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Experimental and numerical analysis of isolated structures

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ABSTRACT: Dynamic experiments were performed on both full-scale and scaled isolated structure mock-ups and actual isolated buildings (one of those forming the SIP Administration Center at Ancona, an isolated house at Squillace), supported by high damping steel-laminated elastomer bearings. Both snap-back tests and forced excitation experiments were performed, to large displacements. The latter were both sinusoidal and (on a 1/4 scale mock-up) seismic, with one- and multidirectional simultaneous excitations. Test results have already demonstrated the adequacy of seismic isolation and have provided data useful for the comparison with single bearing test results and validation of numerical models for the analysis of isolated structures.

1 INTRODUCTION

In a separate paper, Martelli et al. (1992) have mentioned that - in addition to tests on single high damping rubber bearings (HDRBs) described by them - current studies in Italy on seismic isolation also include tests on structure mock-ups and actual buildings, isolated by HDRBs.

Mock-up tests were performed by ISMES on behalf of the National Agency for New Technologies, Energy and Ambient (ENEA), while building tests were carried by ISMES on behalf of the National Utility (ENEL), and partly, ENEA. Further mock-up tests are beginning at the ENEA-ANSALDO Centre of Boschetto (Genova). Numerical analysis of the experimental results is in progress at ENEA and ISMES (see also Serino et al. 1992).

This paper summarizes the main features and results of the above-mentioned tests and analysis (more details have been provided by previous papers, such as that of Forni et al. 1991, and Serino et al. 1992).

2 TESTS OF ISOLATED STRUCTURE MOCKUPS

The mock - ups used in the laboratory tests performed to date were such as to only reproduce the mass of actual structures, being characterized by very large stiffness. However, the definition of experiments on more realistic mock-ups of isolated structures is also in progress.

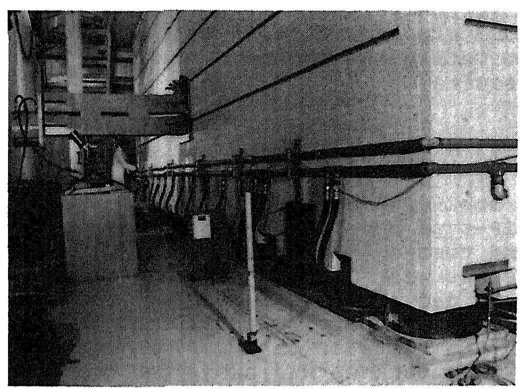

Figure 1. 9,500 kN isolated mock-up.

Tests have already been performed on a full-scale mock-up and a 1/4 scale mock-up; experiments are also beginning on a 1/2 scale mock-up.

2.1 Tests of a full-scale mock-up

The first laboratory tests were performed in August 1990. They made use of the inertial mass of the ISMES multiexcitation rig, supported at the base by six full-scale bearings (see Fig. 1). The use of this mass (which weights 9,500 kN) allowed for a close approximation of the actual design vertical load (1,600 kN) that is prescribed for each of the 500 mm diameter bearings which support the five isolated buildings of the Administration Center of the National Telephone Company (SIP) at Ancona (see Martelli et al. 1992 and § 3).

This mock-up was subjected to snap-back tests (making use of collapsible devices), where the initial displacements were equal to 13 mm, 30 mm, 65 mm and 85 mm (Fig. 5). The largest value corresponded to about 60% σ (σ = shear strain), i.e. to a displacement equal to about 60% of the total rubber height. This value - such as to hinder sliding of the mass (which could not be attached to the steel-end plates of bearings) - was sufficiently close to the design value (144 mm = 100% σ) as to provide reliable information on the behaviour of isolated structures and demonstrate the adequacy of the snap-back mechanisms, for their subsequent use in the in-situ tests of the SIP building (§ 3.1).

The campaign was concluded by a second experiment at 65 mm displacement to verify the reproducibility of test results.

2.2 Tests of a 1/4 scale mock-up

A mock-up supported by four 1/4 scale SIP-type bearings was also fabricated and tested (Serino et al. 1992). Its weight was 394 kN, which correctly provided a vertical load per isolator equal to about 1/16th of that present in the tests of the 9,500 kN mock-up.

This mock-up was subjected to both snap-back and forced excitation experiments on the six-degrees-of-freedom shake table of ISMES (MASTER) in February 1991 (Figs. 7 and 8). All tests were performed with response displacements gradually increasing to 100% σ (9, 18 and 36 mm, corresponding to 25%, 50% and 100% σ, respectively).

Forced excitation tests consisted of both one-directional (1D) sinusoidal experiments and seismic tests with 1D, 2D and 3D simultaneous excitations (for the two horizontal directions and the vertical): the latter corresponded to recordings of actual Italian earthquakes (Friuli and Irpinia) for rigid, medium and soft soil conditions. Very large amplifications of the actual ground motion were found necessary to reach 100% σ for medium soils (a 2.5 factor), and especially, rigid soils, while margins were obviously rather reduced - although existing (12%) - for soft soil (see also Serino et al. 1992).

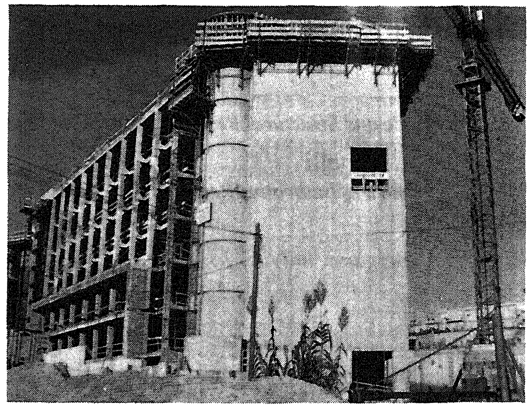

Figure 2. SIP building subjected to in-situ experiments at Ancona.

2.3 Tests of a 1/2 scale mock-up

Tests on a third mock-up are beginning (February 1992) at the Boschetto Centre. The campaign will consist of both snap-back and forced excitation tests on a mock-up formed by the inertial mass of SCORPIUS shake table. This mass weights about 1,600 kN, thus, it will be supported by four 1/2 scale SIP bearings. Both SIP type and dowelled and bolted isolators will be used (as usual, all of them will be previously characterized at ISMES on the SISTEM machine of ENEA, see Martelli et al. 1992).

Forced excitation will be provided by the shake table. Snap-back tests will be performed with initial displacements increasing to about 150% σ (this is possible because the mass has been equipped so as to allow for bolting the end plates of bearings).

3 IN-SITU TESTS OF ACTUAL BUILDINGS

In-situ forced-excitation and snap-back tests were performed by ISMES, mainly with ENEL funding, on one of the SIP buildings at Ancona, in September and October 1990 (Fig. 2). These are seven-floor buildings, 25 m high, each weighting 70,000 kN.

Starting in June 1991, experiments were also carried out by ISMES, on behalf of ENEL, on both an isolated and a non-isolated houses at Squilla-

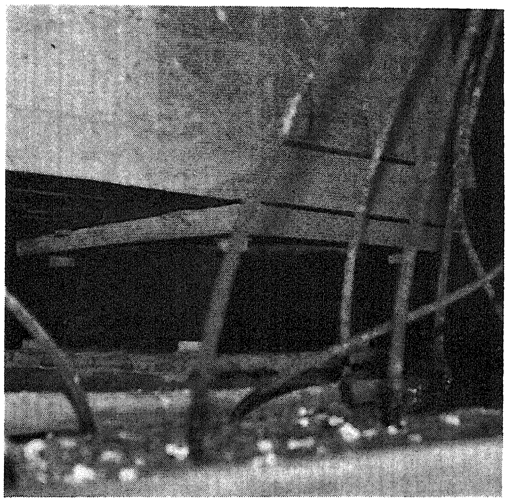

Figure 3. Bearing displaced at the SIP building base, during snap-back tests.

ce, Calabria. These houses are four-story reinforced concrete space frame structures: apart from the isolation system, they are characterized by identical sizes, mechanical properties and construction methods (see Forni et al. 1991).

All the buildings tested will be provided with a seismic monitoring system.

Further tests may be carried out - before and after seismic retrofitting - on a church at Frigento (Sparacio et al. 1992) and other new isolated buildings, in the framework of the promotion activities of the National Working Group on Seismic Isolation (GLIS, see Martelli et al. 1992).

3.1 Tests of the SIP building

The SIP building of Fig. 2 weighted about 63,000 kN at the time of tests, because it was practically still "nacked". Test feasibility had been demonstrated by the results of GLIS collaborative activities, concerning numerical pre-test analysis of the building (§ 4), and experiments on the 9,500 kN isolated mockup (§ 2.1). Furthermore, tests took advantage of the results of a numerical study, concerning the propagation of vibrations through the soil due to the collapse of snap - back mechanisms, which had demonstrated the absence of damage induced to the surrounding houses (Forni et al. 1991).

Forced vibration tests were carried out using a 100 kN two-eccentric mass mechanical vibrator installed on the building roof. For snap-back tests, use was made of hydraulic jacks to displace the building and collapsible devices to release it, similar to the laboratory experiments of the 9,500 kN mock-up. These devices were provided with explosive bolts, to ensure simultaneous release at all loading positions (Martelli & Castoldi 1991).

Four snap-back tests were carried out by applying initial displacements of 7.5 mm, 37 mm, 70 mm and 107 mm; the latter (corresponding to about 75% σ, see Fig. 6) was sufficiently close to the design value. A final test was repeated by ENEA at 70 mm displacement with a very detailed instrumentation of the building.

The in-situ experiments had been preceded by detailed acceptance tests of the actual bearings (Bonacina et. al. 1991) and some further characterization tests of one of such bearings on the SISTEM machine (Martelli et al. 1992).

3.2 Tests on the houses at Squillace

Both houses at Squillace were subjected to forced excitation tests (by use of a mechanical vibrator located on the roof) and ambient vibration measurement (wind- and train-induced microtremors). Forced excitation was provided in the two main directions at different amplitudes.

Prior to the in-situ tests, some bearings had been characterized dynamically by Martelli et al. (1992) on the SISTEM test machine.

4 NUMERICAL ANALYSIS

A finite-difference program (ISOLA) was set-up by ENEA for the analysis of an isolated structure in the case that this can be represented by a set of one-degree-of-freedom oscillators. This program also applies to the analysis of single bearing data. It solves the motion equation of such an oscillator in the case that both stiffness and damping depend on displacement. It allows various damping models to be considered, and also accounts for viscous creep effects.

This model is being used for the analysis of experimental results concerning both isolated mock - ups and buildings, based on the single bearing test data for horizontal stiffness and equivalent viscous damping

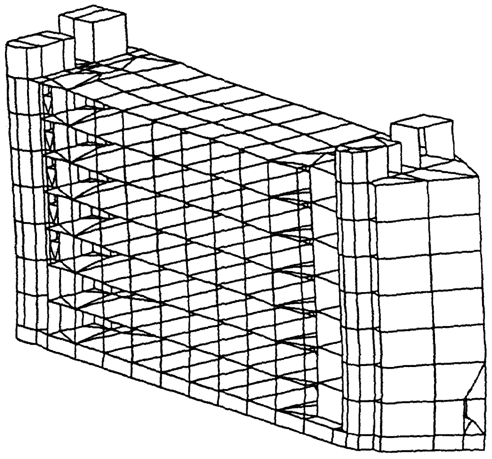

Figure 4. First vibration mode computed for the superstructure of SIP building subjected to in-situ tests.

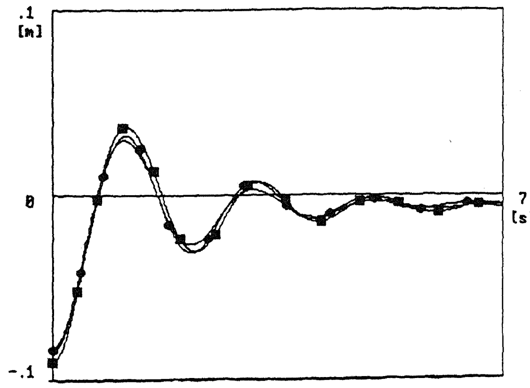

Figure 5. Comparison between the horizontal displacement measured for the 9,500 kN mock-up in the most severe snap-back test (●) and values computed with ABAQUS (■) and ISOLA (—).

(Martelli et al. 1992).

Furthermore, finite-element (f.e.) models were implemented by ENEA in the ABAQUS program for the different structures (by assuming a very large stiffness for the SIP building also). ABAQUS runs allow for calculations in the case of multidirectional excitation also. However, while the dependence of bearing horizontal stiffness on displacement can be taken into account by the program, only constant viscous damping can be assumed until now. The consequence is that a good agreement between calculations and measurements is being obtained - for snap-back tests - only by use of damping values that are considerably larger than those obtained in single bearing tests (Martelli et al. 1992).

In addition to the aforesaid simple models, a sophisticated three-dimensional (3D) f.e. model was also developed for the SIP building (Fig. 4). This work was performed by ENEA in collaboration with the designer (Giuliani 1991) - within the cooperative activities of GLIS - to allow for pre-test analysis of the building, as necessary to get the permission for the testing campaign (Bonacina et al. 1991). The model - which had been previously applied to the SYSTUS program - was later implemented in ABAQUS, so as to enable faster analysis of the test data (this analysis has already been started).

3D analysis of the test results of both houses at Squillace is also being started by ENEA within the collaborative activities of GLIS.

5 EXPERIMENTAL AND NUMERICAL RESULTS

Tests and analysis provided essential information on the behaviour of isolated structures and isolation systems, in particular for the assessment and validation of calculation procedures (see also Serino et al. 1992).

They were also extremely important to demonstrate the excellent performance of seismic isolation to both the technical milieu and public opinion: a careful inspection of the SIP building after tests' conclusion absolutely excluded any damage of the structure and the few brick wall partitions that were already present.

5.1 Snap-back tests

In snap-back tests, the motion in the initial displacement direction lasted a very few seconds for both the building and the mock-ups (about 3 s), and consisted in three appreciable cycles only (Figs. 5 to 7). The mock-up responses indicate a quasi exclusively horizontal translation mode in that direction after mass release; for the building, some translation in the normal direction was due to the structure asymmetry.

Residual displacements of some millimeters were always detected at test conclusion; these were partly recovered within some hours; their values seem not to be related to those of the initial displacement, but appear dependent on the deformation history

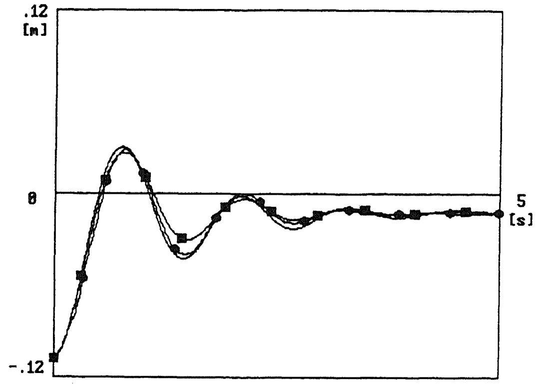

Figure 6. Comparison between the horizontal displacement measured for the SIP building in the most severe snap-back test (●) and values computed with ABAQUS (■) and ISOLA (—).

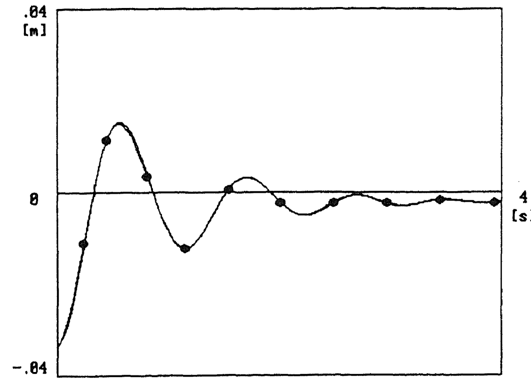

Figure 7. Comparison between the horizontal displacement measured for the 394 kN mock-up in the most severe snap-back test (●) and values computed with ISOLA (—).

and rest intervals to which the isolators were subjected.

Reproducibility of test results was successfully verified for both the mock-ups and the SIP building (Martelli & Castoldi 1991).

The first response frequency (f_1) increased considerably during motion, as displacement amplitude decreased (Figs 5 and 6); for the building, the f_1 values were larger, due to the lower mass per isolator and presence of mostly 600 mm diameter isolators. This behaviour is consistent with the non-linear correlation that exists between bearing elastic forces and displacements (Martelli et al. 1992).

For similar reasons it was impossible to define an unique damping value for each entire test. The assumption of equivalent viscous damping (β_v) and use of the logarithmic decrement technique led to β_v values that vary from 17% of the critical (at the largest cycle) to 20% for the full-scale mock-up, and between 16% and 20% for the building. These values are rather larger than those obtained in the single bearing tests, due the strong increase of β_v with decreasing displacement during each test and the hysteretic nature of energy dissipation (Serino et al. 1992).

The numerical analysis of free-vibration test data performed with ABAQUS showed that horizontal stiffnesses (k_h) are consistent with those related to single bearing tests, if the dependence of k_h on displacement is correctly accounted for (Figs. 5 and 6). Moreover, the response measured in each test was well calculated by use of a constant β_v value that was only slightly larger than the average test data, and by translating the force-displacement curve from the origine along the abscissae axis, of a quantity equal to the residual displacement, so as to account for the non-zero center of motion cycles that is due to creep and other phenomena.

The agreement with β_v values measured in the single bearing tests was much better by use of the ISOLA program (§ 5), accounting for the dependence of both k_h and β_v on displacement (Figs. 5 to 7) or by means of numerical methods based on hysteretic damping (Serino et al. 1992). It is noted that such an agreement is good not only for the mock-ups (which were actually formed by rigid masses), but for the building also.

Finally, measurements during SIP building tests confirmed the results of a numerical study on the propagation of vibrations through the soil (Martelli & Castoldi 1991).

5.2 Forced excitation tests

The numerical analysis of the results of the shake table experiments performed on the isolated 394 kN rigid mass confirmed the applicability of the single bearing test data to the analysis of isolated structures, as well as the need for taking into account the variation of stiffness and damping with displacement (see Fig. 8 and Serino et al. 1992).

As to the results of forced vibration tests of the SIP building , it

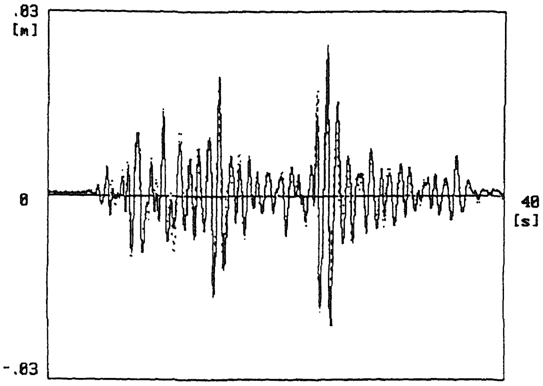

Figure 8. Comparison between the horizontal displacement measured for the 394 kN mock-up in the most severe 1D seismic test for Calitri earthquake (—) and values computed with ISOLA (···) (WE direction, + 1db).

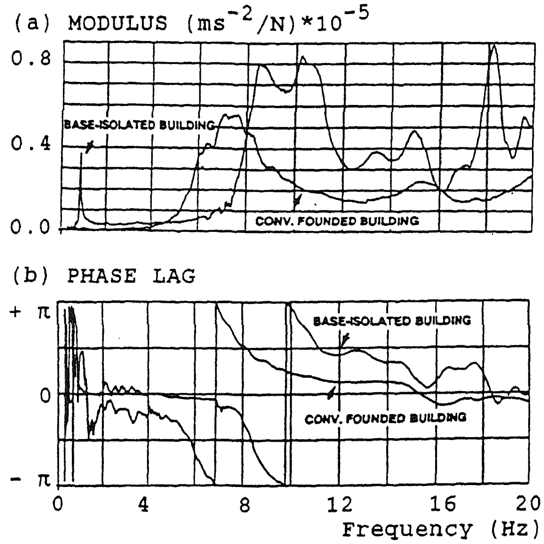

Figure 9. Transfer functions measured on the Squillace buildings.

is noted - among others - that modes corresponding to elastic deformations of the superstructure are located above 5 Hz, according to pre-test analysis (Bonacina et al. 1991).

Finally, tests on the two houses at Squillace confirmed the large, beneficial effects of seismic isolation (Fig. 9).

6 CONCLUSIONS

Experiments of structure mock-ups and actual buildings, isolated by means of high damping elastomer bearings, clearly demonstrated the adequacy of seismic isolation to guarantee the integrity of the structures and their contents.

Test results provided excellent data for the characterization of isolation systems, comparison with the single bearing experiments and validation of numerical models for the analysis of isolated structures. Such results stressed the adequacy of single bearing tests to determine the bearing characteristics (stiffness and damping) to be used in this analysis, provided that their dependence on displacement accounted for in the calculations. As to damping, its largely nonviscous nature was confirmed.

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