XA0202121

CONTRIBUTION OF THE JRC ISPRA TO THE INTERCOMPARISON OF ANALYSIS METHODS FOR SEISMICALLY ISOLATED NUCLEAR STRUCTURES

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Abstract

Aim of the work done at JRC has been essentially to investigate the potentiality of the Pseudo-Dynamic (PsD) method to test structures incorporating anti-seismic protection devices based on materials with a strain-rate dependent behaviour. This is of relevant importance due to the interest to perform tests on large-scale mock-ups to assess the behaviour of realistic structure of civil engineering interest. Two specific typologies of protection have been analysed and tested at the European Laboratory for Structural Assessment (ELSA) of JRC Ispra. The first dealing with base isolation and the second with energy dissipation devices. In both cases the protection devices were based on high damping rubber material which is characterised by a moderate dependence from the strain rate of the application of the displacements. To validate a standard procedure to test base isolated structures by the PsD method, a collaboration was set up with the Italian Working Group on Seismic Isolation which includes the national research centre ENEA, the national electricity board ENEL, the industrial research centre ISMES and a manufacturer of isolators ALGA. In the framework of this collaboration it was decided to test at the ELSA laboratory a scaled 5-storey frame structure (provided by ENEL), isolated by means of high damping rubber bearings (HDRBs), which had been tested on the shaking table of ISMES. This experimental activity aimed to compare the results which can be obtained by means of the PsD testing technique with those which can be obtained by means of a truly-dynamic test on a shaking table. To validate a standard procedure to test structures incorporating energy dissipation devices, an international collaboration has been set up with Industries, Research Centres and Universities in the framework of a project partially funded by the European Commission through the General Directorate for Science and Technology. The obtained results show once more that the PsD method, when properly applied, may reliably be used to test structures protected by devices based on high damping rubber. This has been shown effective both in the case of base isolation and energy dissipation devices by using a specific procedure for the improvement of the PsD method.

1 INTRODUCTION

The European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre (JRC) is specially fitted out with up-to-date means for carrying out Pseudo-dynamic (PsD) tests to reproduce the behaviour of large scale structures subjected to earthquake loading.

The ELSA laboratory is at present engaged in international consortia to develop, optimise and test innovative anti-seismic devices based on passive vibration control. To this end, a collaboration was set up with the Italian Working Group on Seismic Isolation (Gruppo di Lavoro sull'Isolamento Sismico GLIS) which contributed to the present work [1, 2]. In the framework of this collaboration it was decided to test at the ELSA laboratory a scaled 5-storey frame structure (provided by ENEL), isolated by means of high damping rubber bearings (HDRBs), which had been tested on the shaking table of ISMES.

PsD testing is, by virtue of the expanded time scale of the tests with respect to real seismic events, normally restricted to materials assumed to behave in a rate-independent manner. As regards to seismic isolation by rubber bearings, although the strain rate effect cannot be taken into account at the experimental stage, it can be taken into account in the numerical part of the method. A standard procedure for the PsD testing of large-scale models of base-isolated structures has been developed and validated at the ELSA laboratory.

The experimental activity described in this paper aims to compare the results which can be obtained by means of the PsD testing technique with those which can be obtained by means of a truly-dynamic test on a shaking table.

The PsD test procedure includes the following steps:

- Characterisation of the isolators for different frequencies to evaluate the stiffening effect due to the strain rate and the corresponding correction that must be applied to the shear force.
- Comparison between a dynamic snap-back and a PsD snap-back.
- PsD tests for seismic inputs and comparison with shaking table results.

2 PRINCIPLES OF SEISMIC ISOLATION

In the last years an important effort has been done to introduce new seismic protection techniques, some of which are now included in design standards for seismic areas.

Traditional earthquake design methodologies use high strength or high ductility concepts to mitigate damage from seismic effects. An alternative approach consists in isolating the structure base from the ground by means of flexible devices, called isolators, placed between the superstructure and its foundation [3]. A base-isolated system is characterised by a very low frequency, such that during a strong earthquake, the superstructure moves like a rigid body over its isolation system. Deformations and energy dissipation are mostly concentrated in the isolators. A seismic isolator must be rigid in the vertical direction (to support the dead load of the superstructure), flexible in the horizontal plane (to allow for large relative displacements between the superstructure and the ground) and possibly, it must be able to dissipate a significant amount of energy.

From the various devices proposed for seismic isolators, the laminated elastomeric bearing is emerging as the preferred device for large buildings/structures, such as nuclear reactors plants. A great number of experimental and numerical studies have already been performed for all kinds of rubber bearings and several applications to bridges, buildings and industrial plants already exist in many countries. HDRBs are formed by two end plates and several relatively thin inner steel plates embedded in a high damping rubber matrix, to which they are connected through bonding. These isolators can sustain large vertical loads with small deformations due to confining effect of the inner steel plate and are characterised by a low horizontal stiffness when subjected to horizontal loads, which allows for large transverse deformations in severe earthquakes. In these bearings, high damping is obtained by mixing the rubber with suitable additives (carbon, oils and resins); this allows combining in a single element both the frequency filtering and energy dissipation capacities necessary to achieve an effective isolation action. The HDRBs behaviour is mostly characterised by the rubber mechanical properties, which are highly non-linear, both in terms of stiffness and damping. As a matter of fact, the 'width' of the experimental hysteresis loop, that determines the amount of damping, increases with the shear strain. The horizontal force-displacement envelope is described by an initially high stiffness that decreases to a nearly constant stiffness in the range between 50% and 150% shear strain; finally, the stiffness increases up to isolator severe damage, which can occur even over 400% shear strain [4].

3 ISOLATION DEVICES

3.1 Specimen Rubber Bearings

The HDRBs used in this test campaign were fabricated with a soft compound (G = 0.4 MPa), attached to the structure with bolts and a dowel system, and provided an isolation frequency (about 1 Hz) in the range of interest for seismic isolation. These isolators have a diameter of 125 mm and are made of 12 rubber layers with a thickness of 2.5 mm (30 mm of total rubber height and a shape factor S equal to 12), and 11 steel layers of 1 mm alternating between the rubber layers. A 10 mm thick steel plate is used at each end of the bearing for mounting to flange plates of 15 mm which, in turn, are attached to the base and the superstructure [5]. Consequently, the total height of each isolator was 91 mm. They were designed for a working shear strain of 100% (30 mm of horizontal displacement) and a nominal load of 50 kN. Six of these isolators were made available to ELSA for this test campaign.

3.2 Characterisation tests and Strain Rate Effect Compensation

For elastomeric bearings, a decrease in the testing speed of two or three orders of magnitude, as is usual for PsD tests [7], may introduce considerable changes in the stress-strain behaviour, especially for filled rubber bearings [8]. As reported before, these changes may be described as a proportional force reduction.

Because high damping rubber exhibits some viscous behaviour, it is to be expected that both the stiffness and damping of the bearings evaluated here will show some dependence on loading frequency. In general an increase in the rate of loading will lead to an increase in both the effective modulus and the equivalent viscous damping. In order to analyse the variations in stiffness and damping as a function of the loading frequency, a campaign of characterisation tests was undertaken. Before installing the test structure over the isolator bearings, preliminary tests were performed by using a specific set-up which was able to supply a constant vertical load while simultaneously imposing a specified horizontal displacement history to four rubber bearings. Using a vertical load of 40 kN per isolator, sinusoidal displacement histories with amplitudes decreasing from 200% shear strain (i.e. to a horizontal displacement equal to two time the total rubber height) were imposed at different speeds (Fig. 1).

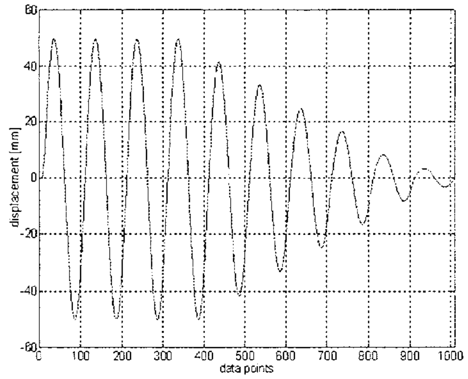

Figure 1: Decreasing amplitude characterization signal.

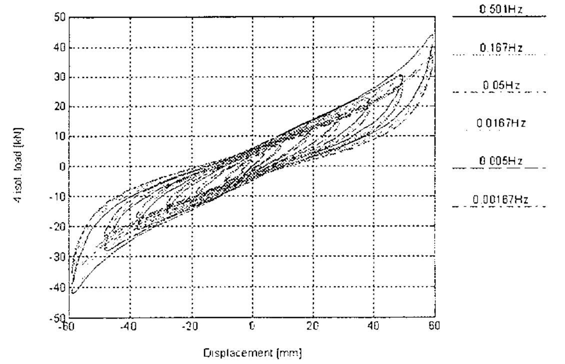

Figure 2: Hysteretic behavior of the HCRBs at different strain rates.

The highest speed corresponded to the application of a sinusoidal displacement with a frequency of 0.5 Hz. In the successive tests this speed was reduced by a factor of 3, 10, 30, 100, and 300 respectively, while practically identical displacements were attained for all the tests thanks to the quality of the digital control system [6]. After disregarding the initial 3 large amplitude cycles, the relationship between the shear force and the shear strain of the four isolators set is represented for different speeds in (Fig. 2.) From this figure, it was found that the shear stiffness tends to increase as the frequency of the cycle increases, while the rubber damping is hysteretic, i.e. practically independent of velocity. It was estimated that for the fast test the required horizontal force was 19% greater than for the slowest test.

(Fig. 3) shows in detail the results of two strain rate tests performed with a speed ratio of 300. The multiplication of the shear force of the lowest speed test by a correction factor of 1.19 has generated corrected force-displacement hysteresis loops which are very close to the loop produced by the fastest test.

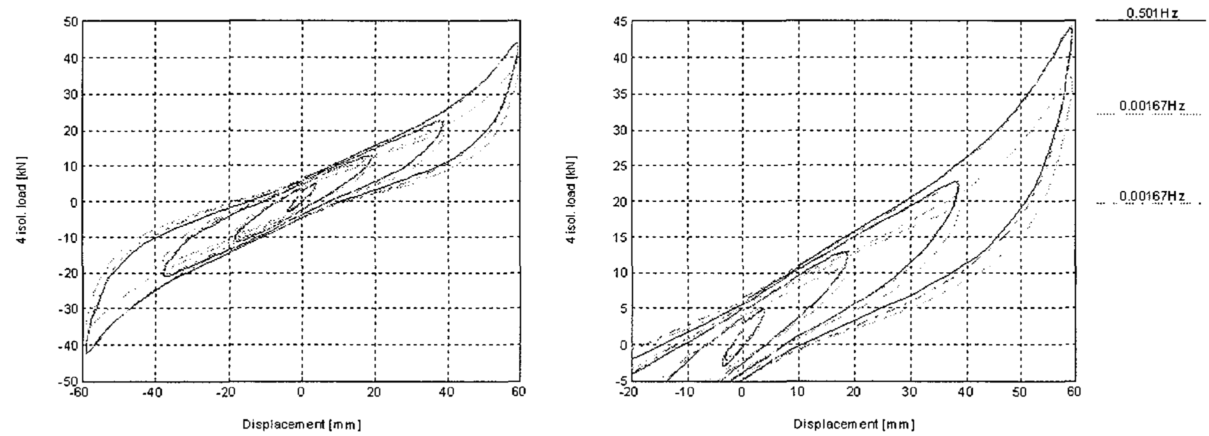

Figure 3: Hysteric behaviour of the isolators: Fast test, slow test and slow corrected test (corr. fact. 1.19).

The hysteretic behaviour showed also that the bearings provided relatively stable and repeatable behaviour with minor variations in damping in function of the loading frequency and loading history, and that the HDRBs can sustain several cycles at very large strains without appreciable change in their dynamic properties (in general, the first load-displacement cycle of a bearing shows higher damping values than the succeeding cycles, and conditions close to steady state are reached after 2 or 3 cycles).

These considerations opened the possibility of using a compensation technique within the PsD tests. In the proposed tests a correction function has been inserted into the PsD algorithm to allow for strain-rate effects in the isolators. That is to say, at every integration step, the measured force should be corrected so as to account for an increase of a specified percentage on the force in the isolators. More details on this compensation technique may be found in [9, 10 and 15].

3.3 Description of the Structure

The mock-up MISS (Model of Isolated Steel Structure) was realised in the framework of a co-operation among European partners, aimed at the optimisation of seismic isolators

[11, 12]. The MISS was subjected to a wide-range experimental campaign of shaking table tests consisting in the application of sinusoidal excitations and natural artificial earthquakes (1D, 2D and 3D) for both the isolated and fixed-base configurations.

The MISS structure is described in detail in the ISMES Test Report [13]. The characteristics of the model that are relevant to the present work are described in the following.

MISS is made of HEM and HEB steel sections of 275 MPa strength. The structure is a four storey, six column tri-dimensional frame, composed of two 2-bay frames in the x direction and of three 1-bay frames in y direction. The centre to centre corner column dimensions in plan are 3.30 m in the x direction and 2.1 m in the y direction; interstorey heights are set at 0.9 m. This structure can support up to 20 concrete masses, each weighting 1300 kg (Fig. 5).

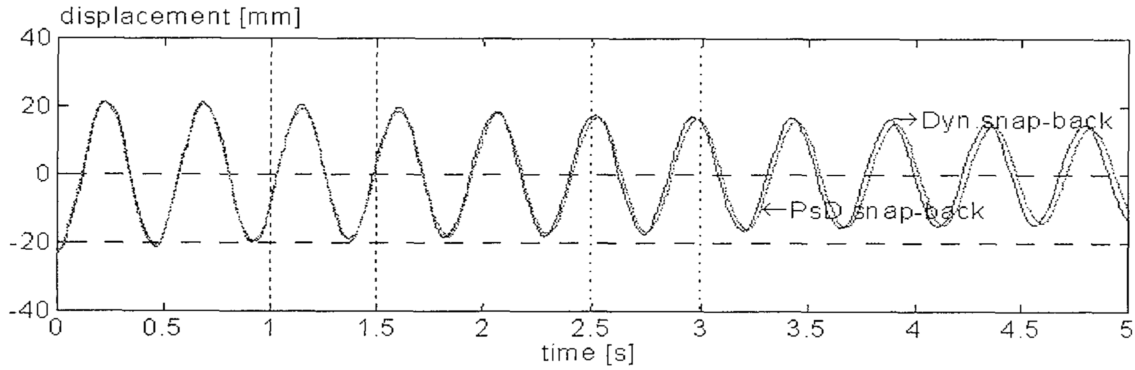

Figure 4: Non –isolated structure: Comparison of displacement time history at 4th floor for the dynamic and PsD snap-back tests.

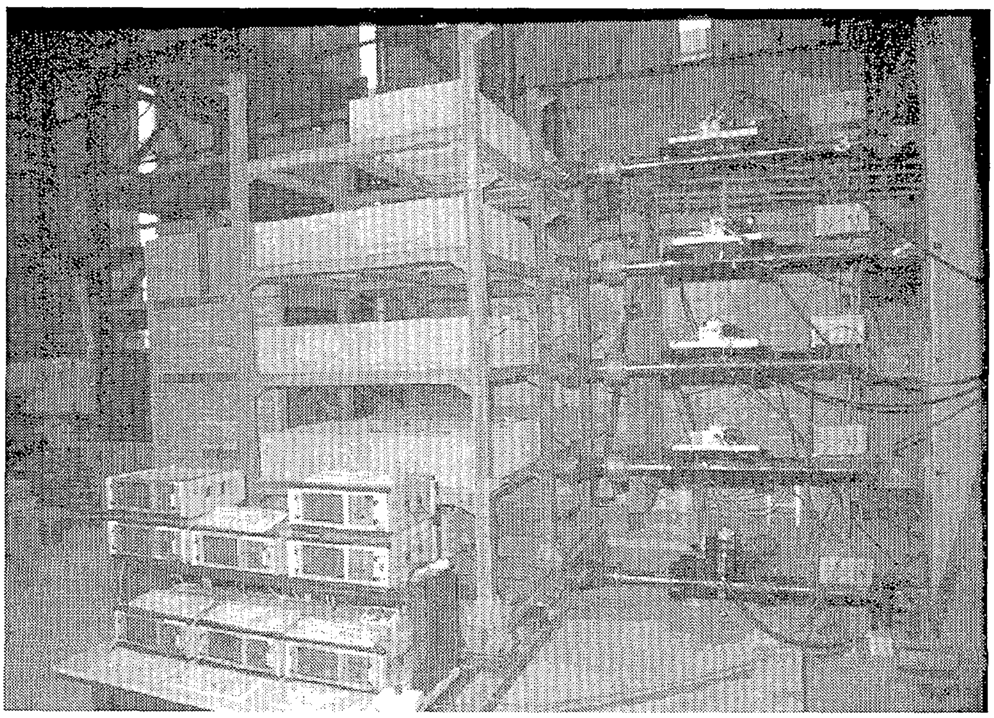

Figure 5: MISS mock-up and PsD apparatus.

The frequencies of the structure can be chosen to vary in quite a large range, depending on the interstorey distance and the number of masses used and their disposition (which can also be asymmetric). The actual isolation system is formed by 6 HDRBs (Fig. 6) described in the previous paragraph, and provides an isolation frequency in the range of interest for seismic isolation (below 1 Hz). Following specifications provided by ISMES, the maximum bending strain allowable at the base of the steel frame resulted to be (800 $\mu\varepsilon$); after this limit undesired plastic deformations are expected.

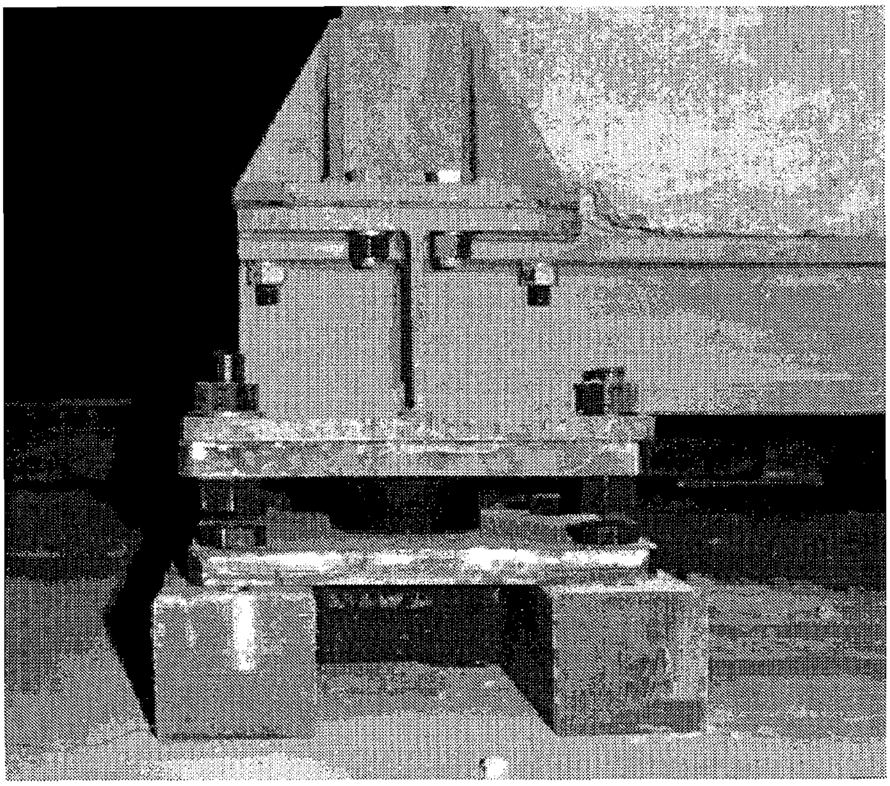

Figure 6: MISS mock-up: rubber bearing detail.

The structure was analysed in two of the four configurations tested at ISMES [13]:

- B9 configuration: non isolated, four masses placed on each one of storeys 1 to 4;
- B19 configuration: base isolated, four masses placed on each one of storeys 1 to 4.

4 CONTINUOUS PsD TECHNIQUE

The conventional PsD test procedure requires a considerable time to complete a test run, because pauses in driving the test machines must be set to adjust the actuators at right positions and to acquire the instrument readings [6]. Moreover, the pauses in driving prevent the smooth movement of the structure. The quality of the PsD tests described in this paper has been improved by applying a technique called continuous PsD testing, which can considerably reduce the test duration and opens the way to more accurate testing of the earthquake response of structures with velocity-dependant devices.

In the conventional PsD test procedure, the actuator motion is stopped when the test specimen reaches the target displacement (hold period) so that the reaction force can be measured and the next target displacement computed. Instead of stopping the actuator, in continuous PsD testing, the actuators move continuously and the reaction force is measured when the specimen passes the target displacement. Recognising this reaction force as the restoring force at the target displacement, the equations of motion are integrated 'on the fly' (without hold period), the next target displacement is determined and the motion proceeds without any interruption. This has been achieved by incorporating the central difference algorithm (to solve the equation of motion) into the digital controller of the electro-hydraulic system, in place of the displacement target generator.

One significant departure from the conventional PsD system is that in the continuous PsD technique, for each of the **m** g^{m} discrete values of the ground acceleration read from the acceleration file, a sequence of **n** acceleration values g_n^{m} is computed by interpolation between g^{m} and $g^{m\ 1}$ (i.e. $g_0^{m}(\ \ g^{m}), g_1^{m}, \ldots g_n^{m}, \ldots g_{\mathbf{n}\ 1}^{m}$).

After completion of computation of these **n** intermediate acceleration values, the PsD procedure is computed **n** times at the sampling rate of the controller performing **n** sub-steps in one conventional PsD step.

The basic sequence used in the continuous PsD test system remains the same as that used in the conventional PsD test. That is, at sub-step n of step m, this sequence proceeds as followed:

g_n^{m} is read and the external load is computed

the restoring force r_n^{m} is measured.

the equation of motion is solved by direct integration; the displacement is computed and used as target displacement by the control algorithm. The actuators leads the test structure to the target position; wait the end of the controller sampling time (2 ms), and then go to 1).

In the tests considered here, we had typically N=1000, Δt =2 ms, ΔT =5 ms giving λ=500, which means that 1 second of the earthquake takes 500 seconds in the test.

In the PsD sequence described here, the reaction force is measured at the sampling rate of the controller (typically 500 or 1000 Hz). This procedure not only generates a smooth displacement of the structure, but also performs a noise filtering of the load measurements with respect to a classical PsD test in which much less measurements enter in the algorithm. The conjunction of these two improvements has made possible to run tests on the 5 degree of freedom (DoF) structure considered here without having to insert numerical dissipative mechanism in the algorithm. These numerical damping techniques are usually required when using the classical PsD method on structures with many degrees of freedom [7].

Moreover, the results of exploratory tests performed on a large-scale 3-Dof steel structure which is described in [9], have shown that this procedure enabled test speed to be improved by a factor ranging between 10 and 20. Further investigations are currently in progress. This increase of the loading rate will improve the quality of PsD tests especially those conducted on structures with load rate sensitive material.

In the present work, even though the continuous technique was used, the PsD tests were driven at relatively low speed, due to the incompatibility between the size of the actuators (500 kN) and the maximum load requested at each level (20 kN max.). For most of the time, the actuators and load cells were used within 1 or 2% of their actual range. In these conditions, it was not possible to increase the speed of the test without an explosion of the higher modes due to force-measurement errors that result in artificial energy input to those higher modes.

4.1.1 PsD Tests on the non isolated structure

Every seismic PsD campaign is usually preceded by a snap-back test that is performed both dynamically and pseudodynamically. The result of these tests gives valuable data for checking the quality of the whole PsD modelling system.

4.1.1.1 Real-Time Snap-Back Tests

The bottom of the MISS mock-up was fixed to the strong floor of the ELSA. For the snap-back test, the mock-up was pushed by means of a hydraulic jack acting at the centre of the fourth floor. After reaching the desired displacement, the structure was released using a mechanical uncoupling device. This test was repeated by acting on the first floor, to excite more the higher modes. The PsD model consisted of a 4-DoF structure and used the diagonal mass matrix: diag(5140, 5450, 5340, 5460) kg. The applied forces and the displacements were recorded at every floor during the tests.

4.1.1.2 PsD Snap-Back Tests

Four actuators were connected between a strong reaction frame and the centre of each floor of the structure. Each actuator was equipped with a load cell and the displacement was controlled by means of a digital optical displacement transducer fixed to an independent common reference structure [6]. The digital control loop of each actuator also included an additional feedback signal from an accelerometer to improve the stability margin of the control. The dynamic snap-back was repeated pseudodynamically by prescribing as external load the history of load measured during the dynamic test. The integration was made by the Explicit Newmark Method with a time increment of 0.005 s.

The results of the dynamic and PsD snap-back tests of the displacement of the fourth floor are plotted in (Fig. 4). They show a good agreement between the dynamic and the PsD responses as is typical for a linear structure. The small discrepancies are mainly due to the diagonal discrete mass matrix adopted in the PsD tests. The eigen frequencies tabulated in Table 1 confirm the good quality of the PsD snap-back test.

TABLE 1: COMPARISON OF EIGEN FREQUENCIES AND DAMPING RATIOS FOR DYNAMIC SNAP-BACK AND PSD TESTS ON THE NON-ISOLATED STRUCTURE

	Mode 1		Mode 2		Mode 3		Mode 4	
	Hz	Damp.	Hz	Damp.	Hz	Damp.	Hz	Damp.
Dyn. snap-back	2.19	0.7 %	8.38	0.5 %	17.0	1.8 %	23.3	5.4 %
PsD snap-back	2.17	0.8 %	8.00	1.3 %	16.7	1.5 %	23.8	0.9 %

4.2 PsD Seismic Tests

On the shaking table of ISMES, several synthetic and natural base acceleration time-histories had been applied to the MISS mock-up. The Tolmezzo NS –6dB record was selected because it was the only one for which mono-axial responses of the structure in the non-isolated and isolated configurations were available.

The input accelerogram used in the PsD tests is displayed in (Fig. 7). This signal is the registration of the acceleration response of the shaking table during the test of MISS submitted to the Tolmezzo NS –6dB earthquake. It was recorded in the y direction with a sampling time of 10 ms. Fig. 7 also shows the displacement response spectrum of this accelerogram for damping ratios of 1, 6 and 15%. The PsD experiments were performed for the first 12.5 s of the time history.

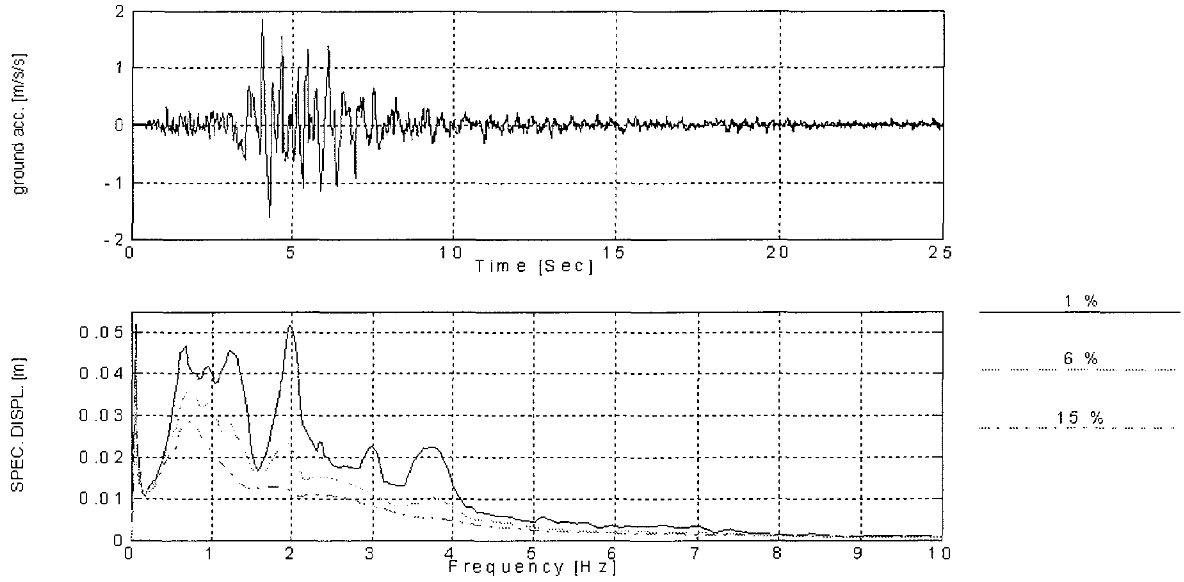

Figure 7: Ground acceleration and associated displacement responses spectrum (for damping ratios 1, 6 and 15%) recorded on the shaking table and corresponding to the Tolomezzo Earthquake – 6db.

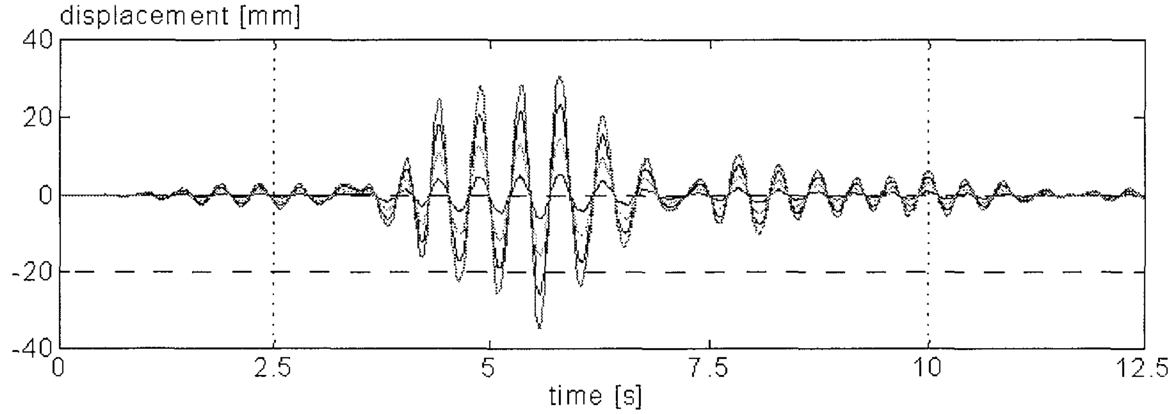

Figure 8: Non-isolated structure seismic PsD test: floor 1,2,3,4 displacements.

(Figs. 8 and 10) illustrate, respectively, the structural displacements of the four floors and the shear loads and inter-storey drifts. Usually, this type of result, which is very useful for the identification of damage or development of numerical models, cannot easily be measured during shaking table tests.

(Fig. 11) shows the comparison of the displacement at the second floor of the structure measured in the PsD and shaking table tests. To analyse the discrepancies of the PsD and shaking table results, a Finite Element Model (FEM) of MISS was elaborated using the program CASTEM [14]. The steel structure frame was represented using linear beam elements that consider bending, shear and axial deformations. The flexibility of the beam to column connections was modelled with Timoshenko beam elements of infinitesimal length. The FEM was condensed to the transverse degrees of freedom of the four storeys of the structure. The mass matrix was further lumped at each storey to simulate the PsD testing. Rayleigh damping was set for the first eigenvalue and for a frequency of 25 Hz. Time history analysis was performed using the step-by-step centered Newmark algorithm.

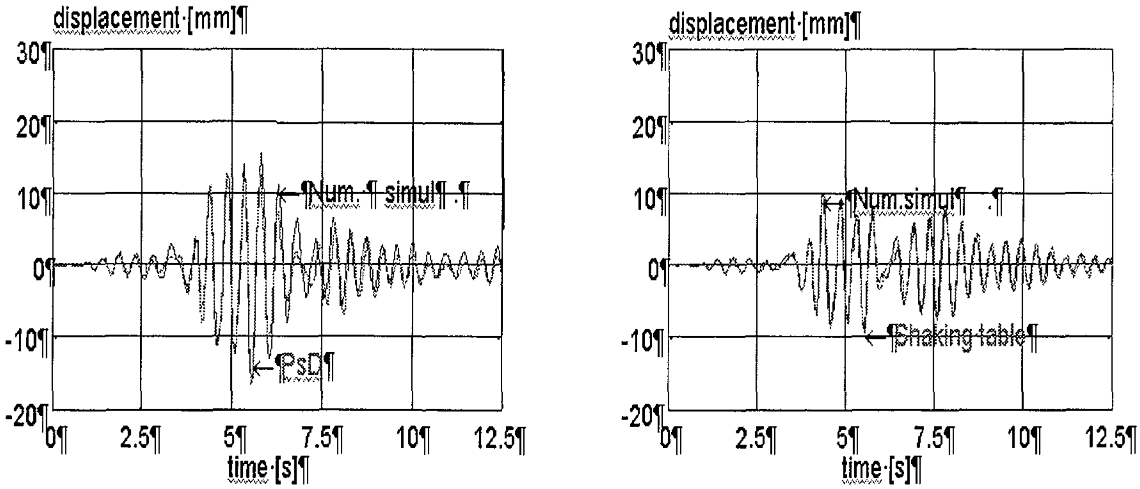

Figure 9: Non-isolated structure seismic tests: Second floor displ., PsD, Shaking tale and Num. comparison

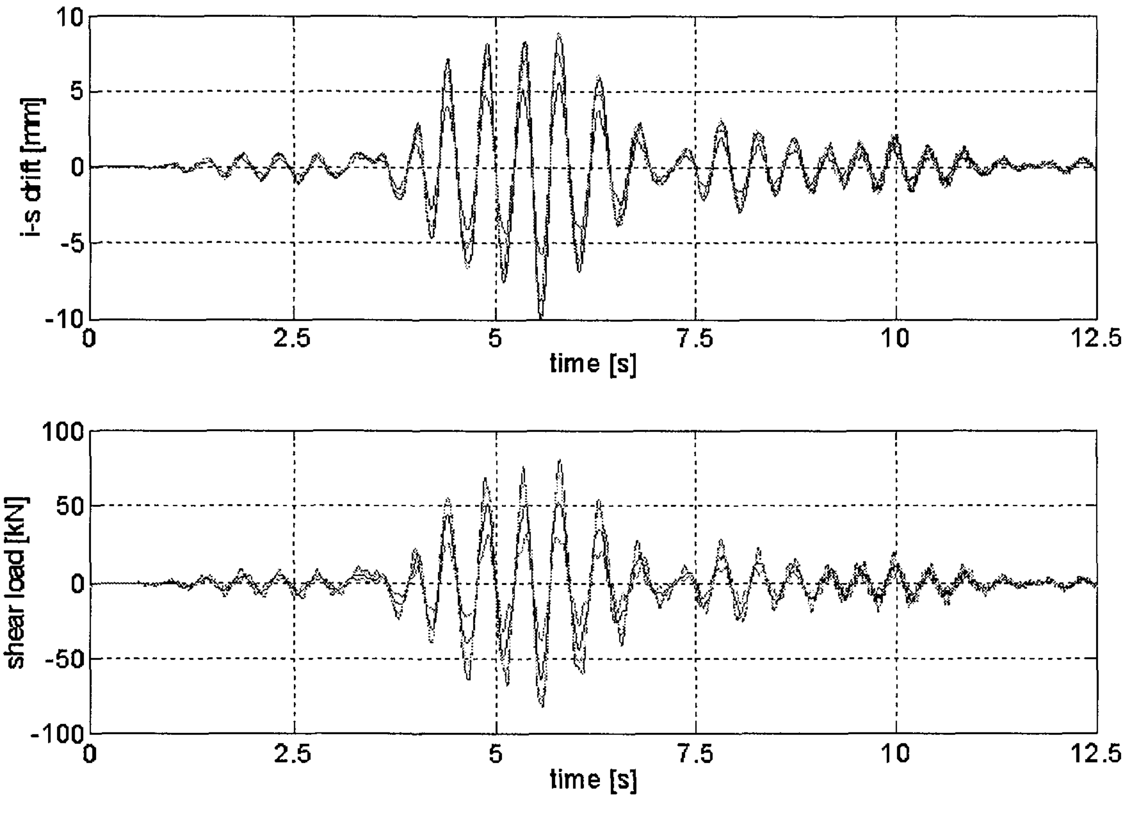

Figure 10: Non-isolated structure seismic PsD test: floor 1,2,3,4 inter-storey drift and shear load

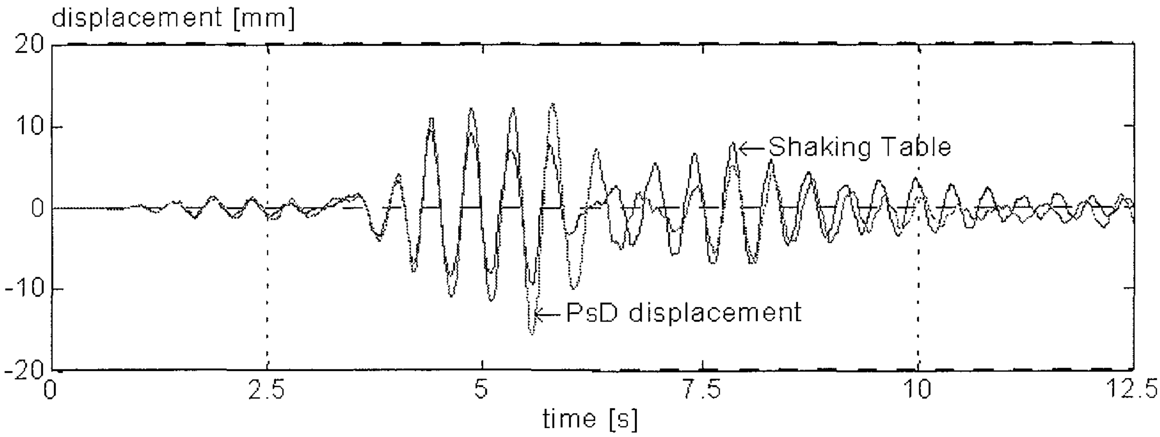

Figure 11: Non isolated structure.-6dB Tolomezzo Earthquake: second floor displacement shaking table and PsD test comparison.

On (Fig. 9), a comparison is made between the experimental results of the PsD and shaking table tests with the numerical model whose parameters were adjusted in order to obtain the best fitting of the respective tests. From that figure and from the data contained in Table 2, one can see how the experimental results are well matched by a linear model, which is reasonable for this type of structure within the range of attained deformations. However, the parameters of the best-fit model differ for both tests, mainly for the damping ratio of the first mode and lightly for the associated frequency. In the case of the PsD test, that damping ratio was found to be about 1% both for the dynamic and PsD snap-back tests as well as for the PsD seismic test. However, in the case of the shaking table test, the damping was found to be about 6%, which could be due to: differences in the coupling bolts stressing, attachment to the table, existence of residual pitching of the table, or some other facts which are still to be analysed in collaboration with ISMES. The response spectrum contained in Fig.7 may also justify why, for a frequency around 2.2Hz, a difference in damping from 1% to 6% may represent a decrement of a 30% in the response as was observed in the shaking table test with respect to the PsD test.

TABLE 2: COMPARISON OF SEISMIC TESTS EIGEN FREQUENCIES AND DAMPING RATIOS FOR SHAKING TABLE TEST, PSD TEST AND NUMERIC SIMULATION ON THE NON-ISOLATED STRUCTURE

	Mode 1		Mode 2		Mode 3		Mode 4	
	Hz	Damp.	Hz	Damp.	Hz	Damp.	Hz	Damp.
Shaking table	2.37		9.20		18.90		27.1	
PsD	2.17	0.8 %	8.00	1.3 %	16.70	1.5 %	23.8	0.9 %
Num. 6%	2.30	6.0 %	8.46		18.35		29.76	
Num. 1%	2.25	1.0 %	6.35		11.81		17.97	

5 PsD TESTS ON THE ISOLATED STRUCTURE

5.1 Real-Time Snap-Back Tests

The base of the mock-up was mounted on six HDRBs isolator devices. This new base floor will be called here floor 0. The real-time snap-back was executed as described before by pushing at the centre of the isolated base (floor 0). The applied force was recorded during the entire loading phase. Two snap-back tests were performed at an initial displacement equal to 22.5 mm and 40 mm, which correspond to a 75% and 133% shear strain in the rubber bearings respectively. As expected, the curves (Fig. 12) indicate a free damped response, with a significantly high value of damping. The figure shows a decrease of the time interval between two subsequent peaks during the oscillation; this is due to the non-linear behaviour of the isolators, which display an increasing horizontal stiffness with decreasing displacement.

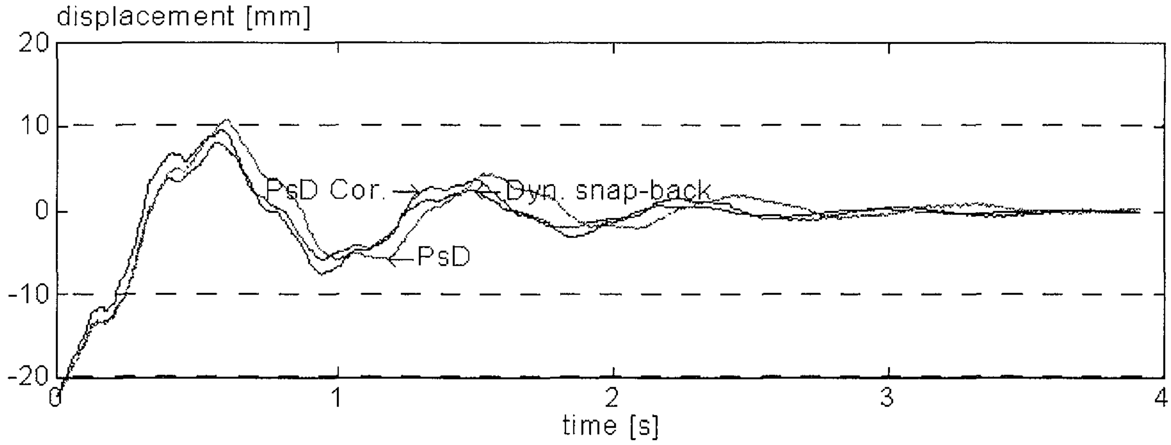

Figure 12: Dynamic snap-back tests on the isolated structure (initial displacement: 22.5 mm), non corrected PsD and corrected (23%) PsD.

5.2 PsD Snap-Back Tests

The base of the mock-up was guided in a rail system fixed on the strong floor to assure a motion in the transversal direction only while avoiding any torsional displacements. Five actuators were attached to the structure and the snap-back tests were repeated pseudodynamically by prescribing as external load the history measured during the dynamic test. This time, the PsD model consisted of 5-DoF (one per floor including the base) and the following mass matrix was used: diag(1840, 5140, 5450, 5340, 5460) kg. Firstly, a PsD test without strain rate compensation was performed. In order to assess the validity of the strain rate compensation, the PsD test was repeated adding a 23% correction to the shear load measured at the isolators. Such value was selected after some trial and error in order to optimise the frequency and amplitude in comparison with the dynamic snap-back test. Note that this correction of a 23% is larger than the one of the characterisation tests (19%, see Fig.3). This is due to the larger time scale used in this tests ($\lambda = 500$, instead of 300). Fig. 12 shows the free vibration displacement history of floor 0 recorded during the 22.5 mm snap-back test and the comparison of the results of this test with the non-corrected and corrected PsD tests. Table 3 gives the natural frequencies and the equivalent damping ratios of every mode. From Fig. 12 and Table 3, it is clear that the strain rate effect slows down the frequency of the first mode (rigid body oscillation of the isolated frame) in the non-corrected PsD test, while this effect is compensated in the corrected PsD test.

From the data of this table, it appears that the applied technique of force correction on the isolators was able to compensate the strain rate effect by adjusting the frequency of the first mode, while it showed no significant influence on any of the damping ratios or any of the higher frequencies.

TABLE 3: COMPARISON OF EIGEN FREQUENCIES AND DAMPING RATIOS FOR DYNAMIC, NON-CORRECTED PSD AND CORRECTED PSD (23%) SNAP-BACK TESTS ON THE ISOLATED STRUCTURE

	Mode 0		Mode 1		Mode 2		Mode 3		Mode 4	
	Hz	Damp.	Hz	Damp.	Hz	Damp.	Hz	Damp.	Hz	Damp.
Dyn.	1.20	15.5 %	4.5	4.4 %	11.9	1.3 %	21.6	1 .0 %	27.9	7.8 %
P 0%	1.05	14.6 %	4.32	3.8 %	11	1.3 %	20.3	0.6 %	29.7	3.0 %
P 23%	1.15	14.9 %	4.4	3.9 %	11	1.4 %	20.2	0.5 %	29.3	1.9 %

5.3 PsD Seismic Tests

The above described PsD tests have shown the possibility to correct in a suitable way the response of the isolators to account for the sensitivity of the material to strain rate effect. Since the time-scale factor of the seismic PsD test with respect to real-time always remained approximately of the same order of magnitude as for the snap-back test ($\lambda = 500$), the 23% of shear load correction was maintained for seismic tests.

(Fig. 13) shows the comparison of the displacements at the base floor and at the second floor of the structure for the PsD and shaking table tests. Both PsD and dynamic approaches have produced results very close to each other. Some small discrepancies in the comparisons are fully justified by the experimental errors and by minor variations of the HDRBs stiffness and damping as a function of the manufacturing series, loading frequency and load history. In fact, much of the variation in the observed behaviour can be attributed to the loading history on the isolators.

(Fig. 14) shows the inter-storey drift and shear load measured at each floor of the isolated MISS, in the PsD tests. As expected, respectively to Fig.10, a relevant reduction both in drift and shear due to isolation is observed.

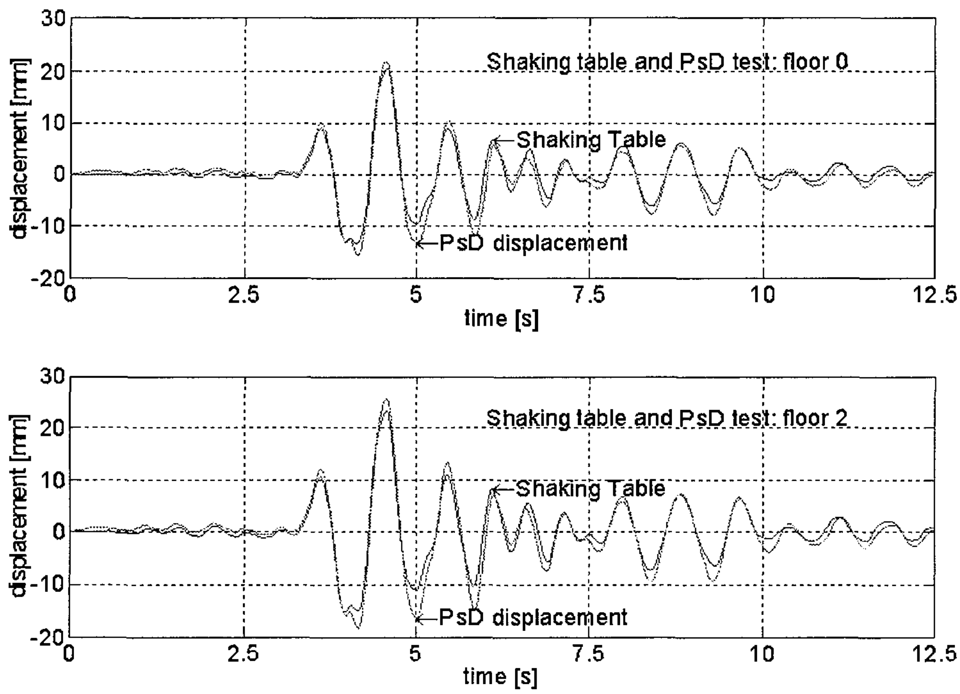

Figure 13: Isolated structure.-6dB Tolmezzo Earthquake: floor 0 and 2 displacements Shaking table and PsD tests comparison.

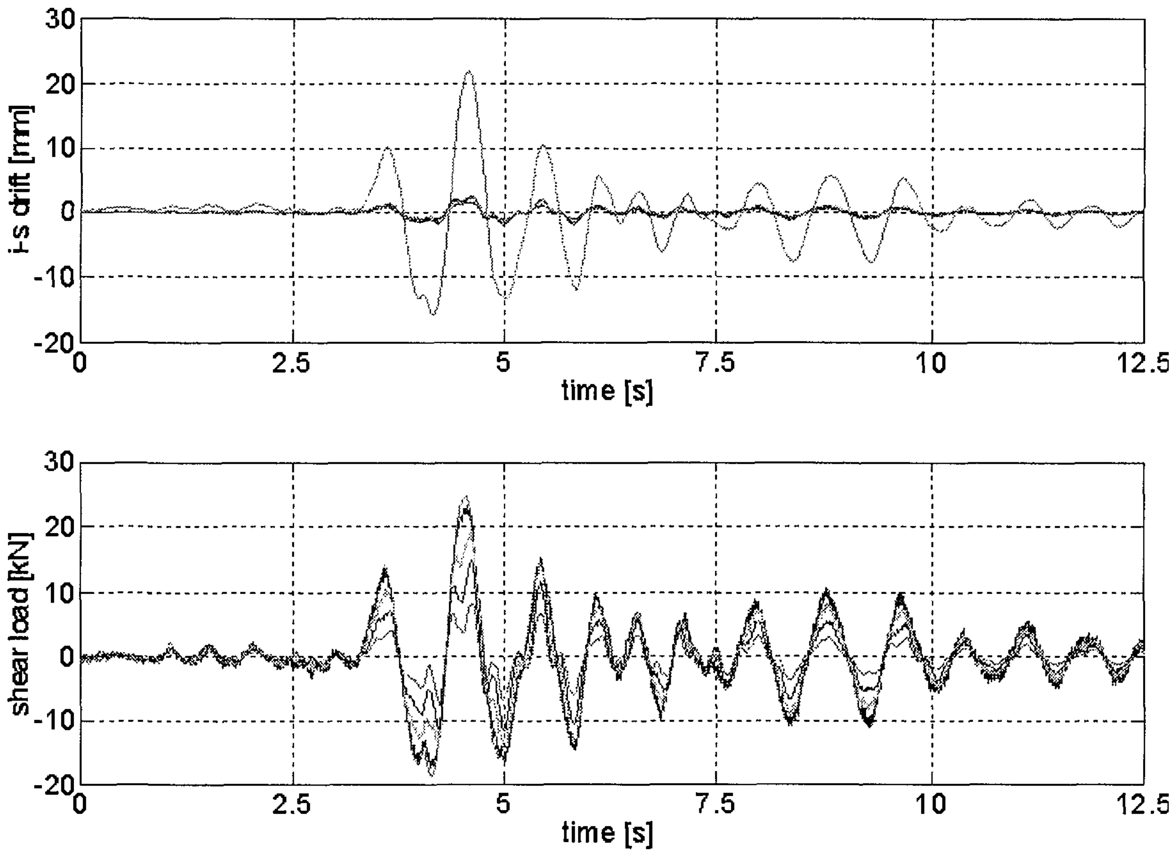

Figure 14: Isolated structure: -6dB Tolmezzo Earthquake: inter-storey drift and shear load.

6 PSEUDO-DYNAMIC SEISMIC TESTING OF LARGE SCALEMODELS OF CIVIL BUILDING WITH DISSIPATION DEVICES

The problem of the correction of the coefficients of the PsD method must be applied also in the case of testing of mock-up protected with dissipation devices based on materials with a strain rate dependent behaviour. As well known, this is the case of rubber and in the previous paragraphs it has been shown how to overcome the difficulties correlated with the PsD method.

A very similar procedure of correction applies also to the case of energy dissipation devices based on high damping rubber. This has been investigated and validated at JRC ELSA laboratory by testing a large-scale civil building incorporating such type of devices.

7 CHARACTERIZATION OF THE MODEL

A project, named "REEDS", was funded by the EC through the Brite-EuRam programme. It has been set up to focus the efforts of manufacturers, developers and end-users of anti-seismic devices towards identifying methods to augment the options currently available and therefore greatly increase the possibility that economic seismic protection can be provided to any particular structure, plant or equipment.

ELSA took part in the research by testing a large-scale model of reinforced concrete building protected with energy dissipation devices. These are made with high dumping natural rubber interposed between steel plates subjected to differential displacements through cross bracing. The main point to be investigated were the characterization of the model and the performance for imposed earthquake signals defined according the Eurocode-8.

A major point was the comparison of the behavior of the building with and without the protection system.

7.1 Description of the Mock-up

A two-storey mock-up of a reinforced concrete office building was designed for pseudo-dynamic (PsD) testing to be performed at JRC [16]. To make the mock-up compatible with the experimental equipment and with the available space in the laboratory, it was necessary to agree about its dimensions and about the characteristics of the attachment of the electro-hydraulic actuators. The mock-up (10m long, 4m wide and 5.2m high) represents a portion of the building scaled by 2/3 in dimension and consists of two bays of 5m in the direction of testing and of one bay across its width (Fig. 15). Eight energy dissipation devices were placed in each bay along the longitudinal facades and were supported by steel K-bracings (Fig. 16). The RC frame was constructed at the ELSA laboratory following the design specifications provided by Bouygues.

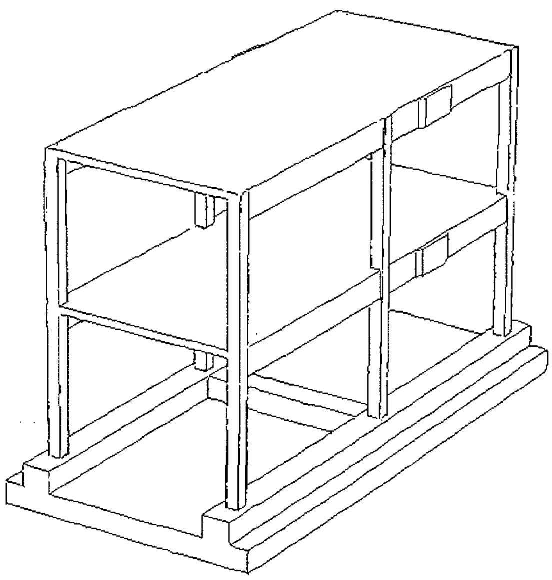

Figure 15: Isometric view of the mock-up.

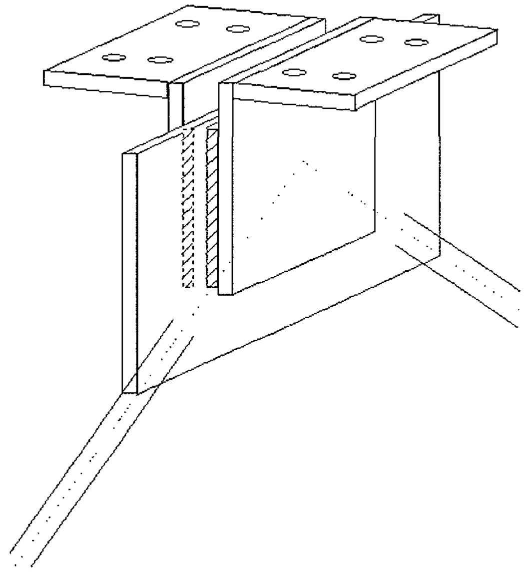

Figure 16: Details of the attachment of the VE devices to the mock-up structure.

The civil building has been moved into the laboratory and fixed to the strong floor. The steel wedges for the application of the force from the actuators were mounted against the floor slabs by means of post-tensioning rods. The bracing was installed in the bare frame and a specific interface has been designed and mounted to connect the visco-elastic device provided by TARRC. The connections of the steel bracing with the reinforced concrete frame have been made by means of anchor bolts to simulate a real retrofitting situation. The masses to be placed on the floor slabs have been installed. JRC in co-operation with Bouygues carried out material characterization of the concrete and reinforced steel used in the construction of the mock-up.

A particular attention has been devoted to the instrumentation of the mock-up, to measure the relative rotation between beam and column at the joints, and to measure the deformation of the antiseismic devices. The JRC has designed and instrumented the steel bracing in order to measure the shear force developed by the TARRC devices. This measurement was necessary to compensate the strain rate effect induced by the PsD method.

7.2 Characterization of the system

The identification of seismically vulnerable structures and equipment leaded to the adoption of a reinforced concrete frame civil structure. The choices practiced until now to meet seismic criteria for this type of structure are mainly based on strengthening of the design. The introduction of Viscoelastic Energy-Dissipative (VED) devices brings a "soft" alternative to the well known strengthening method or more recent seismic isolation technology. Seismic regulations are relatively recent and consequently many buildings have no or very little protection. The fact that the life of most buildings is around 100 years has lead to the realization that seismic retrofitting is potentially a big market, and VED devices may well be the most economic solution in many cases. The tests performed at the ELSA laboratory have been lasted to verify and quantify the effectiveness of such a system. To this end a large-scale two-floor and two-bay building was built outdoor of the laboratory and brought indoors in front of the reaction wall to be tested with the Pseudo-Dynamic (PsD) method (Fig. 17).

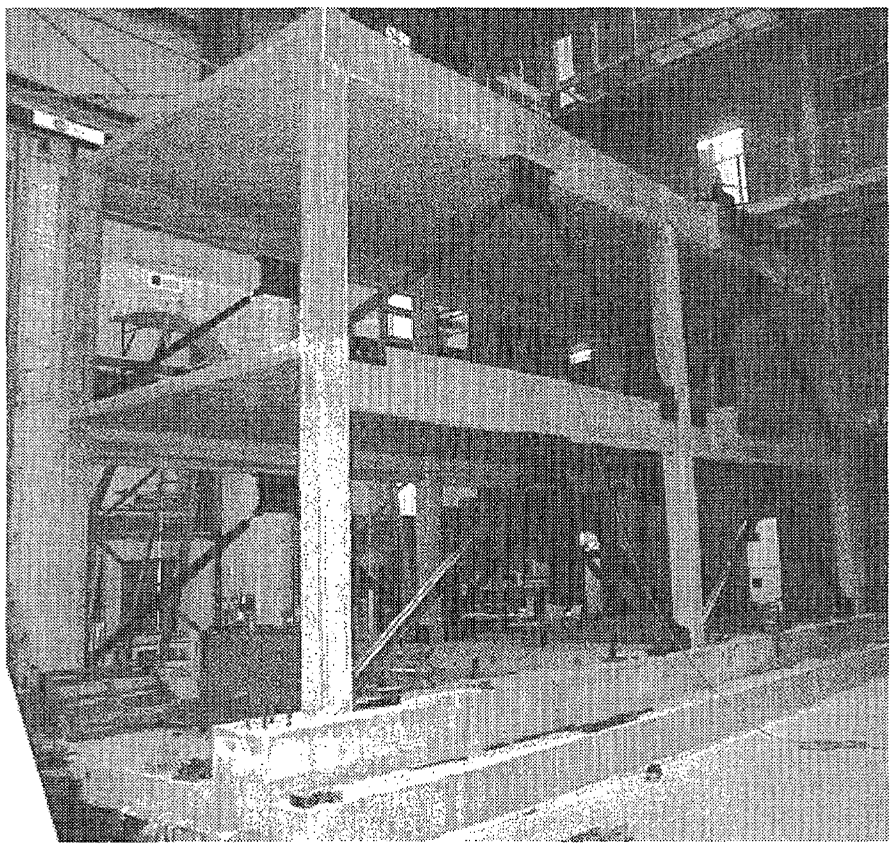

Figure 17: Large-scale model of the civil building with anti-seismic protection for earthquake simulation tests at ELSA.

The model of building has been equipped with damping devices made with natural rubber and the tests were performed with and without the damping devices for the same earthquake signal used as input. Being the rubber behavior of the devices sensitive to strain-rate, the execution of the PsD tests needs a specific characterization of the devices in order to take into account the strain rate effects as a numerical correction to be applied to the forces measured on the devices themselves. This procedure is made possible tanks to the flexibility of the PsD intrinsic characteristics. It is in fact a hybrid numerical-experimental method coupling the equation of the motion (used to evaluate the displacements induced by the earthquake) with the restoring forces of the structure measured on line on the model during the ongoing of the testing. This procedure bypass the problem of the theoretical assessment of the restoring forces and allows the precise calibration of the PsD method also for materials moderately sensitive to strain rate by introducing correction factors to account the real expected forces produced by the strain-rate dependent devices.

The results of the characterization tests for various strain-rates and the effectiveness of the correction by comparison of dynamic and PsD tests including a correction factor are shown in (Fig. 18).

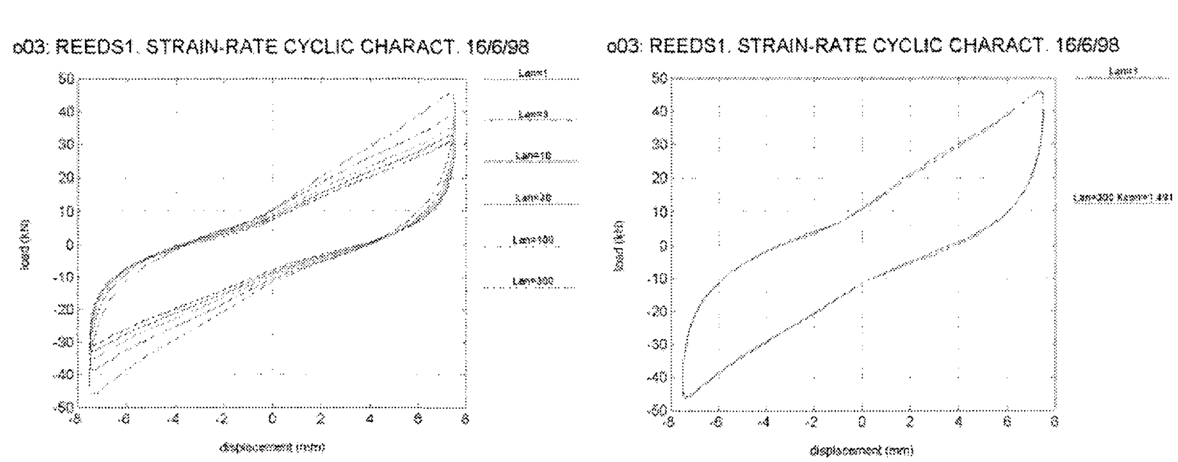

Figure 18: Results of the characterisation tests on the devices and comparison of a high strain rate test with a corrected PsD test.

8 PSEUDODYNAMIC TESTING OF THE SYSTEM

8.1 The pseudodynamic method

The Pseudo-Dynamic (PsD) test method is a hybrid numerical-experimental technique based mainly on the knowledge of the mathematical equation of the motion of the structure. When strong non-linear behavior occurs, the Restoring Force of the structure is no more computable so that the numerical integration becomes impossible. To overcome this difficulty the PsD method consists in running in parallel the integration of the numerical equation of the motion of the structure, imposing the assessed displacements generated by the earthquake and measuring the Restoring Force.

The experimental measure of the Restoring Force allows the integration of the equation of the motion until the end of the signal also for structures with strong non-linear behavior. The process doesn't need the generation of the inertia forces, computed from the equation, so that the time-scale of the operation is strongly expanded. This allows the direct visual diagnosis of the state of the structure and decisions about the limit to reach during the test.

The PsD method is fully complementary to the dynamic analysis based on Shaking Table. The main advantages of the PsD approach is the possibility to test full/large scale model of structure being the pumping power used to impose displacements and not for generating inertia forces. A second relevant advantage is the possibility of substructuring the model limiting the test to the part of structure with non-linear behavior while the linear one is computed in parallel with the numerical part of the PsD equation. The two substructures are coupled at the points of contact. With this technique it is possible to assess bridges only testing the piers, computing the deck and coupling the numerical part of the two structures.

The PsD method cannot be applied in case of materials whose behavior is strongly sensitive to strain rate or of structure with fully distributed mass. For this class of models it is mandatory to use the Shaking Table to perform meaningful tests.

8.2 Main results and achievements from the tests

The tests performed at JRC-Ispra showed a relevant reduction of displacements and highlighted the effectiveness of the devices for earthquake engineering applications.

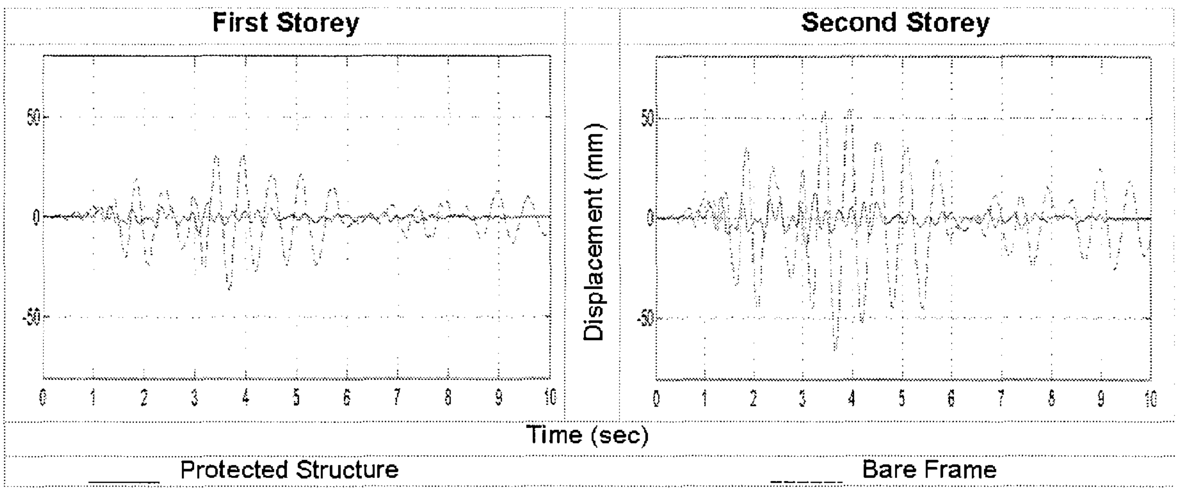

Figure 19: Dispalcement comparison between PsD tests ofthe protected structure an bare frame.

The VED devices need to experience a minimum amount of displacement during an earthquake to operate efficiently. Therefore their total stiffness per floor must be of the order of the floor stiffness of the building. Consequently, the use of these devices could be difficult for very stiff concrete structures, especially those containing shear walls. Nevertheless, with frame structures, which are quite common in seismic areas of Europe, the technical study has proved that reinforced concrete frame buildings designed initially for non-seismic areas may be up-graded, by incorporating viscoelastic dampers to respond elastically to earthquakes specified in European Seismic Code - EuroCode 8.

The devices can indeed provide an alternative protection strategy for such buildings. The dampers raise the stiffness between floors, the increase itself contributing to the reduction in the response. However, the inherent damping of the devices reduces the response much further. The PsD tests carried out at ELSA on the large-scale civil building have shown that when the structure is installed with the devices it responds elastically to earthquakes twice the magnitude of that for the bare structure.

The first and second storey displacements of the PsD tests on the protected and bare frame are shown in (Fig. 19). The efficiency of the energy dissipation devices is demonstrated by a reduction of the displacements of the frame by more than a factor of four, keeping thus the ductility demands on the RC members below unity, as shown by the hysteresis loops of the RC frame.

The efficiency of the energy dissipation devices can also be demonstrated by examining the energy absorbed during the PsD test of the protected frame, as shown in (Fig. 21), where the energy dissipation devices absorb 75% of the total energy that goes into the system

Although the forces in the RC frame are not sensibly reduced in the protected frame test, only a fraction of the force goes into the RC frame, the remaining of the force is absorbed by the energy dissipation devices. The introduction of stiffness of comparable value to the intrinsic interstorey one and of dissipation capability of the devices allowed a strong reduction in the hysteretic loops. This is shown in (Fig. 20) where the forces, for the protected case, are referred only to the structure (the horizontal component of the K-bracings is not accounted).

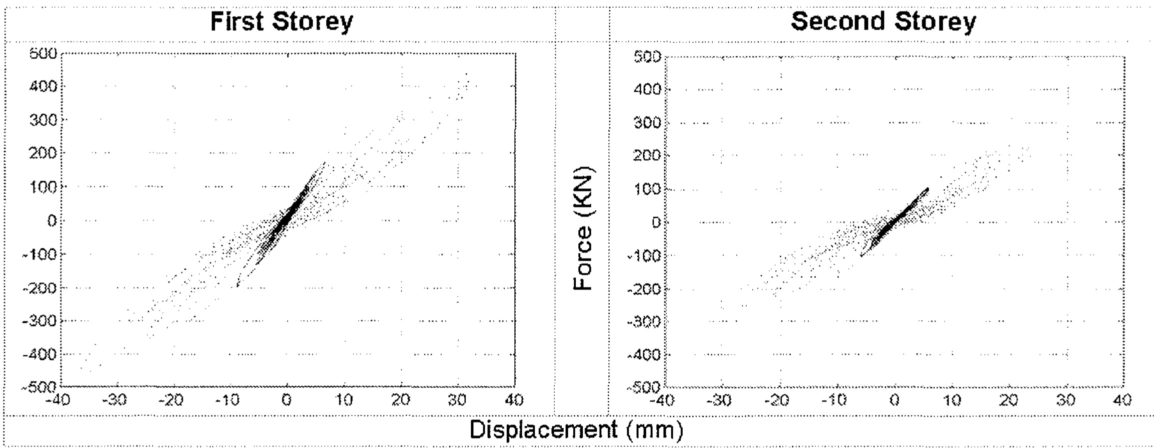

Figure 20: Comparison of energy dissipation in bare and protected frame.

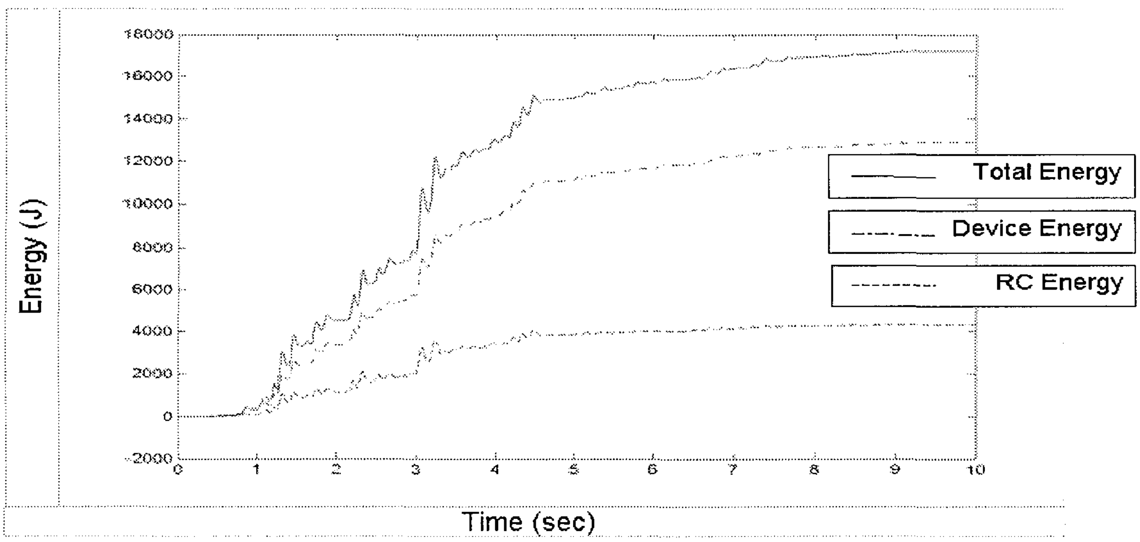

Figure 21: Energy absorbed during the PsD test of the protected structure.

9 CONCLUSION

The work performed and presented was finalised to the improvement and validation of the PsD testing method for structures protected against earthquake by devices based on materials strain rate dependent as it is the case of high damping rubber.

The investigation was done both for cases of base isolated mock-ups and for a model of civil building protected by energy dissipation devices.

As regards base isolation the work done at JRC, in collaboration with the Italian Working Group on Seismic Isolation, was finalised to compare the results obtained from PsD and shaking table tests performed on the isolated MISS mock-up. PsD seismic excitation tests performed on the isolated and non isolated structure have confirmed that HDRBs allow a very effective reduction of the earthquake response of the structure.

As regards energy dissipation devices the work was done in collaboration with an international consortium in the framework of a project partially financed by the European Commission. The mock-up was a large scale model of civil building not designed for seismic zones and seismically upgraded by using energy dissipation devices.

In both cases the test results showed that, thanks to specific strain-rate compensation procedure, the PsD method is able to reproduce with good accuracy the response of a large-scale model of structures protected by strain rate dependent devices. This was observed during the dynamic snap-back tests or the seismic tests performed on shaking table.

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