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Experiments on seismic isolation bearings

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ABSTRACT: Static and dynamic tests have been performed on high damping steel-laminated elastomer bearings in various scales and rubber specimens, in the framework of studies in progress in Italy to support seismic isolation development. They have already provided important data (vertical and horizontal stiffnesses, damping, creep, temperature, aging and scale effects, etc.), necessary for the development and validation of numerical models, and comparison with the test results of isolated structure mockups and actual buildings.

1 INTRODUCTION

Considerable efforts are being devoted in Italy to seismic isolation development and application. The interest in this technique is rapidly increasing in our country, both because it can already be widely used in civil buildings (especially those important for emergency and disaster planning), and due to very promising perspectives for industrial plants (Chang et al. 1991). In particular, the Italian Agency for New Technologies, Energy and Ambient (ENEA) is also quite interested in verifying the applicability of seismic isolation to high risk plants, including the innovative nuclear reactors (Martelli et al. 1992). For such applications, the advantages of this technique appear such as to warrant further work to resolve some of the outstanding technical problems.

Since 1989, a wide-ranging R&D work has been undertaken by ENEA, the National Utility (ENEL) and ISMES, in cooperation with ALGA and ANSALDO: these organizations were the main promoters (in 1989) of the National Working Group on Seismic Isolation (Gruppo di Lavoro Isolamento Sismico, or GLIS), which is being chaired at present by ENEA: this group is now part of the Italian Association for Earthquake Engineering (ANIDIS); it already includes representatives of all the organizations, universities, firms and designers dealing with innovative antiseismic techniques.

2 RESEARCH AND DEVELOPMENT ACTIVITIES

The Italian R&D activities are focusing at present on the use of the high damping steel-laminated elastomer bearings (HDRBs): they are considered very innovative and adequate for a wide-ranging application (including to high risk plants), and have been adopted in most isolated buildings in Italy. However, extension to other bearing types has also been planned.

Studies consist of both numerical work and experiments, for rubber specimens, individual isolators, isolated structure mock-ups and actual isolated buildings. Tests are being performed by ISMES and at the ENEA/ANSALDO Laboratories of Boschetto (Genova). In addition, development of design guidelines is also in progress: a first proposal has alrealy been published by Martelli et al. (1990) for isolated nuclear reactors using HDRBs; it is being extended to other bearing types in the framework of activities supported by the CEC, and also to application to nonnuclear structures (Martelli et al. 1992).

The aforementioned work takes advantage of both national collaborations (within GLIS activities) and international collaborations (mainly with the USA, Japan and France).

This paper summarizes the work performed for rubber specimens and isolators, and reports some important results, while the papers of Bettinali et al. & Serino et al. (1992) deal with tests on isolated structures.

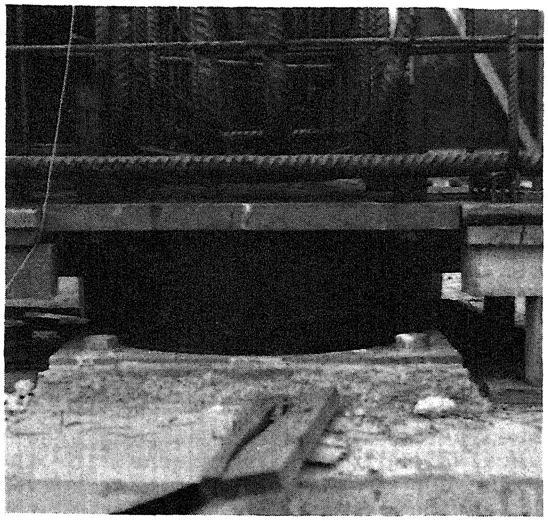

Figure 1. HDRB during installation at the SIP building base at Ancona.

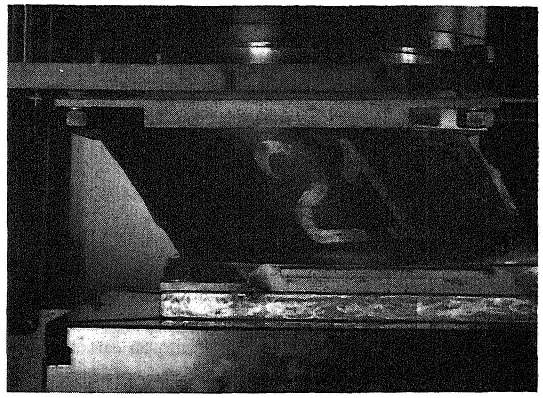

Figure 2. Dynamic test of a single full-scale SIP-type HDRB (100 % σ).

3 BEARING FEATURES

All the HDRBs adopted in the isolated buildings in Italy and those used in our tests have been fabricated by ALGA. Most of our tests have been based on one (500 mm diameter) of the two HDRB types used by SEAT in the five isolated buildings of the Administration Centre of the National Telephone Company (SIP) at Ancona which are at present the most important application of seismic isolation in Italy. This choice was mainly due the possibility of performing in-situ experiments on one of such buildings, and thus, to compare the results of tests performed on single bearings to those obtained for a real isolated structure (Bettinali et al. 1992).

The basic parameter for the fabrication of the SIP bearings (see Fig. 1 and Serino et al. 1992) was the horizontal displacement of 144 mm which was assumed by Giuliani (1991) for their design at 100% σ (σ = shear strain), i.e. at a displacement equal to the total rubber height.

Several SIP-type bearings, in both full and reduced scales were fabricated and tested (28 full size isolators, together with 22, 20 and 40 in 1/2, 1/3 and 1/4 scales, respectively). Experiments performed until now (Fig. 2) corresponded to the original attachment solution used for bearings in SIP buildings, where the steel-end plates are provided with a machined groove to restrain them; however, experiments are also being initiated on new bearings provided with attachment devices that also allow for dowelling or bolting them, and modified rubber materials, as well (see also § 4).

4 TESTS ON RUBBER SPECIMENS

Tests on rubber specimens are being performed by ENEA in cooperation with ALGA and ANSALDO, with the aim of improving fabrication processes, controling bearing quality and determining rubber properties.

In particular, shear tests on rubber specimens preceded all experiments on bearings and isolated mock-ups. These were carried out for all bearing batchs, to mainly measure the shear modulus of elasticity (G). Two G values were determined: G_1, which corresponded (as required by existing national codes for rubber supports of bridges) to deformations from 0 to 60% σ, and G_2, which corresponded to deformations from -100% σ to +100% σ. It was found that G_2 is about 40% lower than G_1. This result is consistent with the decrease of bearing horizontal stiffness by increasing displacements (see § 6 & Bettinali et al. 1992). The scattering of G data was rather small (Forni et al. 1991).

It is noted that some differences were detected for G_1 with respect to values measured for the (nominally equal) rubber of the actual bearings used for SIP buildings (the latter being about 10% higher, on the average). The scattering of G data was also more limited than that found for such bearings. These results are certainly partly due to modifications

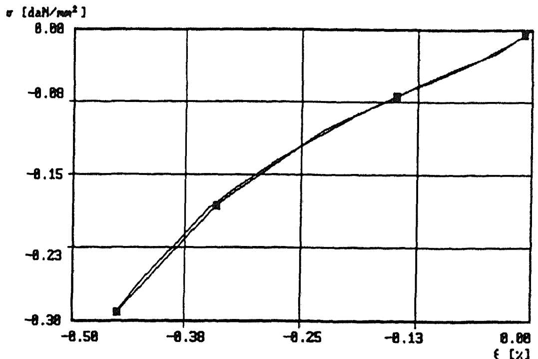

Figure 3. Stress-strain correlation for compression tests of specimens (—— = experimental; ■ = ABAQUS).

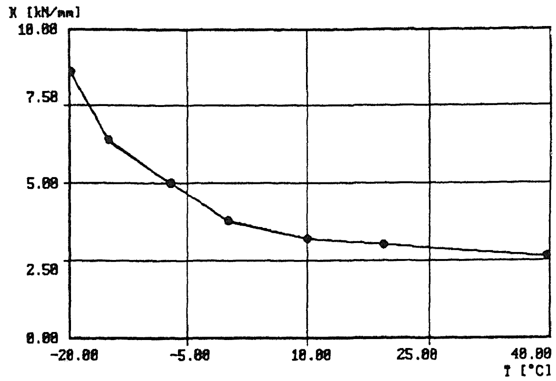

Figure 4. Temperature effects on stiffness, measured in specimen shear tests of the SIP HDRB compound (o).

in the fabrication process, which was completely automated after the acceptance tests of SIP building bearings only (Martelli et al. 1992).

Tests on specimens have also been performed for new rubber materials: the aim (which has been achieved) was to define three HDRBs with improved rubber-steel bonding and different compounds, to be later tested (§ 3). With respect to SIP HDRBs, the first compound has a higher (10%) ultimate tensile strength and equal creep, while the second has a better (15%) elongation (for both, the condition of a damping decrease lower than 20% with respect to SIP HDRBs - see § 6 - has been respected); the third is a very soft compound (SHORE A3 equal to 30-35, against a value of 60 for SIP-type HDRBs), provided by Malaysian Rubber Producers Association to ALGA.

Further tests on the new compounds aimed at defining a hyperelastic model of the rubber to be implemented in the ABAQUS computer code for the detailed analysis of isolators (§ 7). More precisely, following tests were performed: (a) dynamic tests for the determination of damping; (b) quasi-static and sustained compression experiments (7 days long) of cylindrical specimens (Fig. 3); (c) static tests, with tensile loads on ring-type specimens and sustained tensile loads on dog-bone-type specimens; (d) quasi-static, sustained (96 hours long) and dynamic shear tests; (e) threeaxial compression tests to evaluate rubber compressibility.

Experiments on specimens formed by the compound used in SIP HDRBs have also been performed by ALGA at CERISIE to define the accelerated aging methods to be used in the analysis of aging effects on bearing response (§ 5). The extrapolation of test data to the assumed normal temperature (T_N = 30°C) - by use of the Arrhenius law - led to the following results: (a) compression tests, performed at constant deformation and temperatures equal to 50°C, 70°C and 90°C, indicate a relaxation of pressure equal to 50% of the initial after 142 years at T_N; (b) elongation tests, performed in the air at the aforesaid temperatures and 600% elongation, indicate a residual deformation of 60% after 44 years only at T_N, due to more severe oxigen attack (a longer time is expected in vacuum conditions); (c) shear tests, performed at 90°C and 110°C, indicate an increase of G of 33% after 110 years at T_N.

Finally, tests are in progress at the Boschetto Centre for a first analysis of both temperature (Fig. 4) and accelerated aging effects (see also § 5): it has already been demonstrated that temperature does not produce any permanent modification of compound features and that it has a non-negligible effect on horizontal stiffness at the low values (Fig. 4).

5 TESTS OF ISOLATION BEARINGS

Tests of single SIP-type bearings were defined according to the guidelines document of Martelli al. (1990). They were started by ENEA at ISMES in June 1990, to determine vertical and horizontal stiffnesses, damping and failure modes, as well as the effects of bearing scale, dynamic excitation, creep, vertical load variation and natural aging (Martelli et al. 1992).

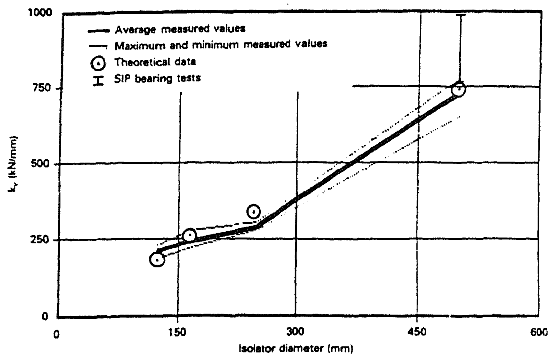

Figure 5. Static vertical stiffness versus bearing diameter.

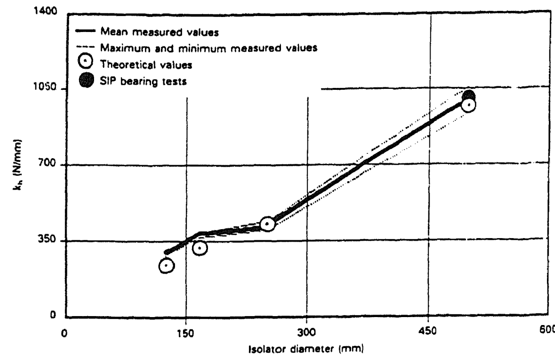

Figure 6. Static horizontal stiffness versus bearing diameter.

The latter will be continued in cooperation with SEAT (within GLIS activities) using bearings placed inside the Ancona buildings, under the actual compression load and close to those in operation, so as to subject them to the actual aging conditions.

The following experiments have been completed: (a) tests for the evaluation of static vertical stiffness; (b) cyclic tests for the evaluation of static horizontal stiffness; (c) sustained compression tests for the evaluation of creep effects; (d) tests for the static evaluation of the effects of vertical load variation on the horizontal stiffness; (e) three sets of static tests for the evaluation of natural aging effects on the horizontal stiffness (one every six months); (f) sinusoidal horizontal excitation tests at fixed frequencies; (h) a static failure test.

Tests for the evaluation of accelerated aging and temperature effects have also been initiated on bearings (in addition to those on specimens, see § 4) at the Boschetto Centre. Moreover, experiments were performed on bearings used in an isolated house at Squillace, Calabria (see Bettinali et al. 1992). Finally the experimental analysis of the effects of bearing attachment and compound features is being started, and tests on isolators used in other buildings have been planned (again in the framework of the promotion activities of GLIS).

For bearing tests, use was made of the SISTEM machine, which had been designed and fabricated by ENEA: it allows for static and dynamic testing of both single bearings and a pair of superposed isolators to large displacements, with one- and two-directional, simultaneous, horizontal excitations under vertical static load (see Forni et al. 1991).

6 SOME RESULTS OF BEARING TESTS

Test results so far obtained for bearings (Forni et al. 1991) have already provided very useful information to improve the knowledge on isolator behaviour, test procedures and design guidelines.

Figs. 5 and 6 (where data obtained for the actual bearings mounted at SIP building base are also reported for a matter of comparison) show that the simplified formulas suggested by Martelli et al. (1990) to calculate vertical and horizontal stiffnesses (starting from bearing geometry and rubber properties) are reasonably accurate: this result will allow future acceptance tests to be limited to a much lower number of bearings, with considerable economic advantages (tests on specimens are obviously rather less expensive); it also enables the simplification of complicated studies such as those of temperature and aging effects, for which a large use of tests on specimens can thus be made (§ 4).

However, the application of such formulas requires - like in our case - a good knowledge of rubber properties. In particular, a correct measurement of G is essential. Also, the spread of G data must be limited as much as possible: this makes it necessary to improve the bearing fabrication process. Such an improvement, together with that of the characteristics of bearing materials, may enhance bearing performance, and thus safety margins with respect to the design displacement.

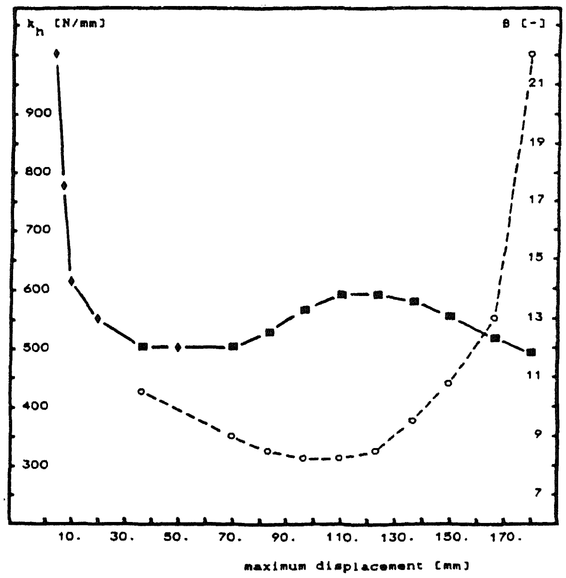

Figure 7. Horizontal stiffness k_h [■] and fraction [%] of critical equivalent viscous damping ß [o] measured in the failure test, versus applied displacement (♦ = stiffness measured in previous tests).

The dynamic similitude was sufficiently well respected by the response of scaled bearings (Figs. 5 and 6): this permitted a reliable use of data obtained on scaled isolated mock ups, such as those described by Bettinali et al. & Serino et al. (1992).

Bearing damage started at about 160% σ in the failure test performed to date (which concerned one isolator only, without lateral rubber cover), but no collapse nor overturning occurred even at 260% shear strain (Fig. 7). Damage might have been caused by some initial defect, due to bearing reworking performed to eliminate the lateral rubber cover; anyway, further failure tests will be performed on bearings with better bonding features and improved geometric details of steel-plates.

Horizontal stiffness was only slightly affected by vertical load variation; it correctly decreased considerably by increasing displacement, to 50% σ; then it remained quasi-constant (10% decrease) to 100% σ; finally, it increased slightly to the excitation level at which bearing damage started (Fig. 7).

Damping nature (Figs. 7 and 8) was largely non-viscous; equivalent viscous damping was similar for the

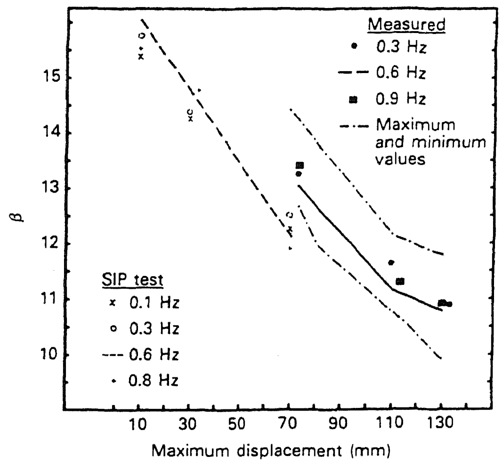

Figure 8. Fraction [%] of critical equivalent viscous damping ß for full scale bearings measured in dynamic tests at fixed frequencies, versus applied displacement.

various bearing scales; it decreased by increasing excitation, to the excitation level at which damage started (it remained larger than 10% of the critical in dynamic tests).

The effects of dynamic excitation on damping were found more important than those on horizontal stiffness (on which it had no effects at 50% σ and increased the quasi-static value by less than 10% at 100% σ).

Creep effects due to vertical load were small (7%-8%. of the dead load deflection). Finally, no effects of natural aging have been found, yet.

7 NUMERICAL MODELS OF ISOLATORS

Numerical activities mainly concern the definition of models for bearings and isolated structures, and their use for test design and the analysis of experimental results (see also Bettinali et al. 1992).

Simple bearing models have been set up, and the development of finite-element three-dimensional (3D) and 2D axisymmetric models is in progress.

Simple models - to be also used for the analysis of isolated structures - have been based on the results of single bearing tests: models formed by a spring in parallel to a viscous damper, where both horizontal stiffness and viscous damping coefficients vary with displacements, have been successfully applied by ENEA to the analysis of the results of tests per-

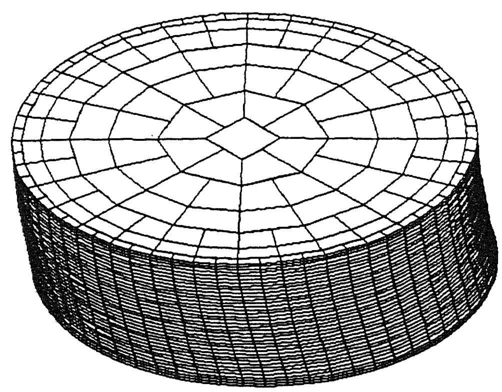

Figure 9. First vibration mode of the 3D model of SIP-type HDRB.

formed on isolated mock - ups and the SIP buildings (see Bettinali et al. 1992). Models based on other assumptions are also being successfully used (Serino et al. 1992).

Detailed models include separate elements for the rubber and steel plates. Three element sub-layers have been defined for each rubber layer and one for each steel plate. The 3D model that is being considered at present is formed by solid elements (8 nodes) for the rubber and shell elements (4 nodes) for steel plates. This model has been implemented in the ABAQUS computer code.

Linear elastic calculations were performed with this model, to evaluate stiffnesses and natural frequencies of the single bearing and the bearing loaded by the superstructure (Fig. 9). The implementation of an elastic-plastic model for steel is also being completed (so as to evaluate the effects of steel plate deformations), together with that of a hyperelastic model of the rubber, based on the tests on specimens mentioned in § 4 (Fig. 3 shows an example of the extent of agreement between measured stress-strain curves and values obtained by approximation of the polynomial equations used in ABAQUS).

Detailed models will be validated based on measured data. They will be used for bearing design and analysis of the effects of defects: some bearings with artificial defects have been fabricated to this purpose.

8 CONCLUSIONS

Tests described have already provided useful information to understand the behaviour of isolation bearings, enable the numerical analysis of isolated structures, and improve design guidelines for such structures. The experimental analysis of the effects of temperature and accelerated aging and the execution of further failure tests will complete the information required. Further tests on SIP-type bearings with modified compound and dowelled and bolted attachments will enable the application of improved bearings to important public and industrial structures, and will provide data to begin a detailed study for optimizing bearing performance.

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