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Experimental and numerical evaluation of benefits of optimized HDRBs for seismic isolation

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ABSTRACT: Presented in this paper are the main features and results of the experimental and numerical studies which were performed by the Italian partners in a research project funded by the European Commission, to evaluate the benefits related to the use of optimized High Damping Rubber Bearings as seismic base isolators on the design of structures.

INTRODUCTION

It has been mentioned in a separate paper [1] that, in the framework of the studies performed in Italy on seismic isolation (SI), a 30 months research project [2], funded by the European Commission (EC) and aimed at developing optimized High Damping Rubber Bearings (HDRBs) and evaluating the benefits of their use on the design of structures of various kinds (including nuclear plants), was completed in 1996. It has also been mentioned in [1] that the contributions of the Italian partners to this project comprised (among others) wide-ranging tests and detailed numerical analyses of (a) rubber specimens and single isolators, and (b) isolated structures [2-8].

This paper summarizes the activities concerning item (b) and reports some of the most recent results, while the separate paper [1] deals with the R&D work related to item (a). More details, with respect to those given in this paper, will be provided in ref. [9].

ANALYSED STRUCTURES

The Italian partners in project [2] (ENEL, ENEA and ALGA) contributed to the evaluation of benefits of SI systems formed by optimized HDRBs by performing experiments on two structure mock-ups at ISMES and ANSALDO-Ricerche (ARI) and by numerically analysing the results of both such experiments and those of on-site tests which had been previously carried out by them on actual buildings [3, 7, 8].

Mock-up experiments consisted of shake table tests of ENEL at ISMES on the MISS (Model of Isolated Steel Structure) mock-up, which has a flexible superstructure (Fig. 1a), and pull-back tests of ALGA at ARI on a mock-up having the same rigid superstructure as in previous experiments there [3, 7, 8]. MISS is a four storey steel frame, provided with movable masses on each storey and variable interstorey distances, which allows for different stiffnesses, mass profiles and eccentricities. This mock-up, weighting to 330 kN, was supported by six "further optimized" soft 125 mm diameter HDRBs (shear modulus G = 0.4

MPa) with an attachment system formed by a combination of central dowel and bolts (CDB) [1]. As far as tests at ARI are concerned, the superstructure (weighting 1,600 kN) was supported by four 250 mm diameter "further optimized" HDRBs with medium hardness rubber (G = 0.8 MPa) and CDB attachment system [1].

The considered actual buildings were one of the five TELECOM Italia buildings at Ancona (Fig. 2a) and the twin isolated and conventionally founded apartment houses at Squillace (Fig. 3a), where HDRBs have been installed [7, 8]. All the aforesaid buildings had been subjected to on-site tests by ISMES, on behalf of ENEL and ENEA, using a mechanical vibrator on the roof in various directions; in addition, the TELECOM Italia building at Ancona had been subjected to pull-back tests using collapsible devices provided with explosive bolts to release the displaced building [3, 7, 8]. For the Ancona building, the first tests allowed for the characterization of the superstructure, while the second - which were performed by gradually increasing the initial displacement to 110 mm (75% of the design value) - allowed for the evaluation of rigid body modes, thus also strongly contributing to the qualification of the SI system. For the Squillace buildings, which have smaller sizes, the SI effects were also sufficiently well detected in spite of relatively low excitation level.

For all above-mentioned mock-ups and buildings a large number of data was recorded in various locations at the different floors, axial positions and directions: these data were also very useful for the optimization of the seismic monitoring systems, which were installed by ENEL at both Ancona and Squillace.

EXPERIMENTAL TESTS ON THE STRUCTURE MOCK-UPS

Similar to previous mock-up tests [3, 7, 8], MISS was tested by appyling one-directional (1D), 2D and 3D simultaneous excitations corresponding to real earthquakes for various soil conditions and excitation levels. In addition, synthetic earthquakes, consistent with EuroCode-8 (EC8), were also applied. Among the results, it is worthwhile noting that [9]:

- quite large shear deformations were measured without any problem (up to 286% shear strain under the 3D simultaneous excitation corresponding to the Calitri record of the 1980 Campano-Lucano earthquake);
- the beneficial effects of SI were always very evident (with respect to the fixed-base structure), in spite of the very low isolation ratio (1.75), even when the shake table acceleration was amplified by a factor 100% at the MISS base under the aforesaid Calitri excitation (in general, however, deamplification of the input acceleration was measured on MISS).

The rigid superstructure mock-up was subjected to five pull-back tests at ARI; in these tests, the initial displacement was gradually increased up to the maximum value which was compatible with the used jack, namely 130% shear strain.

NUMERICAL MODELLING OF ISOLATORS

ENEL and ENEA analysed the results of all the above-mentioned tests, using the ABAQUS computer code, where implemented had been simplified models of the isolators and 3D finite-element models (FEMs) of the superstructures.

With regard to isolator modelling, it is noted that the FEMs described in ref. [1] are unnecessarily too complicated as to be applicable in the analysis of isolated structures. Thus, to this aim, the definition of simplified numerical models of the HDRBs, again based on the results of single HDRB tests, is necessary [7, 8]. Such models, however, shall be capable of accounting for non-linear horizontal stiffness and the mostly hysteretic nature of damping. To this purpose the computer program ISOLAE of ENEA was first improved [7, 8], to enable the evaluation of the effects of the SI system on the excitation of the superstructure base and the subsequent FE calculation of the latter with the assumption of fixed base (in ISOLAE stiffness and viscous damping coefficient can be both assumed as dependent on lateral displacement).

Later, a new simplified model of the HDRBs which can be directly implemented in ABAQUS was jointly developed by ENEA and ENEL. This model (MEP, namely Multilinear Elastic-Plastic) consists of a non-linear spring combined with an elastic-plastic beam [7, 8]. By appropriately defining the physical parameters of the system (spring stiffness values, Young's modulus and yield point of the beam) it is possible to approximate the hysteresis cycle of a HDRB, including hardening and/or yielding and hysteretic damping. In fact, the non-linear spring allows for describing the dependence of horizontal stiffness on lateral deformation, while the beam permits to account for the hysteretic nature of damping, although not for its exact dependence on lateral deformation and for the viscous effects (the latter, however, may be included, if necessary, by adding a suitable viscous damper to the model). The advantage of MEP, with respect to ISOLAE, is that energy dissipation has been made independent of velocity.

NUMERICAL MODELLING OF ISOLATED STRUCTURES AND RESULTS OF THE ANALYSES

Detailed FE analysis of MISS was jointly performed by ENEA and ENEL with ABAQUS to design the mock-up itself and the test campaign; such a FEM was later used to analyse of the measured data (Fig. 1b). The analyses of the experimental results confirmed the adequacy of the numerical models used for both the isolators and MISS superstructure (good agreement was obtained between measurements and calculation for both natural frequencies and seismic response time-histories); however, they stressed the need for a careful selection of the damping value to be used, which shall be consistent with the maximum response displacement if the aim is, as usual, to correctly calculate such parameter (Fig. 1c, d): this may require some iterations of the dynamic calculations, if the experimental value is not known (see below).

As regards the TELECOM-Italia building, a 3D FEM of its superstructure (Fig. 2b), corresponding to the construction stage at the time of on-site tests, was developed by considerably refining the existing design model [7, 8]. It was validated and calibrated based on the results of the previously mentioned forced vibration tests. To this aim ENEA performed 3D parametric calculations where the building excitation conditions were exactly simulated and isolator stiffness and the damping values associated to the various modes of the isolated structure were defined based on best fit between computed and measured transfer functions (a linear spring was used to simulate the HDRBs, due to their very small deformation). The agreement between calculations and measurements was excellent [7, 8]. As expected for such small displacements, rather small damping ratios (2.8%) were found for the rigid body motions (modes 1 to 3), against the value 1.7% for modes 4 to 6, which are the first deformation modes of the superstructure.

The calculations concerning pull-back tests of the Ancona building were performed using a MEP model that was based on the results of single bearing tests performed at the building response frequency (0.8 Hz) in the lateral displacement range which had characterized the tests. The agreement between calculations and measurements was fully satisfactory, which confirmed the adequacy of the MEP model for seismic calculations of the building [7, 8]. It is noted that the results previously obtained by means of ISOLAE runs were even better: the reasons are that the elastic-plastic beam of MEP model was calibrated on the data measured for the single HDRB at an average displacement (that of the pull-back test) and that viscous damping was fully neglected. In the above-mentioned previous calculations, however, the superstructure had been approximated by a rigid mass; furthermore, the model adopted in ISOLAE for energy dissipation (which remains proportional to the velocity) had been found to be not fully adequate for seismic excitation conditions.

Similar analysis was also performed by ENEL to validate and calibrate FEMs of both base isolated and conventionally founded houses at Squillace, again corresponding to the construction stages at the time of on-site tests (Fig. 3b). The agreement between calculations and measurements was again excellent [7, 8].

The final recent step of the analysis was, for both Ancona and Squillace buildings, the evaluation of earthquake effects in the case of both presence and absence of the SI system, and in the first case, with both the actually installed and the optimized HDRBs. Multidirectional excitations corresponding to the previously mentioned actual and synthetic earthquakes, were applied to FEMs of the completed Squillace buildings. For the Ancona building, only 1D excitations were applied in its longitudinal direction (so as to excite the first response frequency), because the FEM is much heavier and requires very long calculation time. MEP models of the isolators were initially based on the test results measured at 100% shear strain. Since calculations were elastic, some of them were performed with a Young's modulus decreased by 20% to simulate ductility. At least one iteration was necessary to evaluate the correct damping value characterizing the MEP model (see above).

The benefits of SI were found very large; in addition, also those related to the optimization of the HDRBs appear evident (Tables 1-3). For instance, in the case of a synthetic earthquake corresponding to EC8 for medium soil, the acceleration at the roof of the TELECOM-Italia building would be 13% of that corresponding to fixed base with the presently installed isolators and only 7% in the case of the optimized HDRBs; accordingly, the relative displacements between roof and superstructure base would be 56% and 37% of the fixed base values. The use of optimized HDRBs would also reduce to 50% the roof accelerations and to 60% the relative displacements under the Calitri record of the 1980 Campano Lucano earthquake (relatively soft soil), which would be less severe than the previous excitation. With regard to the isolator lateral deformations, only for the aforesaid EC8 excitation the design value of 140 mm would be slightly exceeded (although less for the optimized isolators than for those installed at present). Similar effects were found for the Squillace buildings (Figs. 3c, d).

CONCLUSIONS

The results of experimental tests and numerical analyses of isolated structure mock-ups and actual buildings demonstrated the large benefits of seismic isolation systems, in particular those formed by the optimized HDRBs developed in project [2], on the design of buildings. This result is consistent with the observations of the behaviour of isolated buildings during the 1994 Northridge and 1995 Great Hanshin-Awaji earthquakes. The adequacy of the developed simplified numerical models of the isolators and FEMs of the superstructures was also demonstrated.

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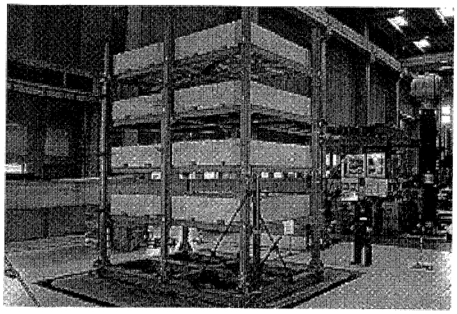

Fig. 1a. MISS mock-up on the ISMES shake table in the fixed-base configuration with 16 masses (240 kN)

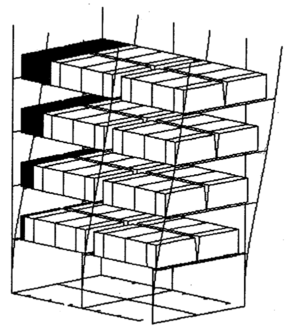

Fig. 1b. FEM of the MISS mock-up with 16 masses (240 kN); first bending mode (F_1=1.49 Hz; experim. = 1.5 Hz; α=1.75)

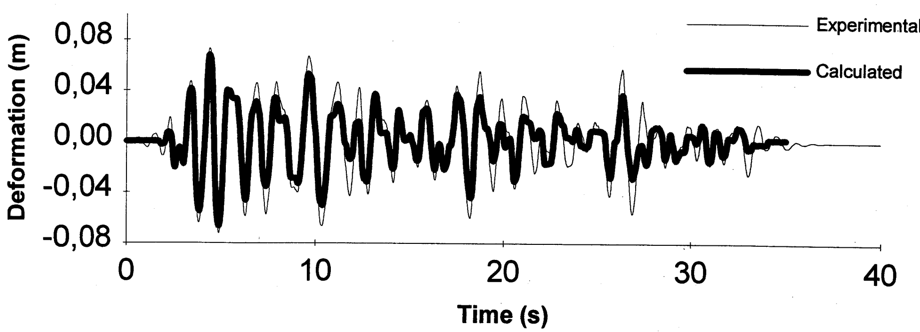

Fig. 1c. Bearing deformation measured and calculated for the isolated MISS mock-up with 20 masses (290kN) in the case of the application of a synthetic earthquake (0.3 g max acceleration peak)

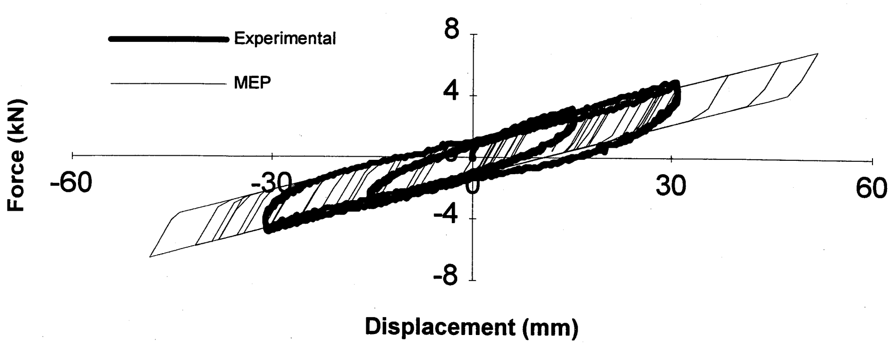

Fig. 1d. Comparison between the hysteresis loops as calculated by the MEP model (synthetic earthquake 0.2 g peak) for isolated MISS mock-up with 20 masses and that obtained by static test on single isolator

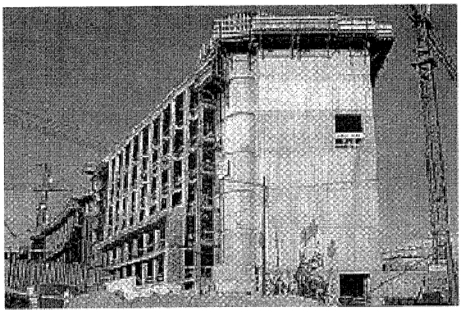

Fig. 2a. TELECOM Italia building at Ancona during construction (1990) and in-situ tests

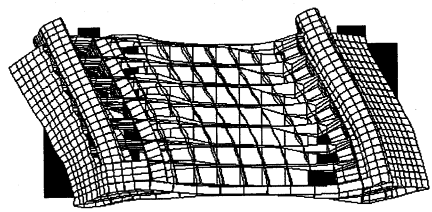

Fig. 2b. FEM of the TELECOM Italia building (first bending mode, fourth global mode, F_1=4.8 Hz)

Tab. 1: Relative maximum displacement values between roof and superstructure base. Summary of all analysed cases. Earthquake in horizontal longitudinal direction [cm].
**: Standard Young's Modulus; **: Decreased (- 20 %) Young's Modulus*

EARTHQUAKES	CALITRI 1980 *	CALITRI 1980 **	TOLMEZZO 1976 *	TOLMEZZO 1976 **	EC8 *	EC8 **
Fixed Base	-	1.58	-	2.17	1.79	2.36
Actual HDRBs	0.89	-	-	-	1.00	-
Optimized HDRBs	0.55	-	0.30	-	0.67	-

Tab. 2: Displacements of bearings. Summary of all analysed cases. Earthquake in horizontal longitudinal direction [cm]. Telecom Italia Building at Ancona: Design Displacement 14 cm.
**: Standard Young's Modulus; **: Decreased (- 20 %) Young's Modulus*

EARTHQUAKES	CALITRI*	TOLMEZZO*	EC8*
Actual HDRBs	14.27	-	16.72
Otimized HDRBs	11.25	5.27	15.88

Tab. 3: Relative maximum acceleration values between roof and superstructure base. Summary of all analysed cases. Earthquake in horizontal longitudinal direction [cm/s^2].
**: Standard Young's Modulus; **: Decreased (- 20 %) Young's Modulus*

EARTHQUAKES	CALITRI *	CALITRI **	TOLMEZZO *	TOLMEZZO **	EC8 *	EC8 **
Fixed Base	-	627.7	-	102.4	846.6	1069.0
Actual HDRBs	97.86	-	-	-	110.5	-
Optimized HDRBs	49.12	-	46.35	-	60.34	-

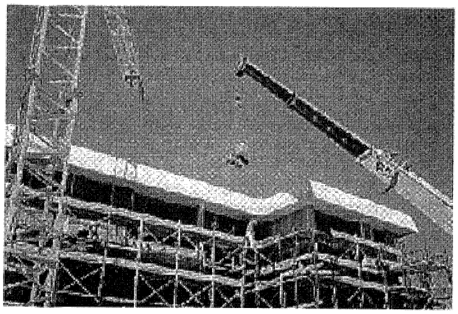

Fig. 3a. Isolated apartment house at Squillace during construction and in-situ tests (1991)

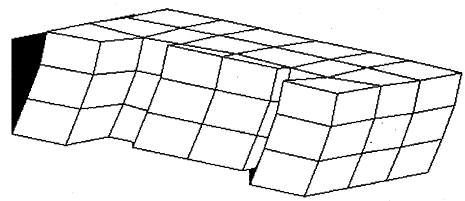

Fig. 3b. FEM of the isolated Squillace apartment house (first bending mode, fourth global mode, F_1=5.3 Hz))

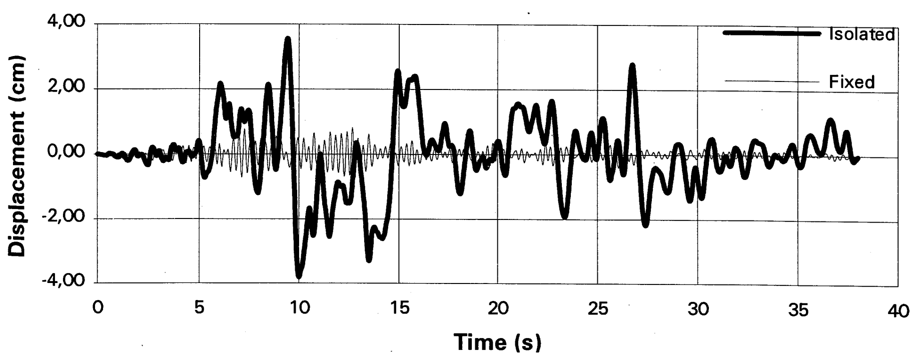

Fig. 3c. Absolute displacement as calculated at the roof of the Squillace isolated building compared to that obtained in the case of fixed-base in the case of application of the 3D 1980 Calitri record

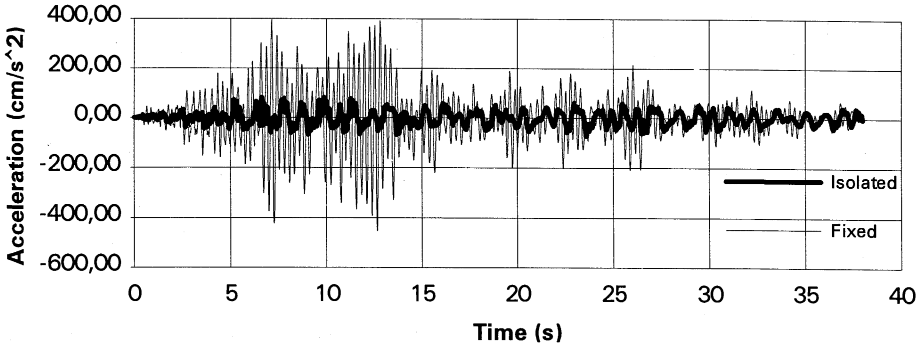

Fig. 3d. Acceleration as calculated at the roof of the Squillace isolated building compared to that obtained in the case of fixed-base in the case of application of the 3D 1980 Calitri .record