has been developed and validated at the European Laboratory for Structural Assessment of the Joint Research Centre of the European Commission.

INTRODUCTION

The European Commission (EC) is currently engaged in research activities about the seismic behaviour of structures, the technologies to lower the effects of an earthquake and the verification of the rules for the design standards.

The effects of an earthquake on large size structures are investigated in the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre (JRC) by means of a Reaction Wall (RW) and the Pseudo-Dynamic (PsD) [1]. The implementation of the PsD method at ELSA is in digital form and allows a very good control of the ramp generation of the target displacements [2]. Presently the main objectives of the laboratory activities are related to the calibration of the rules of the EUROCODE - 8 for the design of steel and reinforced concrete structures [3].

The EC is interested in the follow-up of innovative techniques and mechanisms for seismic risk reduction to verify the effectiveness of the technology, the reliability of the mechanisms and to contribute to the development and validation of the related design rules and standards.

To this end a collaboration has been set up with the Italian Working Group on Seismic Isolation which contributed to the present work.

BASE ISOLATION IN EARTHQUAKE ENGINEERING

In the last years an important effort was done to improve the design capabilities for earthquake engineering and it led to the set up of design standards for seismic areas. Another line of research has been followed with the aim of investigating innovative ways for the control of the induced vibrations. The investigation led to the development of innovative passive anti seismic devices. These are essentially related to the technology of base isolation and energy dissipation.

These two different types of devices can be considered complementary to each other. Base isolation is finalised to the reduction of the frequencies of the structure in order to escape the range of frequencies inducing high acceleration due to resonance, while energy dissipation devices are finalised the protection of the carrying structures by lowering the energy transmitted to them.

The efficacy of base isolation is relevant for hard soils or in general with a frequency capacity of transmissibility spectrum with high acceleration in the range of some Hertz, while it is low for sandys soils or with a spectrum with high acceleration in the range below one Hertz. where for those cases, energy dissipation is more effective. The base isolation technology is well developed, but the its application in earthquake engineering is made difficult by the absence of design rules for isolated structures. To overcome this gap there is the necessity of tests on large scale models of structures to develop and validate the design standards.

VALIDATION OF THE PsD TEST METHOD

In principle there is no doubt about the applicability and the potentiality of the PsD method; the problem is the influence of the test velocity on the characteristics of the isolator material; some literature exists on the subject and probably the influence of strain rate is not such to invalidate the results of a PsD test; moreover, this problem is probably dependent on the isolator materials.

At this stage some structures existing at ELSA have been reused to improve and validate a standard procedure for the PsD testing of base-isolated structures. Because the structures existing at ELSA will be tested in the framework of the planned activity of the laboratory, these structures must thus be repaired before being tested in the framework of the Seismic Isolation Programme. Some additional investigations (as the comparison with the original eigen-frequencies, stiffness matrix, etc.) will be performed to verify the integrity of the structure before the reuse to test using base-isolation devices.

The main aim is to set-up a self-standing validated procedure. In a second stage also a comparison between a dynamic shaking table test and a PsD test will be performed. This will be done only for a small-scale model of structure tested at the laboratory of ISMES, owner of a shaking table, and at ELSA.

EFFECT OF THE STRAIN RATE

The PsD method is based on a quasi-static load application by means of hydraulic actuators acting on selected point of the structure which is connected to the strong floor of the laboratory. The seismic effect is correctly simulated being the differential displacements evaluated by a computer solving, step by step, the equations of motion. Potentially the method is very attractive for structures with masses lumped at the point of application of the actuators and for materials whose behaviour is independent of the strain rate. This last point is not the case for the materials used for the base isolators. To overcome this difficulty is very important for the reliability of the test results; at ELSA a standard procedure to validate the rate-sensitivity of materials has been set up [4].

As it is known, that the PsD method is an hybrid numerical-experimental approach for the solution of the complex structural analyses problems. The basic idea is that the reaction forces measured during the test at the top of the isolators could be multiplied for a correction factor to be introduced in the numerical part of the method [5]. In principle this numerical correction factor is dependent on the materials and on the difference between the strain rates during the real dynamic load application and the PsD quasi-static application.

It has been shown at ELSA that this correction factor can be evaluated by a characterization of the isolators for application of loads with different strain rates. Only few characterization tests can be enough to reach the goal providing that the loads are applied with the same ratio in time scale between the PsD test and the dynamic one (usually this ratio at the ELSA tests is of two orders of magnitude).

STANDARD TEST PROCEDURE

To overcome the difficulties due to the strain rate dependency for testing base-isolated structures, the following standard procedure has been set-up at ELSA:

- characterization of the isolators and assessment of the correction factor for PsD tests;
- dynamic snap-back;
- PsD snap-back assuming the correction factor assessed by the characterization tests;
- comparison of the results obtained from the dynamic and PsD snap-back tests and validation of the procedure;
- tests for earthquake signals with the PsD numerical method implemented to account for the correction factor.

This standard procedure is self consistent and allows the validation case by case. In fact the dynamic snap-back is a reference case for the corrected PsD test of the structure and the isolators under examination.

CHARACTERIZATION TESTS OF THE ISOLATORS

General considerations

The activity is finalized not only to the intrinsic characterization of the isolators, which is of relevant importance, but also to the quantification of the effect on strain rate dependency of the horizontal shear of the isolators.

Usually, for common building materials, the errors introduced by a PsD test may be disregarded since they are less important than the existing variability from specimen to specimen. However, for the isolators, 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.

To compensate for this effect, at every step of the PsD integration, the measured forces may be corrected so as to account for an increase of a specified percentage of the isolators stress. To this end a correction coefficient to be implemented in the PsD numerical algorithm for the tests to be performed, is obtained experimentally before hand. The experimental arrangement for the characterisation tests is shown in Fig. 1.

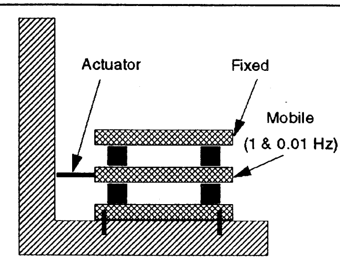

Fig. 1: Characterisation of the isolators

Four isolators are placed in a two-by-two symmetric position and bolted to a mobile apparatus which applies controlled displacements. The tests allow the plotting of the shear force as a function of the displacement at the top of the isolators. The imposed histories are sinusoids of various frequencies.

In practical applications, the aim of isolation is to shift the first frequency of the over-standing structure in the low frequency range (in general less than 1 Hz) to escape the range of the higher values of acceleration in the earthquake response spectrum. The PsD tests are in general, done with a time scale of about one two-to-three hundreds orders of magnitude slower than the real dynamic case. For the above mentioned reasons the characterization tests are done in the low frequency range and assuming a ratio of the boundary frequencies equal to the ratio in time scale between the dynamic and PsD tests.

Isolator geometry and materials

The isolator devices were rubber bearings with a diameter of 250 mm and made of 11 rubber layers with a thickness of 6 mm (66 mm of total rubber height), 10 steel layers of 1.5 mm (alternating between the rubber layers) and two end steel plates of 10 mm which included threaded holes for fixation. Consequently, the total height of each isolator was of 101 mm. The isolator is shown in Fig. 2. The isolators were designed for a working shear strain of 100% (66 mm of horizontal displacement) and a nominal vertical load of 400 kN. Four of these isolators, made of a high-damping rubber mixture called EN60, were made available to ELSA for this test campaign. The results of the characterization tests are shown in Fig. 3.

From these results a bearing shear force of the order of 20% was adopted as correction factor. The figure shows the results for times of 10s and 1000 second; for the last case, the results with the correction factor of 20% is compared with the curve for 1 s. The two curves are very close each other.

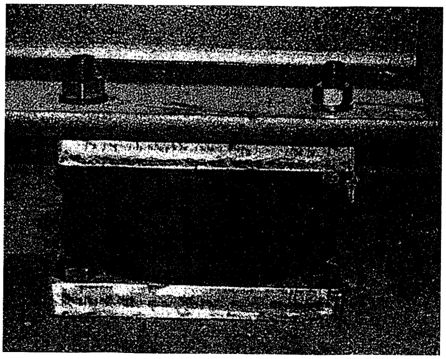

Fig. 2: Isolator

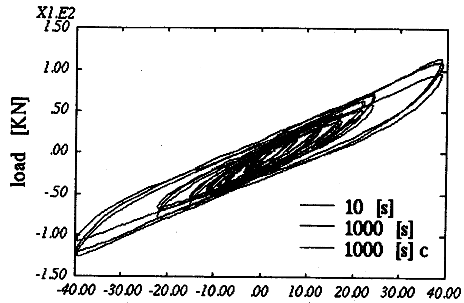

Fig. 3: Characterisation results

DYNAMIC AND PsD SNAP-BACK

The execution of a dynamic snap-back is the second step of the standard procedure. The aim is to obtain a reference data for a PsD simulation accounting for the correction factor in order to validate the PsD tests.

Description of the structure mounted on the isolators.

The structure is a three storey steel frame with a total height of 10.40 m, 5.00 m wide and 5.00 m deep [6] which had been previously used for several test campaigns without isolation and repaired afterwards. The steel frame is shown in Fig. 4.

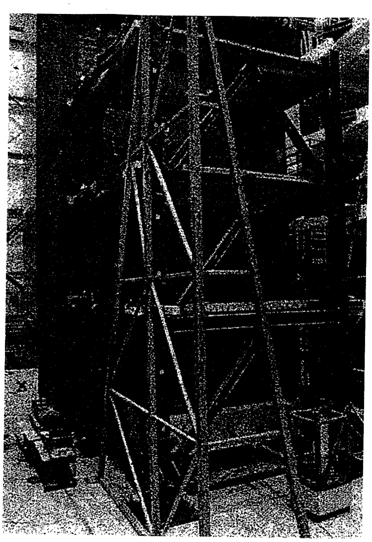

Fig. 4: Steel frame

Each floor of the structure is made of a concrete slab to which two hydraulic actuators were attached (only the front one is seen in the figure). Since the bases of the columns were no longer resting on a rigid foundation, each frame was closed by a stiff beam with the same profile (HEB 400) as the columns and these beams constituted the base floor which was fixed onto the four isolators positioned at the corners. This new base - which will be called here floor 0 - was also provided with an additional concrete block of about 250 kN of weight to which a single actuator was attached. The main function of this block was to increase the total weight of the specimen, which was of about 750 kN. Although this load was only about one half of the design vertical load of the isolator set, it was considered sufficient for the purpose of these tests since the addition of more heavy blocks would have considerably increased the cost of the set up.

The snap-back has been simulated by means of the PsD method in the two cases with and without correction factor applied at the shear forces at the top of the isolators. The correction factor of 20% is included in the numerical algorithm of the method. The results are shown in Fig. 5.

Also the comparison with the Dynamic test is included. The results have shown that the PsD test without correction have significant differences compared with the dynamic one. This is in agreement with the results of the characterization tests. In particular the most relevant difference is in frequency.

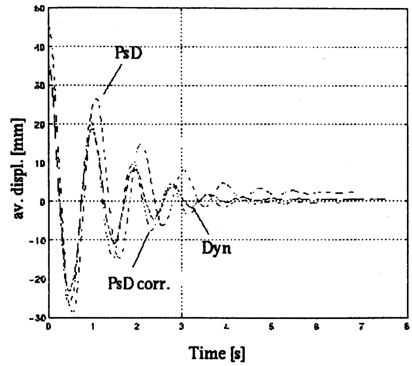

Fig. 5: Dynamic and Psd snap-bak

The results obtained assuming the correction factor of 20% in share force of the isolator are very near to those related to the dynamic tests. The frequencies are close to each other as shown also b the behaviour of the 1st mode frequency spectra. It was found that the acceleration peak is at frequency of about 1.2 Hz for the dynamic and corrected PsD tests, while it is of about 1 Hz for th PsD without correction.

PSEUDO-DYNAMIC SEISMIC TESTS

The above described experimental tests have shown the possibility to correct in a suitable way th response of the isolators to account for sensitivity of the material to the strain rate effect. Finally th PsD settings obtained from the previous tests have been used to perform PsD tests on the steel fram for a seismic input. The aim of the work is to have a first assessment of the effectiveness of th isolation for a large scale base isolated model that is representative of a realistic situation. The goal i reached by comparing the results obtained with and without the isolation applied at the bottom of th structure. As input it has been assumed the accelerogramme of Kalamata, shown in Fig. 6, amplifie for a factor 1.5.

It has been used an elastic spectrum with 5% of damping. The zone of resonance is in the range of 3.2 Hz. Previous experiments on the frame, without isolation, showed a first frequency of 3.96 Hz, whereas the isolated structure has a first frequency of about 1.2 Hz. This first comparison gives a first qualitative indication of the effectiveness of the isolation for the case under examination.

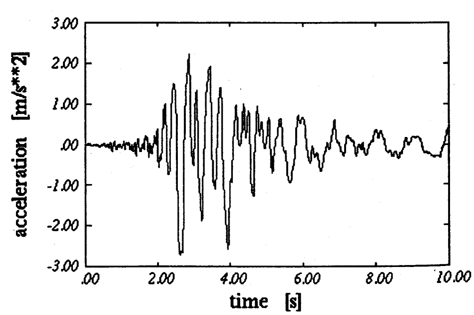

Fig. 6: Kalamata signal

The comparison between the results obtained at the three floors for the two configurations with and without isolation is shown in Fig. 7, Fig. 8 and Fig. 9.

The comparison highlights the strong reduction of the forces, proportional to the accelerations, due to the isolation. The maximum load at the third floor of the order of 700 kN without isolation is drastically reduced to about 100 kN for the isolated structure.

Also the diagrams of the shear loads versus the inter-storey drift showed a relevant decrease both in drift and shear due to the isolation. In particular, for the third floor the inter-storey drift is lowered from about 55 mm without isolation to about 15 mm with isolation. A certain amount of energy is dissipated by a non-linear hysteretic behaviour of the material of the frame in the configuration without isolation, while the behaviour remains elastic in the case with isolation.

CONCLUSION

The work performed at the Joint Research Centre of the European Commission, in collaboration with the Italian Working Group on Seismic Isolation, was finalised to show the possibility of PsD testing of isolated structures and to make available a standard procedure to this end.

The main problem is the strain rate sensitivity of the isolator materials which could affect the reliability of the results. The experimental activity showed the possibility to set-up a standard procedure to obtain an intrinsic validation, case by case, of the tests. This is possible because of the flexibility of the PsD methodology which is a mixed numerical-experimental one. The numerical part allows the possibility to correct, step by step, the measured restoring forces before their usage in the numerical algorithm. To reach this objective, a characterisation test of the isolators for various frequencies allows the definition of a correction factor to be applied to the measured restoring forces at

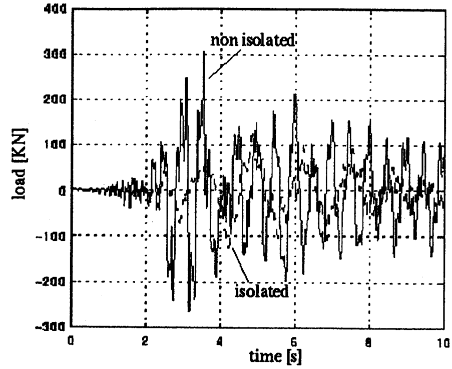

Fig. 7: comparison at the first floor

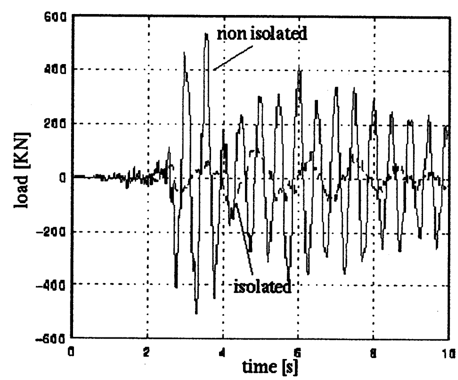

Fig. 8: comparison at the second floor

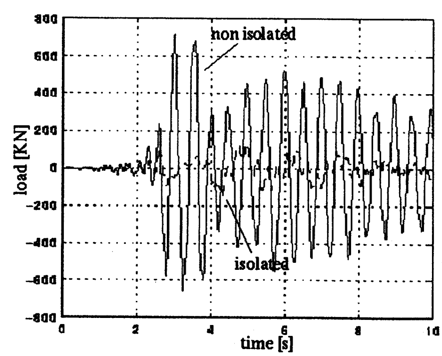

Fig. 9: Comparison at the third floor

the top of the isolators. This correction factor depends essentially by the strain rate ratio between the dynamic behaviour and the PsD simulation. The comparison of a dynamic snap back test with a PsD simulation allows a very good setting-up of the corrected PsD model. The results obtained for the Kalamata earthquake, and verified also for others seismic inputs, showed a relevant efficacy of the isolation technology applied to realistic structures.

In conclusion a tool has been make available, based on a big Reaction Wall and the PsD method, to test base isolated, large scale, structures and to contribute to the verification of the design of relevant projects and the development and validation of standard rules for the design of base isolated structures.

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