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ITALIAN STUDIES FOR THE OPTIMIZATION OF SEISMIC ISOLATION SYSTEMS FOR CIVIL AND INDUSTRIAL STRUCTURES

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ABSTRACT

Wide-ranging experimental and numerical studies are in advanced progress in Italy, in the framework of a project funded by the European Commission, on the High Damping Rubber Bearings (HDRBs) and structures that are seismically isolated by means of such bearings. These studies and those performed by the British and German partners aim at the development of optimized HDRBs. In particular, the Italian partners (1) already designed, manufactured and qualified the optimized bearings, (2) verified by test that they are characterized by large damping, capability of undergoing large lateral displacements and limited temperature effects, (3) developed and validated simplified and finite-element bearing models, and (4) developed finite-element models of isolated structures with the aim of evaluating the benefits of using the optimized HDRBs.

KEYWORDS

Seismic isolation, high damping rubber bearings, bridges, buildings, industrial plants, shake table tests, finite element analysis.

INTRODUCTION

Seismic isolation (SI) and other innovative antiseismic techniques have already been applied in Italy to more than 30 buildings and other structures, and wide-ranging R&D work is in progress to improve these techniques and promote the extension of their use in both civil and industrial structures (Martelli *et al.*, 1995a-b). This work is being performed in framework of both the national collaborations (mainly of the Working Group on Seismic Isolation - GLIS), and international cooperative projects. Among the latter, particularly important is the project BE7010 (ENEL *et al.*, 1993), which is being funded by the European Commission (EC).

This paper focusses on this project, which aims at the optimization of the High Damping natural Rubber Bearings (HDRBs) for seismic and vibration isolation, and at the evaluation of the technical and economic benefits of their use in the design of structures. Activities, which are based on considerable previous R&D experience on the HDRBs (Martelli and Castoldi, 1991, Martelli, 1992, Forni *et al.*, 1993, Bonacina *et al.*, 1994), are now quite advanced and will be completed in 1996. Thus, important results are already available.

The activities and results of the Italian partners in the project are summarized below. The co-operations with

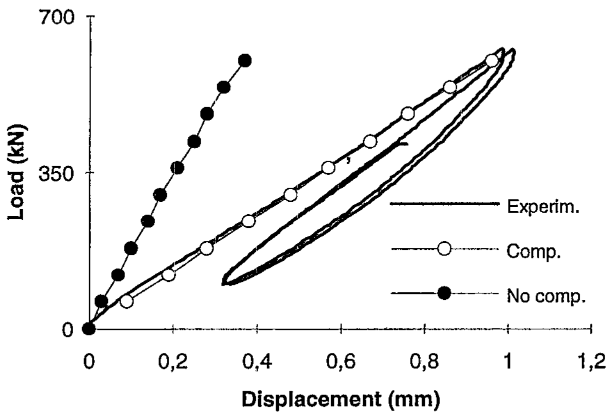

Fig. 1. Effects of the compressibility on the calculated vertical stiffness for a bolted isolator with high shape factor and hard rubber compound

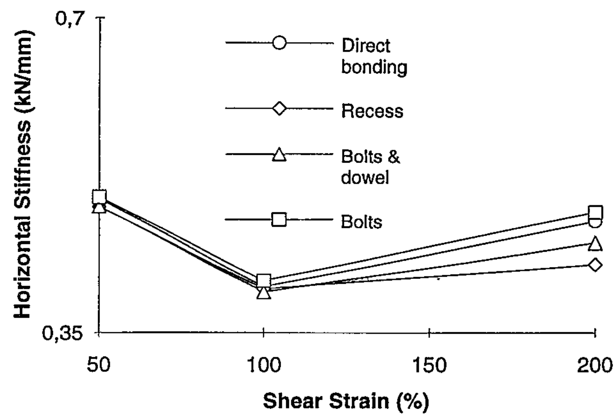

Fig. 2. Effects of the attachment system on the static horizontal stiffness for half-scale isolators with low shape factor and hard rubber compound

the non-Italian partners - namely the British Malaysian Rubber Producers' Research Association (MRPRA) and the German DYWIDAG, SHW and University of Karlsruhe (UNIKA) are also stressed.

DESIGN AND PRODUCTION OF THE OPTIMIZED HDRBs

A considerable number (112) of optimized HDRBs for the experimental campaigns at ISMES, ANSALDO-Ricerche (ARI) and UNIKA were jointly produced by ALGA and SHW, with the cooperation of ENEA as regards the development of bearing attachment systems and assessment of geometrical parameters. These HDRBs are characterized by: (a) two rubber compounds, one harder (G = 0.8 MPa) and one softer (G = 0.4 MPa), which were developed by MRPRA; (b) various scales (diameters D equal to 125 mm, 250 mm, 500 mm and 800 mm); (c) two values of the primary shape factor, namely the ratio between the loaded and the unloaded areas of a single rubber layer (S = 12 and S = 24); (d) five different attachment systems (recess, bolts, central dowel, combination of the dowel and bolts, direct bonding).

Because tests and finite-element (FE) calculations on such isolators showed the possibility of further improving their stability at large deformations by decreasing their height, 30 'further optimized' and 12 'squatter' HDRBs were also more recently designed by ENEA and manufactured by ALGA (see below). The heights have been decreased to 80% of the initial values for the 'further optimized' HDRBs and 60% for the 'squatter' HDRBs. The diameters are D = 125 mm and D = 250 mm for the first, and D = 250 mm for the latter. The attachment system is that formed by bolts combined with the central dowel for the 125 mm diameter HDRBs, while recess has also been considered for the 250 mm diameter HDRBs.

TESTS ON RUBBER SPECIMENS

In addition to experiments performed by MRPRA, tensile, compression, equi-biaxial, shear and compressibility tests on specimens of both the hard and the soft rubber compounds were performed by ENEL, with the cooperation of ENEA. The aim was to define the data necessary for the implementation in ABAQUS of the hyperelastic (HE) models of the rubbers, so as to enable FE calculations of the HDRBs. Detailed guidelines for such tests were developed by ENEA; specific equipment for equibiaxial and planar shear deformation tests was jointly designed and manufactured by ENEL and ENEA, which also jointly analysed the experimental data and defined the HE models of both rubber compounds. The compressibility tests were found essential for a correct numerical evaluation of the HDRB vertical stiffness (Fig. 1).

The effects of temperature on the behaviour of specimens formed by both rubber compounds were evaluated

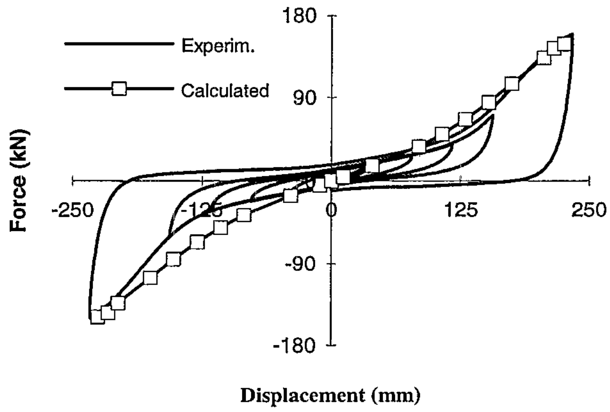

Fig. 3. Combined compression and 300% shear strain test on a bolted half-scale isolator with high shape factor and hard rubber compound

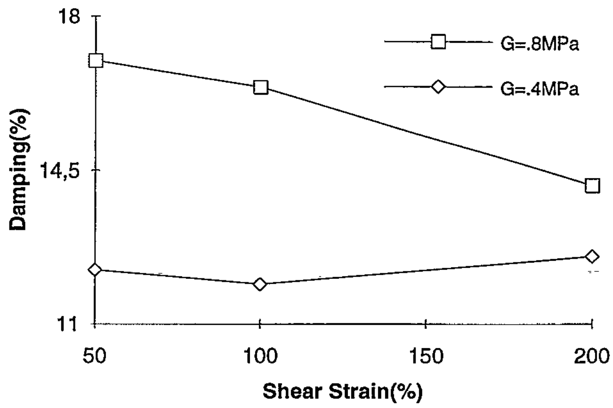

Fig. 4. Equivalent viscous damping of the hard and soft rubber compounds in the case of half-scale isolators with low shape factor (quasi-static tests)

by ARI, in addition to MRPRA, in a climatic chamber. The analysed temperature range was from -20 °C to +40 °C. Limited effects of temperature on G were found; some results are summarized in Tab. 1.

Finally, tests will be performed in Italy on artificially ageed rubber specimens, in order to verify if it possible to develop and implement HE models of the ageed rubbers in the finite-element models (FEMs) of HDRBs. In fact, should it be demonstrated that the ageing effects on HDRBs can be forecasted analytically based on the results of tests on specimens, this would permit to only age and test rubber specimens, thus saving the non-negligible costs of tests on the entire ageed HDRBs. To this aim, ARI will age specimens provided by ALGA using the same procedure as that adopted by UNIKA for entire isolators (4 months at 70 °C), ENEL will test them and ENEA will analyse the test data and will implement them in the HE model of the HDRBs.

TESTS ON THE INDIVIDUAL HDRBs

To date the activities of Italian partners on this topic have concerned the execution of experiments on non-ageed (virgin) HDRBs, (1) at room temperature at ISMES and the Nuclear Engineering Laboratory (LIN) of the University of Bologna (ENEA tests), and (2) at various temperatures at ARI (ALGA tests). In order to optimize test quality ENEA significantly improved SISTEM (Seismic ISolation TEst Machine), which is located at ISMES, and designed and manufactured a second equipment (CAT - Creep and Ageing Test) for long duration creep tests, which was installed at LIN.

The ISMES experiments on the initially developed HDRBs were completed, by means of SISTEM. They concerned several HDRBs with two different scales, both S values, both G values and up to the five different attachment systems (AS) which were previously mentioned, namely: (a) 10 isolators with D = 250 mm, S = 12, G = 0.8 MPa, 4 ASs; (b) 16 isolators with D = 250 mm, S = 24, G = 0.8 MPa, 5 ASs; (c) 4 isolators with D = 250 mm, S = 12, G = 0.4 MPa, AS = bolts and central dowel (BD); (d) 4 isolators with D = 250 mm, S = 24, G = 0.4 MPa, AS = BD; (e) 4 isolators with D = 500 mm, S = 12, G = 0.8 MPa, AS = BD.

These experiments comprised: (i) quasi-static vertical compression tests for the evaluation of vertical stiffness; (ii) quasi-static shear tests under constant vertical compression load (V) for the evaluation of static horizontal stiffness at 50%, 100% and 200% shear strain; (iii) quasi-static shear tests at 100% shear strain with different vertical compression loads (from 0.25 V to 2 V) for evaluating the effects of vertical load variation on horizontal stiffness; (iv) dynamic shear tests at various frequencies (0.1, 0.4, and 0.6 Hz), under constant V and at various shear strain values (from 10% to 200%), to evaluate the equivalent viscous damping and dynamic effects on the horizontal stiffness; (v) some sustained compression tests for evaluating

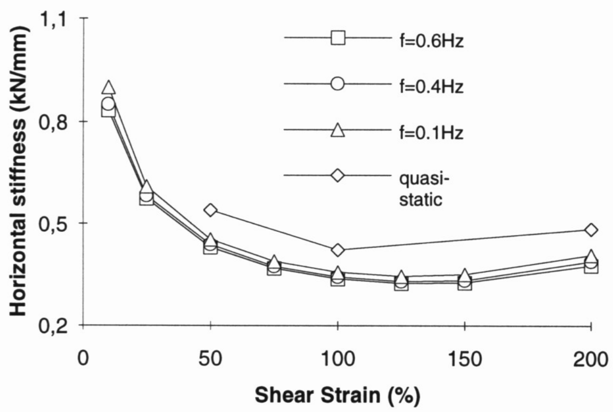

Fig. 5. Dynamic and quasi-static horizontal stiffnesses of a bolted half-scale isolator with high shape factor and hard rubber compound

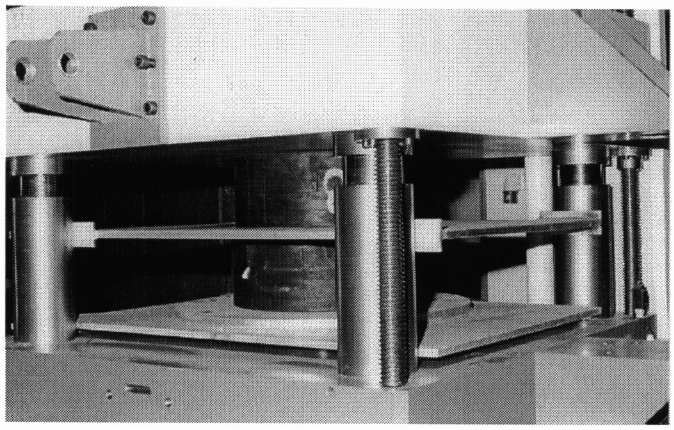

Fig. 6. Isolators during a long period compression test on CAT (Creep & Ageing Test Machine) for the evaluation of the creep effects

creep effects; (vi) quasi-static failure tests due to compression and shear.

ENEA and ISMES already analysed part of the very numerous test data, by confirming the fulfilment of the target values for several parameters, in particular that: (1) the behaviour of all the considered attachment systems is excellent and practically equivalent to 200% shear strain (Fig. 2); (2) the behaviour of the optimized HDRBs with attachment systems consisting in bolts, bolts and central dowel and direct bonding is good to the target value of 300% shear strain at least (Fig. 3); (3) the equivalent viscous damping ratio is well larger than the target value of 10% for both compounds considered (Fig. 4); (4) the dependence of horizontal stiffness on frequency is limited, as desired (Fig. 5); (5) the performance of HDRBs can be further improved by modifying the secondary shape factor, namely the ratio between the loaded and the unloaded areas of the entire isolator.

In December 1995, similar tests were performed at ISMES on seven 'further optimized' HDRBs; these have D = 125 mm, S = 12, G = 0.4 MPa and the attachment system formed by the combination of central dowel and bolts. Six of them are being used (January 1996) for the shake table tests on an isolated structure mock-up, which are described later; the results concerning the seventh isolator, which was subjected to cyclic shear loads gradually increasing to failure, will also be part of the data base for the analyses to be performed in the framework of the Research Coordinated Programme of the International Atomic Energy Agency (IAEA) on "Intercomparison of Analysis Methods for Seismically Isolated Nuclear Structures" (Martelli *et al.*, 1995a).

The 800 mm diameter initially developed HDRBs (together with part of the 500 mm diameter bearings and some 250 mm diameter bearings) were tested by UNIKA, using the same experimental procedures as ISMES. Similar tests were also carried out by UNIKA on virgin 250 mm diameter 'further optimized' and 'squatter' HDRBs: their accelerated ageing is in progress, to allow for tests at UNIKA on ageed HDRBs.

In December 1995 experiments also began at LIN on CAT (Fig. 6) for the four 500 mm diameter HDRBs that were tested at ISMES; at first they consisted in a characterization under vertical compression loads (to compare the results to those obtained at ISMES on SISTEM), then (simultaneously for all isolators) in the beginning of a creep test under V = 1,600 kN, which will last six months.

As regards the evaluation of temperature effects, ARI completed the ALGA tests on the virgin initially developed bearings with D = 125 mm and the attachment system formed by bolts and central dowel, for the harder rubber, and is performing those on the softer rubber bearings. These tests have been and are being carried out on pairs of the HDRBs in a climatic chamber; temperatures range from -20 °C to +40 °C, similar to the rubber specimens. The analysis of results is in progress: some first data are reported in Tab. 2.

Tab.1. Temperature effects on stiffness (K) and equivalent viscous damping (β) on rubber specimens subjected to shear test at 100% shear strain without compression load

Compound	Temp. (°C)	K/K(20°C)	β/β(20°C)
	40	0.912	0.931
	20	1	1
HARD	0	1.312	1.129
	-10	1.392	1.224
	-20	1.608	1.336
	40	0.909	0.922
	20	1	1
SOFT	0	1.160	1.061
	-10	1.329	1.148
	-20	1.553	1.348

Tab.2. Temperature effects on stiffness (K) and equivalent viscous damping (β) on 1:4 scale HDRBs subjected to shear test at 100% shear strain under the design V

Compound	Temp. (°C)	K/K(20°C)	β/β(20°C)
	40	0.882	0.912
	20	1	1
HARD	0	1.224	1.035
	-10	1.482	1.058
	-20	1.930	1.070
	40	0.816	0.986
	20	1	1
SOFT	0	1.117	1.027
	-10	1.214	1.110
	-20	1.557	1.192

ARI will also perform tests on ageed 125 mm diameter HDRBs (for both compounds), so as to allow for comparisons with the results of tests performed on ageed rubber specimens. Isolators will be some of those initially manufactured for the shake table tests (i.e. not those 'further optimized'), which, however, will not be used there for the reasons mentioned below. Since it is not advisable to use the HDRBs which have already been tested at ISMES in virgin conditions (too many tests were performed, even at low and high temperatures), some of the new bearings will be characterized before ageing, so as to clearly identify the ageing effects. Isolators will be ageed by ARI using the same procedure as at UNIKA (4 months at 70 °C, similar to the rubber specimens). Afterwards, ARI will test them both at room temperature and in the climatic chamber: in this way it will be possible to also evaluate the combined effects of temperature and ageing. This activity will be complementary to that to be performed by UNIKA on the 'further optimized' 250 mm diameter HDRBs.

TESTS ON ISOLATED STRUCTURE MOCK-UPS

The MISS (Model of Isolated Steel Structure) structure mock-up was manufactured for shake table tests at ISMES. It was jointly designed by ENEL, ENEA and ISMES. MISS is a four storey steel frame, to be supported by four or six 125 mm diameter HDRBs and provided with movable masses on each storey and variable interstorey distance, so as to allow for different stiffnesses, mass profiles and eccentricities. In the ISMES tests (which began in January 1996) the six previously mentioned 'further optimized' soft HDRBs were installed at the base of MISS.

In December 1995 ENEA and ENEL completed the design of the experiments. To this aim, FEMs of the entire MISS (see Fig. 7) and some critical parts (foot) were implemented in ABAQUS. By means of these models the maximum acceleration and displacement values that are admissible during tests were computed; in addition, natural frequencies of MISS were calculated for different assemblages, including eccentric configurations. The results showed that it will be possible to achieve significantly low isolation ratios and to reach shear strain values of the isolators which are larger than 200%.

In addition, pull-back tests of ALGA are beginning at ARI on a 1,600 kN rigid mass isolated mock-up, supported by four 250 mm diameter 'further optimized' HDRBs. Such tests will be limited to the harder rubber compound, with combined bolt and dowel attachment system: the reasons are both that the softer HDRBs will be used in the ISMES tests on MISS and that the vertical compression load as applied by the rigid mock-up would be too large for the soft bearings. The initial displacement in the pull-back tests will be

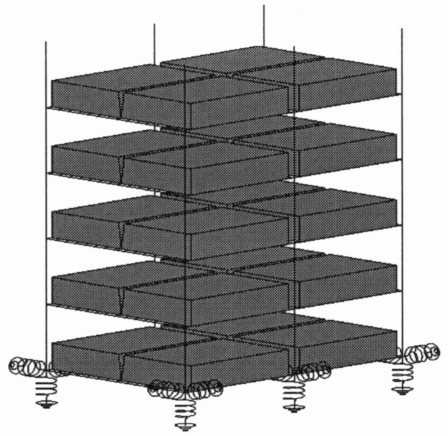

Fig. 7. FEM of MISS in the reference configuration (total height = 3.6 m; total weight = 300 kN; isolation frequency = 0.77 Hz; isolation ratio = 4)

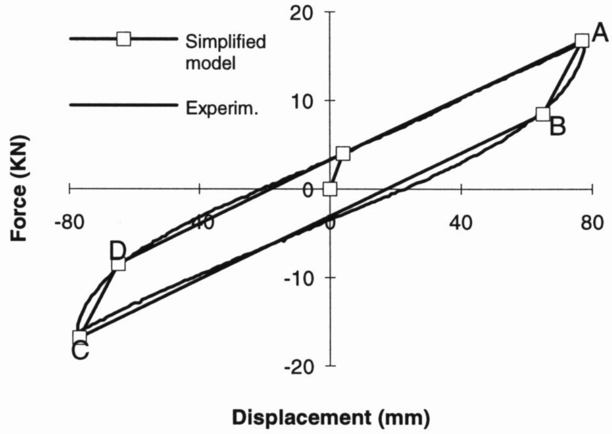

Fig. 8. Simplified model of seismic isolator: comparison between measured and equivalent hysteresis loops (BD attachment system; 100% shear strain)

gradually increased up to the maximum value which will be compatible with the used jack (if possible to more than 200% shear strain).

Finally, the use of some HDRBs developed in this project has been planned for pseudodynamic tests on large scale isolated structures at the Joint Research Center of Ispra of the EC, in the framework of the Seismic Isolation Project (Renda *et al.*, 1995, Martelli *et al.*, 1995).

SIMPLIFIED NUMERICAL MODELS OF THE HDRBs

The definition of simplified numerical models of the HDRBs, based on the results of single bearing tests, is necessary for the analysis of isolated structures (Forni *et al.*, 1993). Such models, however, shall be capable of accounting for non-linear horizontal stiffness and the hysteretic nature of damping. To this purpose ENEA completed the setting-up of an improved version of its computer program ISOLAE for the simplified analysis of SI systems (Martelli *et al.*, 1995a).

However, the development of a new simplified model of the HDRBs that can be directly implemented in ABAQUS also began at ENEA and ENEL. This consists of a combination of a non-linear spring with an elastic-plastic beam (Fig. 8). By appropriately defining the physical parameters of the system (spring stiffness, Young's modulus and yield point of the beam) it is easy to reproduce the hysteresis cycle of a HDRB, including hardening and/or yielding and hysteretic nature of damping. Work has been performed by ENEL to define some identification criteria and by ENEA for the pre-test calculations of shake table experimens at ISMES. Should the excellent results which have already been obtained be confirmed, this will be the model to be used by ENEA and ENEL in the analyses of isolated structures. Otherwise, the programme ISOLAE will be used for evaluating the effects of the SI system on the excitation of the superstructure base. In any case, some comparisons between the two methods are foreseen.

DETAILED NUMERICAL MODELS OF THE HDRBs

ENEA and ENEL jointly implemented the HE models of both rubber compounds in ABAQUS, based on the results of the specimen tests performed by ENEL. Non-linear models of the HDRBs were developed for both shape factors considered and for the various attachment system types. The need for including rubber compressibility effects in the HE model (thus, for specific tests on rubber specimens) was detected (Fig. 1).

The FEMs of the initially developed isolators were defined and validated based on the results of the related

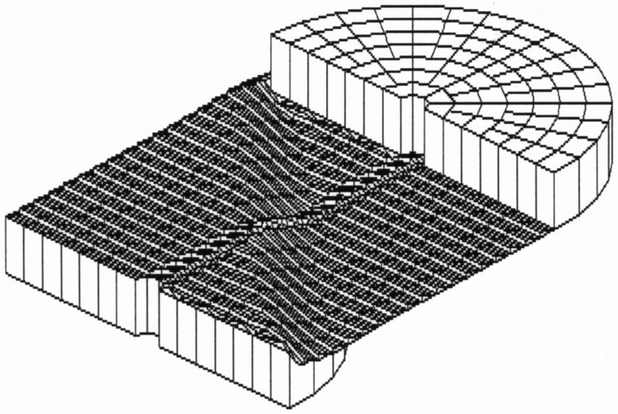

Fig. 9. FEM of the 250 mm diameter 'squatter' isolator with bolts and central dowel attachment system at 500% shear strain under the design vertical load

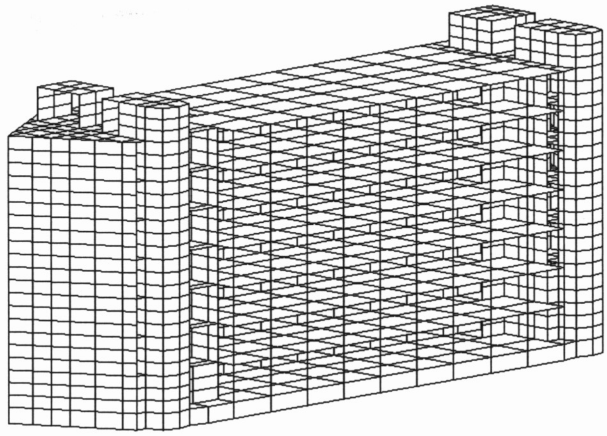

Fig.10. Optimized FEM of the TELECOM Italia building (Ancona) subjected to forced vibrations and pull-back (up to 110 mm) in-situ tests in 1990

single bearings tests (Forni *et al.*, 1995). Detailed HDRB models were also developed for the 'further optimized' and 'squatter' HDRBs (Fig. 9). Pre-test calculations were performed for such bearings to 400% and 500% shear strain, respectively. The results will be compared to those of ISMES and UNIKA tests.

Finally, the HE models of ageed rubbers will be developed based on the results of the specimens tests at ARI. These models will be implemented in the isolators' FEMs, which will be used to analyse the results of tests of ARI and UNIKA on the entire ageed HDRBs.

EVALUATION OF BENEFITS OF SEISMIC ISOLATION

ENEA and ENEL are contributing to the evaluation of benefits of SI through the analysis of the isolated buildings of the Center of the National Telephone Company (TELECOM Italia) at Ancona and the twin isolated and conventionally founded apartment houses at Squillace (Calabria), for which detailed experimental results from on-site tests are available to them in various locations, axial positions and directions (Martelli and Castoldi, 1991, Forni *et al.*, 1993). In all these buildings HDRBs have been used.

A new 3D FEM of the TELECOM building that had been subjected to on-site tests was developed by ENEA. This is much more detailed than those developed in the design analysis and pre-test calculations performed in 1990 (Fig. 10). The purpose was also to permit a very complete comparison between the numerical results and the quite numerous test data. For the calculations related to large displacements, ENEA also developed a simplified HDRB model using a non-linear spring combined with an elastic-plastic beam (see above). On the contrary, for the small excitations, a linear isolator model will be sufficient. The model is being validated by means of 3D calculations using both the data measured on the building during forced excitation tests with a mechanical vibrator on the roof and those measured during the pull-back tests. The first results, which corresponded to small amplitude excitations, will mainly allow for the validation of the superstructure model (deformation modes), while the latter, which corresponded to displacements up to 110 mm (i.e. close to the design value of 140 mm) will allow for the validation of the complete isolated model.

Also as regards the Squillace houses, both of which were tested by means of a mechanical vibrator installed on their roof, previous FEMs and validation analyses are being considerably refined and finalized by ENEL. After validation of all the above-mentioned FEMs, the benefits of SI will be identified by ENEA and ENEL by applying one-directional (1D), 2D and 3D actual seismic records on various soil conditions, corresponding to actual earthquakes (e.g. Tolmezzo records on medium soil of the 1976 Friuli earthquake, Calitri records on relatively soft soil of the 1980 Campano-Lucano earthquake, etc.), to the FEMs of the completed buildings. Such calculations will be performed for various values of the isolation ratio, from the actual isolated building to the conventional fixed base building.

CONCLUSIONS

The studies described above are considerably extending the knowledge previously acquired in Italy on the behaviour of HDRBs and will make optimized isolators available at reasonable costs. The results so far obtained confirm the capability of SI for considerably enhancing the seismic protection of civil and industrial structures, including nuclear plants. They have also provided important input for the development of both standards for seismic isolators (e.g the European standards that are being developed, with the contribution of several partners in this project, in the framework of CENTC 167) and design guidelines for isolated structures, for instance for the improvement of the ENEA proposal concerning the isolated nuclear plants (Forni and Martelli, 1995), which will be updated and extended in 1996 in the framework of EC funded projects. Based on the experience achieved for the HDRBs, wide-ranging studies will also begin in Italy in 1996 (again in the framework of EC funded projects) for other innovative antiseismic techmiques (energy dissipation, shock transmitters, rolling systems and high shape memory alloys).

REFERENCES

Bonacina, G., F. Bettinali and A. Martelli (1994). State-of-the-art of work in progress on seismic isolation technique for civil structures and industrial plants. In: *Proc. 10th European Conf. on Earthquake Engineering* (G. Duma, Ed.), Vol. 3, pp. 2313-2322.

ENEL, ALGA, DYWIDAG, ENEA, MRPRA, SHW and STIN (1993). Optimization of design and performance of high damping rubber bearings for seismic and vibration isolation. EC Contract BRE2-CT93-0524, Project BE7010.

Forni, M. and A. Martelli (1994). Proposal for design guidelines for seismically isolated nuclear plants. Final Report, EC Contract ETNU-0031-IT, EC Report in press.

Forni, M., A. Martelli, B. Spadoni, F. Bettinali, L. Bellingeri, F. Cesari, L. Grassi, E. Sobrero, G. Bergamo, G. Bonacina, C. Mazzieri, M. Olivieri, A. Marioni, G. Serino and F. Vestroni (1994). Most recent developments of the studies for seismic isolation of nuclear and non-nuclear structures in Italy. In: *Isolation, Energy Dissipation and Control of Vibrations of Structures - Proceedings of the Post-SMiRT Conference Seminar held at Capri, Italy* (A. Martelli and M. Forni, Eds.), pp. 355-374.

Forni, M., A. Martelli, F. Bettinali and A. Dusi (1995). Finite-element models of rubber bearings and guidelines development for isolated nuclear facilities in Italy. In: *Proc. Int. Post-SMiRT Conf. Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Structures, Santiago, Chile* (R. Saragoni, Ed.).

Martelli, A. (1992). Most recent activities and new plans for seismic isolation development and application in Italy. In: *Proc. Intl. Workshop on Recent Developments of Base Isolation Techniques for Buildings, Tokyo, Japan* (AIJ, Ed.), pp. 275-297.

Martelli, A. and A. Castoldi (1991). Seismic isolation of structures. In: *Experimental and Numerical Methods in Seismic Engineering* (J. Donea and P.M. Jones, Eds., Kluwer Academic Publs.), pp. 351-377.

Martelli, A., M. Forni, B. Spadoni, A. Marioni, C. Mazzieri, F. Bettinali, G. Bonacina, G. Pucci, F. Cesari and E. Sobrero (1995a). Progress in applications and experimental studies for isolated structures in Italy. In: *Proc. Int. Post-SMiRT Conf. Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Structures, Santiago, Chile* (R. Saragoni, Ed.).

Martelli, A., M. Forni, M. Indirli and B. Spadoni (1995b). Recent developments of seismic isolation technology and prospects for application. In: *Proc. 18th European Regional Earthquake Engineering Seminar, Lyon, France* (AFPS, Ed.), pp. 357-381.

Renda, V., A. Martelli, G. Verzelletti and L. Papa (1995). Research activities and programmes on seismic isolation at the Joint Research Center of the European Commission. In: *Proc. Int. Post-SMiRT Conf. Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Structures, Santiago, Chile* (R. Saragoni, Ed.).