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VERIFICATION AND IMPROVEMENT OF ANALYTICAL MODELING OF SEISMIC ISOLATION BEARINGS AND ISOLATED STRUCTURES

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Abstract

Due to the complexity of dynamic behaviour of seismic isolation (SI) devices, high cost of their tests and non-negligible number of devices having excellent potential for nuclear applications, several countries judged of great interest to extend validation of their numerical models of such devices to the analysis of experimental data obtained by others. Thus, a four-years Coordinated Research Program (CRP) on Intercomparison of Analysis Methods for Isolated Nuclear Structures, proposed by ENEA (1995), was endorsed by the IAEA in 1995. There, Italy was jointly represented by ENEA, ENEL and ISMES, and supplied test results concerning both High Damping Rubber Bearings (HDRBs) and the MISS (Model of Isolated Steel Structure) mock-up, which had been isolated using such bearings. Test data provided by Italy to the other countries were also re-analysed to improve mathematical models. Aim of this final report is to summarise, after a brief description of the devices and structures considered, the most important results and conclusions of the numerical analyses carried out by Italy. For more detailed information, especially as far as the execution of the tests and the implementation of the numerical models are concerned, please refer to the technical reports presented by Italy to the Research Coordination Meetings (RCMs).

INTRODUCTION

At the first RCM held at St. Petersburg (IAEA, 1997) Italy provided test data and results of numerical analyses concerning two HDRBs which were developed within an European Research Programme coordinated by ENEL (1993). In addition to the numerical activities, ENEL carried out in 1997 a complete material characterization of KAERI HDRBs, by testing in its laboratories rubber specimens, and distributed the results to the other participants.

The first data, among those provided by other countries, which were jointly analysed by ENEL and ENEA, concerned U.S. scaled HDRBs that had been manufactured in Italy and tested by University of California at Berkeley; then, Natural Rubber Bearings (NRBs) and Lead Rubber Bearings (LRBs) manufactured in Japan for CRIEPI were analysed. The results concerning U.S HDRBs and Japanese NRBs were presented at the RCM of Taormina (IAEA, 1998a and GLIS, 1998), while information concerning Japanese LRBs was given at the Hertford RCM (IAEA, 1998b). Finally, the results concerning modified Japanese LRBs (with larger lead plug diameter) were presented at the Cheju RCM (IAEA, 1999).

With regard to the analysis of isolated structures, a detailed description of MISS was provided to the other partners (jointly by ENEA, ENEL and ISMES) at the St. Petersburg RCM in 1996. Moreover, at the same RCM, numerical analyses on the behaviour of MISS and other isolated civil buildings were presented. Finally, the results of analyses of an isolated

Korean spent fuel pool and a Japanese isolated rigid mass were presented at the Cheju RCM in 1999.

1. ANALYSIS OF RUBBER BEARINGS

ENEL and ENEA jointly analysed the test data of HDRBs provided by Italy (Martelli et al., 1996; ENEL et al., 1993) and US (Clark et al., 1996) and those concerning Natural Rubber Bearings (NRBs) provided by Japan (Hirata, 1996).

1.1 Description of the Devices

1.1.1 Italian optimised HDRBs

In the framework of the above mentioned research activities involving ENEL, ENEA and other partners (ENEL et al., 1993) a considerable number of optimised HDRBs were designed, manufactured and tested in Italy. These isolators are characterised by:

a) two different rubber compounds: harder (shear modulus G=0.8 MPa) and softer (G=0.4 MPa);
b) two values of the primary shape factor (S = 12 and S = 24);
c) three different geometric scales (diameter D = 125, 250 and 500 mm);
d) two different attachment systems (recess and bolts & dowel).

The devices were produced by ALGA and experimentally tested at ISMES laboratory (Figure 1.1). The optimised bearings analysed using the finite element technique and reported herein, had an overall diameter of 250 mm and both shape factors of 24 and 12. In the case of the higher shape factor, there were 30 elastomeric layers (G = 0.8 MPa), each being of 2.5 mm thick, alternated with 29 steel shims of 2 mm thickness. The steel end plates were 15 mm thick and had a 240 mm diameter. The total height was 114.5 mm. The bearing having S = 12 was formed by 15 layers of rubber (G = 0.8 MPa), each being of 5 mm thick, sandwiching 14 steel shims of 2 mm thickness. The steel end plates were again 15 mm thick, with a diameter of 240 mm. Both the bolts & dowel and the recess attachment systems were considered.

1.1.2 Italian further optimised HDRBs

Tests and FE calculations performed on the so called optimised HDRBs (ENEL et al., 1993) showed the possibility of further improving their stability at large deformations by decreasing their height. Therefore, some 'further optimised' HDRBs were designed by ENEA and produced by ALGA. Several kinds of these devices were manufactured by combining two different shape factors (S = 12 and S = 24), two rubber compounds (G=0.8 and 0.4 MPa), two attachment systems (recess and bolts & dowel) and two geometric scales (D=250 and 125 mm). The 'further optimised' bearing analysed in this study had an overall diameter of 125 mm and a shape factor of 12. There were 12 layers of elastomer (G = 0.4 MPa), each 2.5 mm thick, alternated with 11 steel shims of 1 mm thickness. The steel end plates were 10 mm thick and had a 120 mm diameter. The total height was 61 mm. These devices were used to seismically isolate MISS (§ 3). The Italian HDRBs were also analysed within this CRP by Yoo et al. (1998b) and Selvaraj et al. (1998).

1.1.3 US HDRBs

The test data provided by US concern 1:8 scale prototypes (manufactured by ALGA) of the HDRBs of the ALMR plant (Clark et al., 1996). The bearings are cylindrical supports with a diameter of 146 mm consisting of 15 rubber layers 2.3 mm thick and 14 Fe 430 (Figure 1.4) steel plates 1.9 mm thick. The bearings have a central hole (20 mm diameter) for an easier and more correct assembly during manufacturing phase and for a better heat exchange during vulcanisation process. Each bearing supports a vertical load of 44 kN.

1.1.4 Japanese NRBs

The bearings proposed by the Japanese CRIEPI (Hirata, 1996) have an overall diameter of 1012 mm, a total rubber height of 142.5 mm and a shape factor S equal to 38.9. There are 25 layers of elastomer, each 5.7 mm thick, alternated with 24 steel plates of 3.1 mm thickness. The bearing were fabricated using a compound with a shear modulus G=0.6 MPa. Each isolator supports a design vertical load of 2000 kN.

1.2 Finite Element Analyses

For the Italian and US HDRBs both three-dimensional (Figures 1.2, 1.5) and axisymmetric finite-element models (FEMs) were developed and implemented in ABAQUS computer program by ENEA (Forni et al., 1996 and Dusi et al., 1998c), while similar models were developed and implemented in the same code by ENEL for the Japanese NRBs (Dusi et al., 1998c). Hyperelastic models of the rubber, defined according to the results of suitable tests on both scragged and unscragged rubber specimens, were also implemented in ABAQUS. Extensive numerical work was performed by considering meshes with different refinements and different element types. The numerical analyses, aimed at investigating the effects of the numerous variables of the problem, allowed for optimising the type of material model, discretisation and elements to be adopted, up to large strains.

For HDRBs, good agreement between numerical and experimental results was found by ENEA for horizontal stiffness (Figures 1.3, 1.6), similar to the results of ENEL for the Japanese NRBs (Dusi et al., 1998c); however, the agreement for compression tests was satisfactory only when compressibility was taken into account. This confirmed the importance of volumetric tests on rubber specimens to correctly evaluate bearing vertical stiffness, especially in the case of large shape factors. Analysis of ENEA also stressed that planar tests on specimens shall be performed to very large deformation, in order to allow for the definition of adequate hyperelastic models of the rubber. Moreover, it was found that the unscragged rubber model should be used for reproducing bearing behaviour to 50%–100% shear strain, while the scragged model should be used for larger deformations. Only slight differences were found between the results of 3D and axisymmetric models to 200%–300% shear strain, while 3D models shall be used for larger deformations.

1.3 Conclusions

The achieved results confirmed the conclusions of previous studies (Forni et al., 1995) that FEMs are useful tools for both the detailed design of elastomeric bearings and their qualification; for the latter, they allow for a considerable reduction of the number of tests to be performed (e.g. those concerning effects of parameters like temperature, ageing, vertical load on horizontal stiffness, initial or arisen defects, etc.). In particular, it is worth noting that:

- volumetric tests on rubber specimens are necessary to better reproduce the vertical behaviour of the berings, but can be neglected for reproducing shear tests;
- planar tests must be performed up to very large deformations (300%–400% minimum);
- axisymmetric elements can be used in the bearing modelisation up to deformations of 150% shear strain; for larger deformations, three-dimensional models (for steel plates also) must be used;

- the unscragged rubber model must be used for reproducing the behaviour of bearing up to 50%–100% shear strain; for larger deformations the scragged model must be used;
- the polynomial form of the Energy Function of the elastomer seems to better reproduce the experimental results for both specimen and bearing tests; moreover, the results provided by this solution are more stable (and independing of the length of the curves given as input data) than those obtained using the Ogden form.

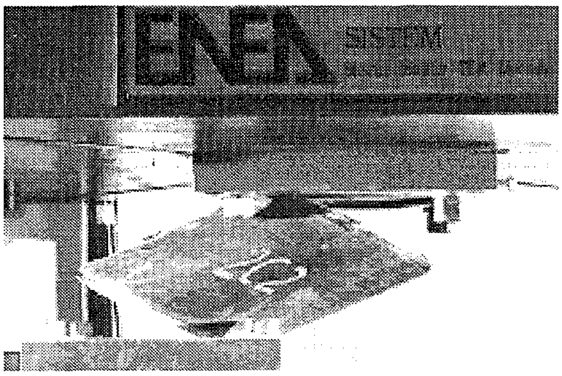

Figure 1.1: Compression and shear test at 300% shear strain on optimised HDRB with recess attachment system.

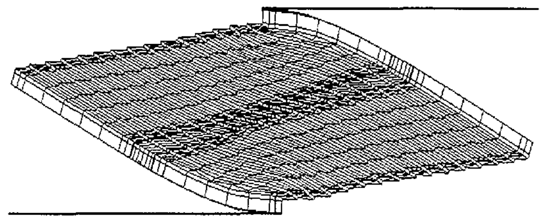

Figure 1.2: FEM of an optimised HDRB at 300% shear strain with recess attachment system.

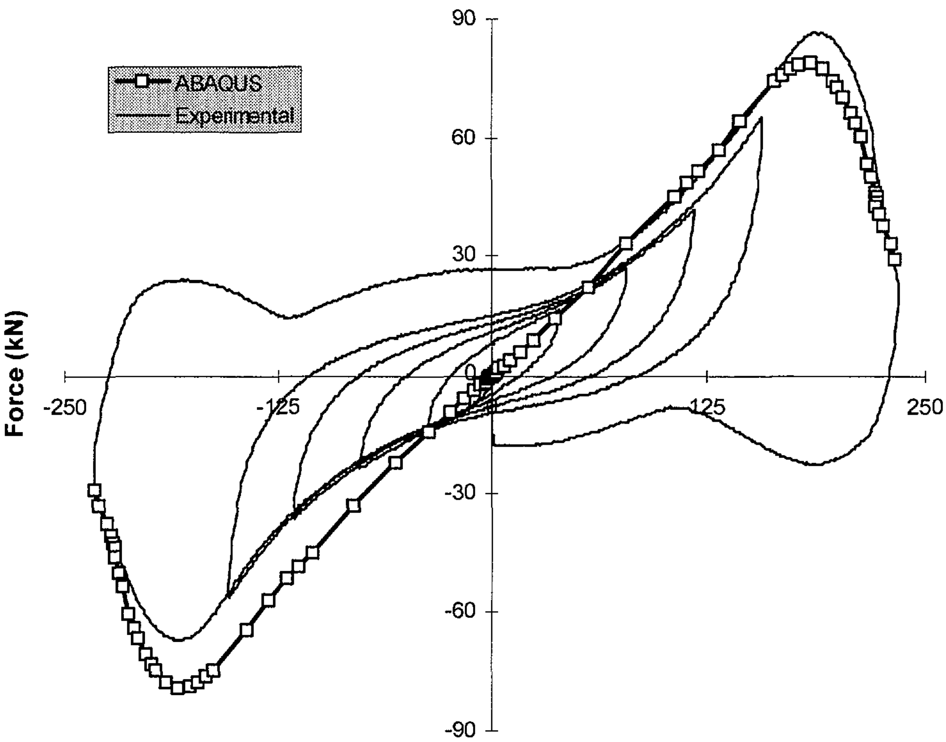

Figure 1.3: Experimental and numerical force-displacement values for a combined compression & 300% shear strain test on optimised HDRB (1:2 scale, diameter=250 mm, H=75 mm, S=12, G=0.8 MPa, recess attachment system).

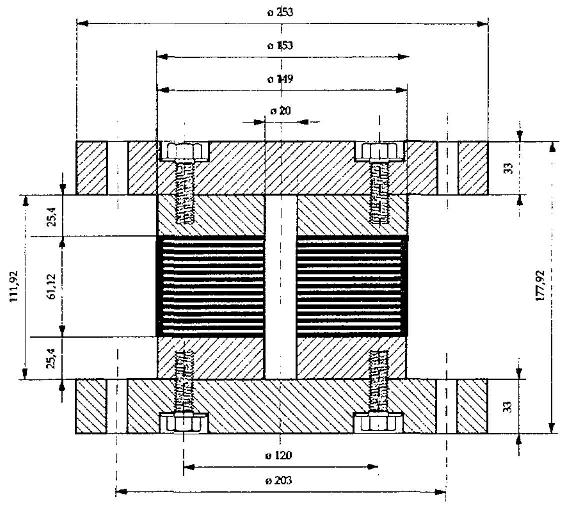

Figure 1.4: Sketch of the 1:8 scale prototype of the ALMR isolation bearing manufactured by ALGA and tested by EERC.

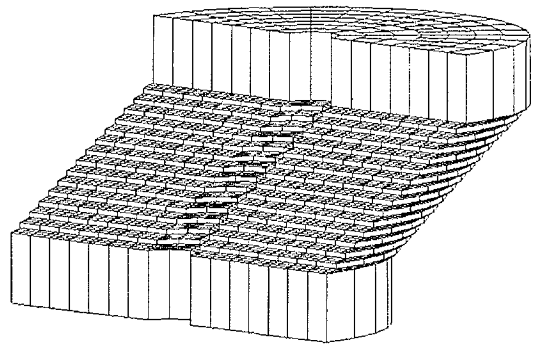

Figure 1.5: Deformed FEM of a bolted ALMR HDRB during a compression (44 kN) and 150% shear strain test.

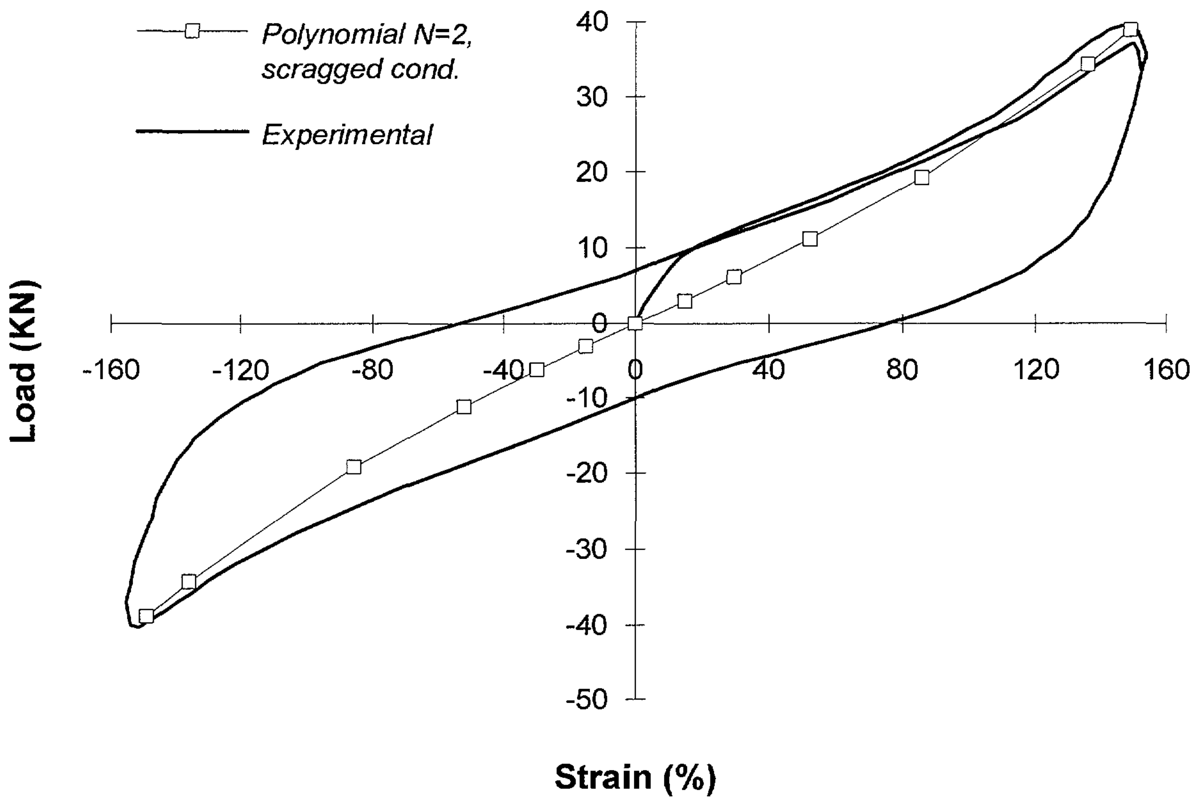

Figure 1.6: Comparison between measured and calculated horizontal stiffness of an ALMR bearing (1:8 scale, diameter=146 mm, H=61 mm, G=1.4 MPa, bolts attachment system) during a combined compression (44 kN) and 150% shear strain test performed at EERC.

2. ANALYSIS OF LEAD RUBBER BEARINGS

ENEL analysed the test data of a first LRBs provided by Japan (Hirata et al., 1998). A second LRB was jointly analysed by ENEL and ENEA (Dusi et al., 1998a).

2.1 Description of the Devices

2.1.1 First LRBs

The first LRB proposed by CRIEPI for intercomparison activities is a 1/1.83 scale prototype of LRBs to be used for the seismic isolation of the Japanese Fast Breeder Reactor. The analysed bearing consists of 25 layers of elastomer (G = 0.6 MPa), 4.9 mm thick, alternated with 24 steel plates having a thickness of 3.1 mm. It has an overall diameter of 876 mm (excluding the coating rubber), a total rubber height of 122.5 mm and a primary shape factor S_1 equal to 44.4. A lead plug of 98 mm diameter is inserted in the centre of the bearing. Each isolator supports a design vertical load of 1500 kN.

2.1.2 Second LRBs

Also the second LRB analysed in the CRP was designed, manufactured and tested by CRIEPI. It consists of 23 layers of elastomer, 2.0 mm thick, alternated with 22 steel plates having a thickness of 1.6 mm. It has an overall diameter of 280 mm and a total rubber height of 46 mm. A lead plug of 70 mm diameter is inserted in the centre of the bearing. The isolator supports a design vertical load of 568.4 kN.

2.2 Finite Element Analyses

2.2.1 First LRBs

Compression test was first analysed using both 3D and axisymmetric finite element models (Dusi et al., 1998a). No sliding effects between lead and rubber were taken into account for these numerical simulations. The comparison between the experimental and numerical results shows that displacements predicted by ABAQUS are smaller than actual ones. No relevant differences were found between 3D and axisymmetric models. Discrepancy between experimental and numerical results is caused by the assumption of incompressible behaviour of rubber in the constitutive equations: as demonstrated by Forni et al., 1995, compressibility should be taken into account in the definition of the strain energy function when analysing compressive loading tests.

The same FE models adopted for the vertical stiffness evaluation were also used for calculating the horizontal stiffness at 25%, 50%, 100%, 200%, 300% and 400% shear strain, under the design vertical compression load. The agreement between tests and calculations is good for horizontal displacements less than about 200 mm. It has however to be observed that, at high shear deformations (more than 200 mm), the simulated response exhibits a higher shear stiffness than the experimental one (at least when considering the second measured cycle).

A comparison between the experimental data and the results obtained from ABAQUS using two different meshes, both with the same materials characterisation and different geometrical discretisation, shows that, for the analysed bearing, mesh density has negligible effects in reproducing the shear behaviour of the isolator.

Results obtained using the simple model, consisting of a single rubber layer, well match those obtained from a 3D FEM, thus demonstrating that the single rubber layer model can be successfully used to calibrate the FEM of the entire isolator and to provide an estimate of its overall horizontal stiffness.

Finally, a comparison between experimental data and numerical simulations obtained considering the effect of sliding at the rubber-lead interface was carried out. An axisymmetric model was used up to 150% shear strain, at which convergence problems occurred. To reach the maximum shear strain (400%) it was then necessary to resort to a detailed 3D model. In spite of the difficulties encountered in setting up the contact problem and the effort in terms of CPU time, results don't differ significantly from those previously obtained.

2.2.2 Second LRBs

The analyses performed on the second LRBs (Dusi et al., 1999a) confirmed the results obtained for the first bearings (see § 2.3). In particular, it was demonstrated that the discrepancies founded by Dusi et al. (1998a) at large deformations between tests and calculations (Figures 21, 2.2) were due to the poor input data for the characterisation of the rubber and not to the lead, which can be assumed elastic — perfectly plastic.

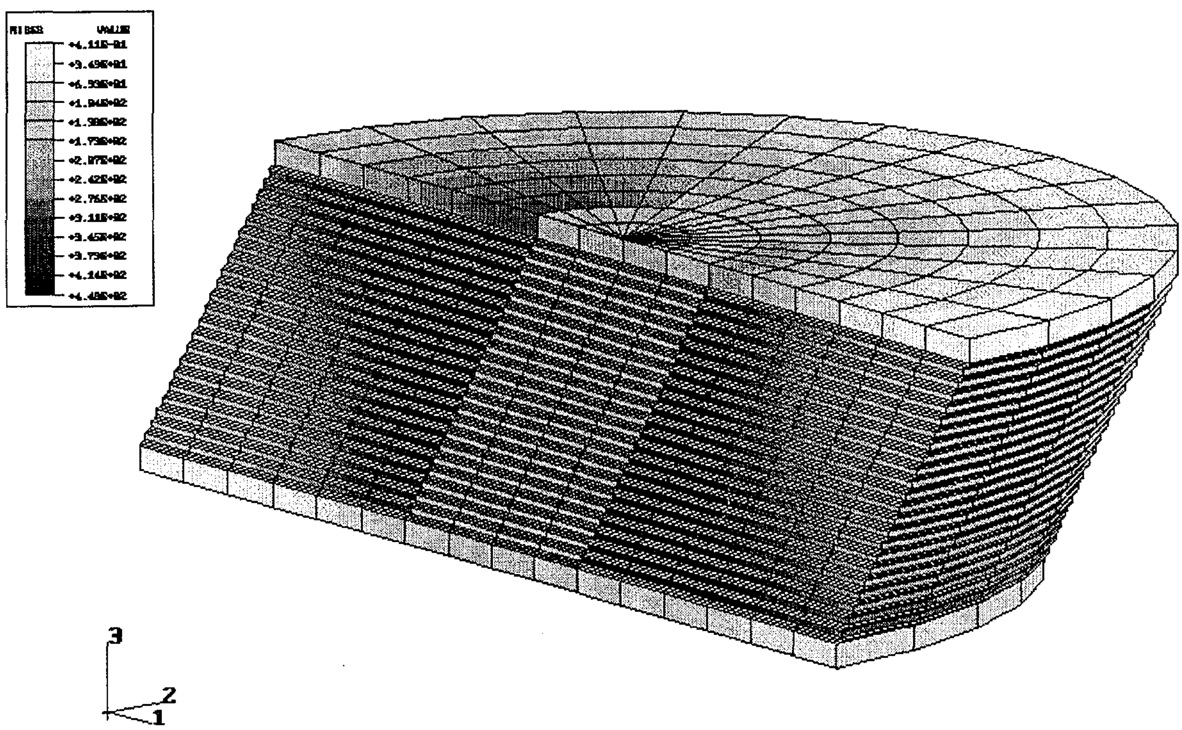

Figure 2.1: Calculated Von Mises stress distribution in the LRB at 150% shear strain.

2.3 Conclusions

From the results obtained in the numerical simulations performed by Dusi et al. (1998a and 1999a) the following considerations may be drawn:

- compressibility must be considered in the strain energy function definition when the behaviour of the bearing under compressive loading has to be analysed;
- mesh density has little effect in reproducing the shear behaviour of the bearing, providing that a sufficient number of elements is used and that the element shape is such to avoid excessive distortions at high deformation;
- axisymmetric elements (with asymmetric deformation) can successfully be used instead of solid element, thus saving computational time;

- the results of a simple model, consisting of a single rubber layer, can be successfully used to calibrate the FEM of the entire isolator and to provide an estimate of its overall horizontal stiffness, greatly reducing computational time;
- when analysing vertical stiffness, at least 3 elements are required in the thickness to get accurate results; on the contrary, in shear deformation the number of elements seems to have little effects on the prediction of the horizontal stiffness
- the behaviour of the lead can be considered elastic — perfectly plastic and the friction effect between lead and rubber can be neglected.

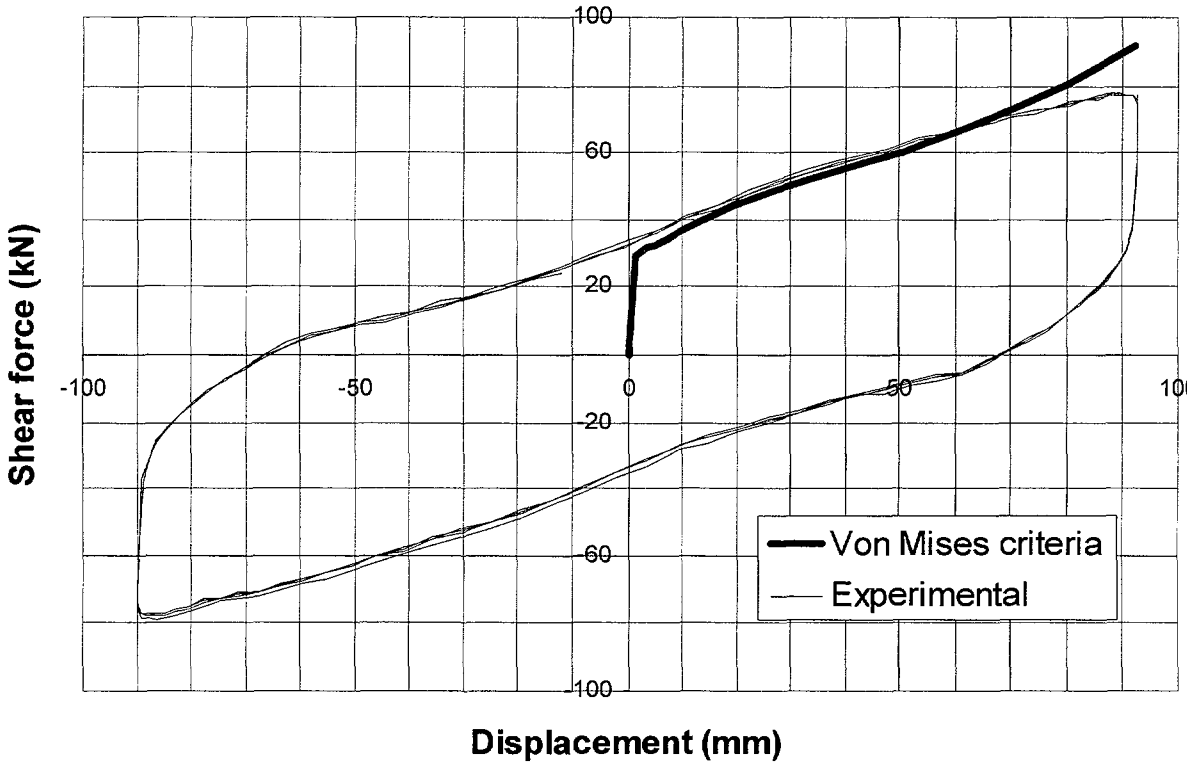

Figure 2.2: Comparison between the measured and calculated hysteresis loops for the LRB (complete FEM, Von Mises criteria).

3. ANALYSIS OF ISOLATED MOCK-UPS WITH SIMPLIFIED FEM OF HDRBS

Two seismically isolated structure mock-ups tested on shaking table were jointly analysed by ENEL and ENEA. The first mock-up was a flexible steel frame (MISS) tested at ISMES in the framework of the above mentioned research programme coordinated by ENEL (1993). The second one was the rigid mass tested by CRIEPI (Hirata et al., 1998). Aim of these analyses was the implementation and validation of a simplified FEM of HDRBs. As a matter of facts, the detailed FEM of isolators described in the previous sections cannot be used in the dynamic analyses of isolated structures and simplified models must be implemented.

3.1 The Multilinear Elastic-Perfectly Plastic (MEP) Simplified Model

The most important problem in the implementation of a simplified model is given by the highly non-linear behaviour of the rubber bearings, especially in terms of damping. The model proposed herein is based on the coupling of a spring, which provides the non-linear stiffness, and a truss element (that is a beam working in the axial direction only), which provides the hysteretic damping with its plastic deformation.

A sketch of the MEP model is shown by Figure 3.1. The spring K_S can be multilinear and even asymmetric with respect to the origin. Usually, only one K_S variation is sufficient to describe the isolator hardening, which usually begins at 75%–125% shear strain and perfect symmetry between the two deformation ways in the horizontal direction is assumed. The hysteretic damping is provided by the beam, which is subjected to pure compressive load: it is initially elastic, then it strains plastically. The beam stiffness is given by the ratio EA/L, where E is the Young's modulus (the material, of course, is completely free), A is the cross-section area and L is the length. The geometry of the beam is free too; however, to avoid convergence problems in the calculations, it is useful to have a non-excessively large Young's modulus, a length/diameter ratio typical of a beam (say, 10 or 20) and a length that is well larger than the expected deformation.

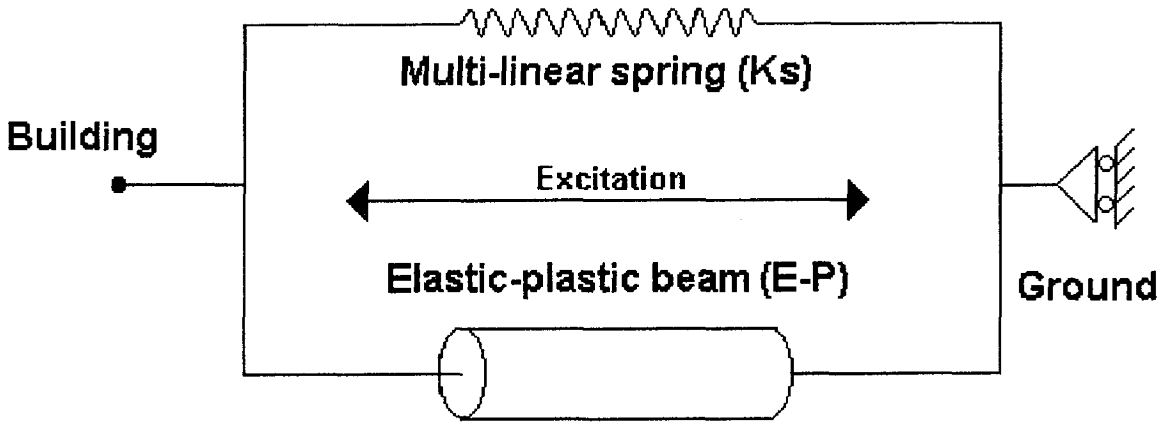

Figure 3.1: Multi-linear elastic-plastic simplified model (MEP) of a rubber bearing (Ks = non-linear spring; E-P = elastic-perfectely plastic beam).

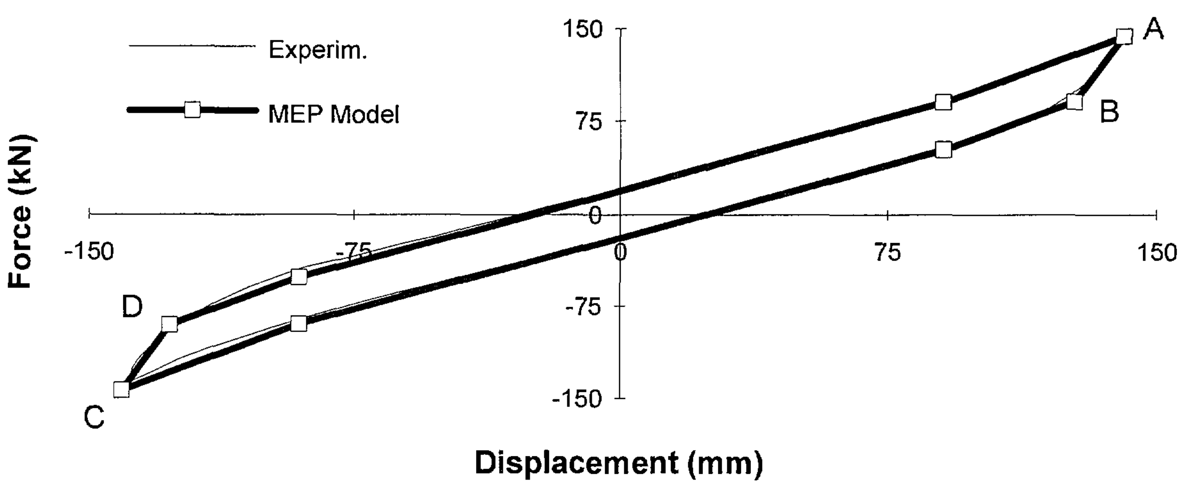

Figure 3.2: Comparison between the experimental and 'MEP' hysteresis loop for the smaller HDRB of the TELECOM Italia building at 100% shear strain (see § 4).

In spite of its simplicity, the MEP model can easily reproduce any given or wanted hysteresis loop (Figure 3.2). Its only limit is given by the constant 'width' of the hysteresis loop, that implies an energy dissipation ratio constant with respect to the deformation rate. Thus, the MEP model shall be calibrated on the maximum expected deformation and used to calculated the response of the structure in this range of deformations. For lower deformations the MEP model will overestimate the damping while, for higher deformations, it will underestimate the energy dissipated (Figure 3.3).

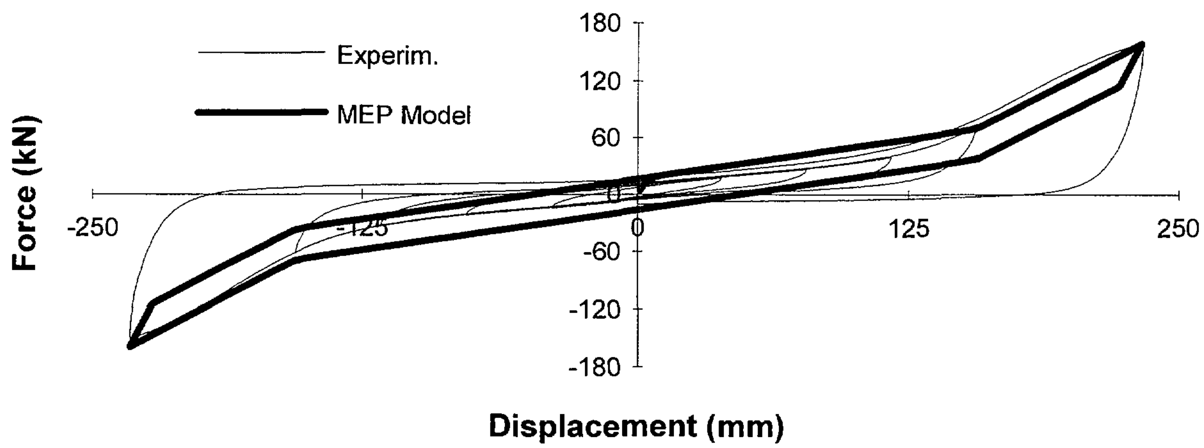

Figure 3.3: The MEP simplified model provides a constant 'width' of the hysteresis loop which underestimates the damping at large shear strain.

3.2 Description of the Structures

3.2.1 MISS

MISS is a steel frame structure mock-up with a rectangular base of 2.1 m × 3.3 m, and four storeys, with an interstorey distance either of 0.9 m or of 1.1 m (Figure 3.4). It can support up to 20 concrete masses, each weighting 13 kN. The frequency of the structure can be chosen 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 isolators fabricated with a soft compound (G = 0.4 MPa, bolts and dowel attachment system, 125 mm diameter, 30 mm rubber height) and provides an isolation frequency in the range of interest for seismic isolation (below 1 Hz). MISS was subjected to a wide ranging experimental campaign of forced vibrations at the top (sinusoidal and random) and shaking table tests consisting in the application of sinusoidal excitations and natural and artificial earthquakes (1D, 2D and 3D) for both the isolated and fixed-base configurations.

3.2.2 CRIEPI Rigid Mass

This rigid mass mock-up was tested by CRIEPI in 1989 and was jointly analysed by ENEA and ENEL (Dusi et al., 1999a). The mock-up consists of a concrete frame of 178 kN weight, 3 × 2.1 × 2.8 m overall sizes, which is supported by 8 LRBs very similar to those described in § 2. The results of the shaking table tests were also analysed by Hirata et al. (1998) and by Yoo et al. (1998a) in the framework of this CRP.

3.3 Finite Element Analyses

The structure mock-ups described in the previous section were modelled by Dusi et al. (1996b and 1999a) and by Forni et al. (1998) using detailed finite element models of the structures (Figure 3.5) and simplified MEP models for the isolation systems. The MEP models were calibrated based on experimental hysteresis loops provided by ISMES and CRIEPI corresponding to maximum deformation obtained during the shaking table tests. Then, the mock-ups FEM were subjected to the excitations really applied on the shaking table and more severe accelerograms, in order to calculate the response of the structures within acceleration range which are impossible to be applied in laboratory. Different types of rubber bearings and wide ranges of deformation and acceleration levels were successfully analysed with the MEP simplified model (Figures 3.6, 3.7 and 3.8).

3.4 Conclusions

The results of shaking table tests performed on a steel frame structure mock-up and an isolated rigid mass have been used for the characterisation and the validation of a simplified finite element model based on the coupling of a spring and a truss element. It was demonstrated that the MEP simplified model can correctly reproduce any given hysteresis loop and the behaviour of an isolated structure, at least in the range of deformations in which the MEP is calibrated.

In section 5, is described a simplified finite element models of HDRBs, implemented by Dusi et al. (1998b) in the ABAQUS code, which can correctly reproduce the behaviour of the bearing independently of the deformation value.

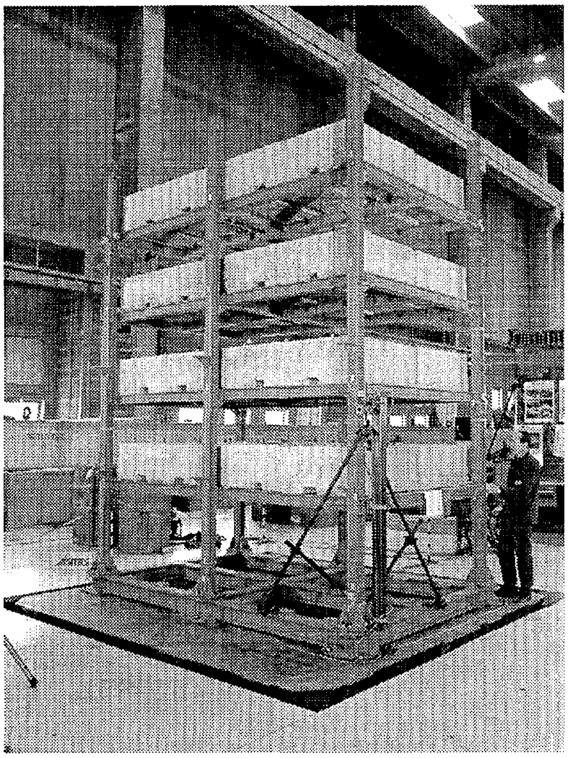

Figure 3.4: MISS on the ISMES shaking table in the fixed-base configuration with 16 masses (250 kN total weight).

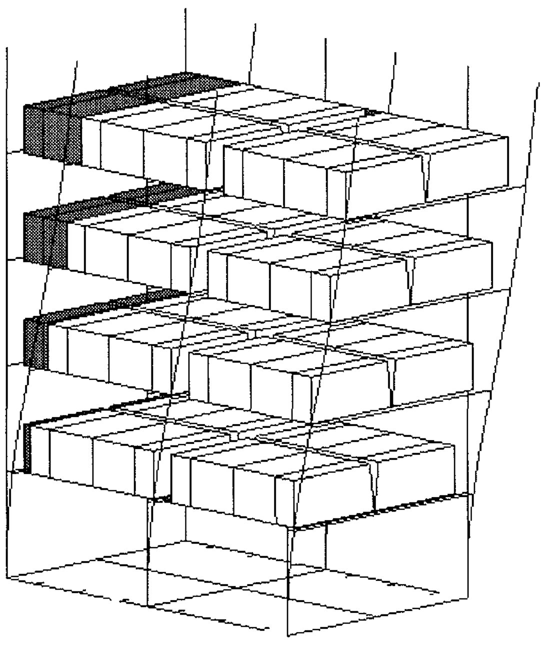

Figure 3.5: 1st modal shape of MISS in the fixed-base conditions with 16 masses (F1=1.49 Hz; exp.=1.5 Hz; α=1.75).

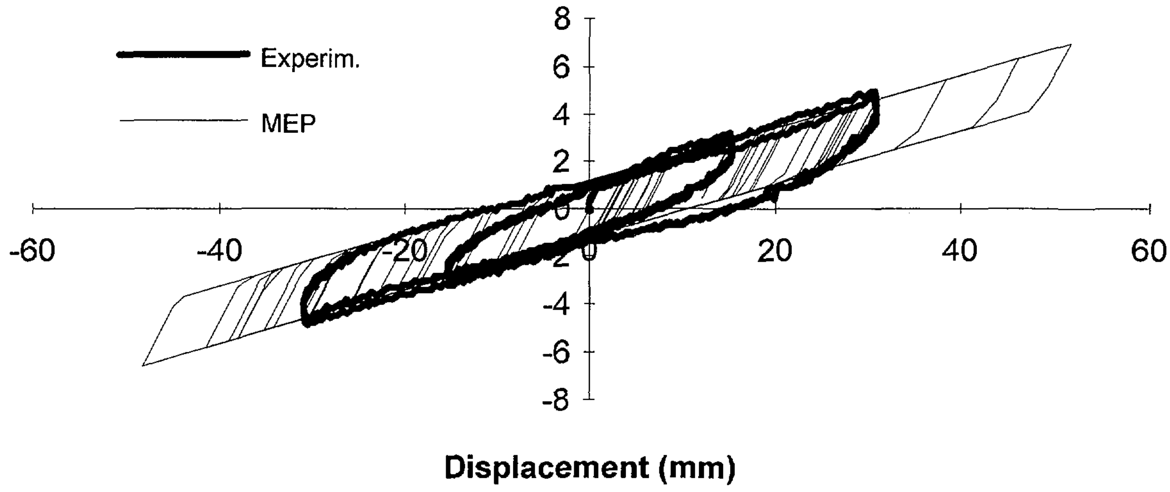

Figure 3.6: Comparison between the hysteresis loops as calculated by the MEP model during the application of a synthetic earthquake and those obtained during the execution of static tests on single device.

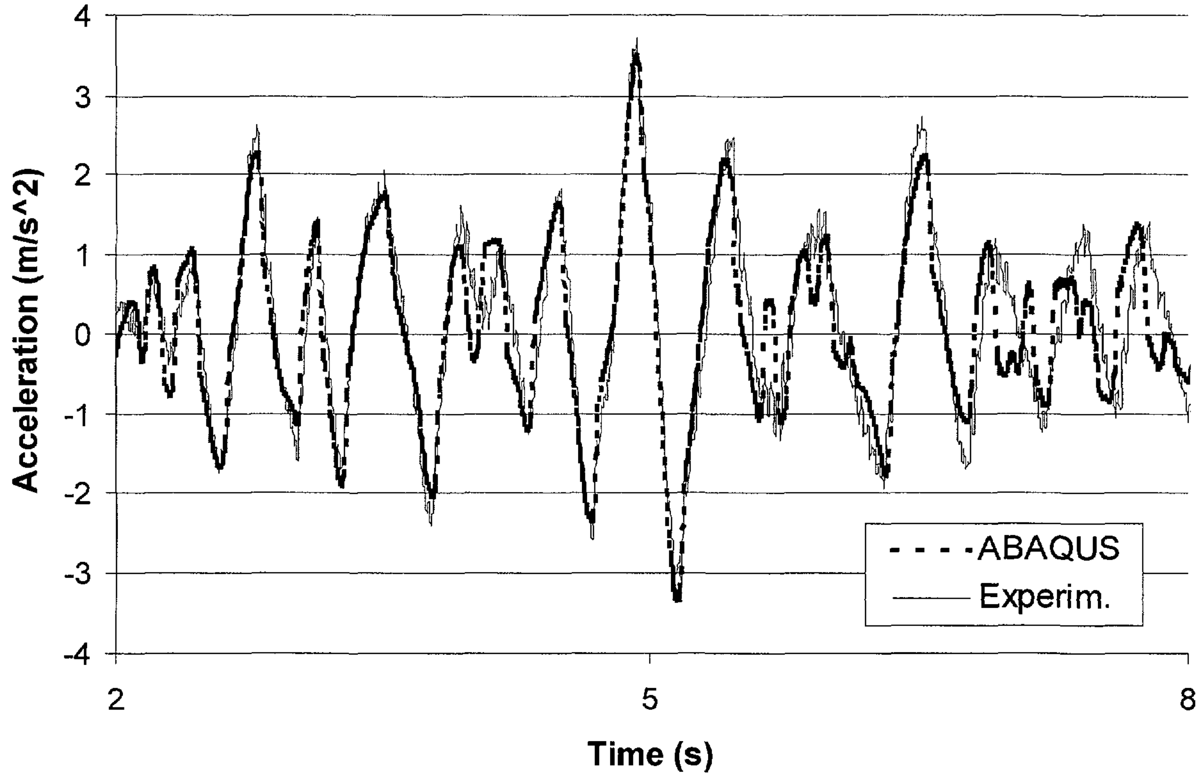

Figure 3.7: Comparison between measured and calculated accelerations at the base of the rigid mass under the A1 acceleration time-history (detail on the strong-motion part).

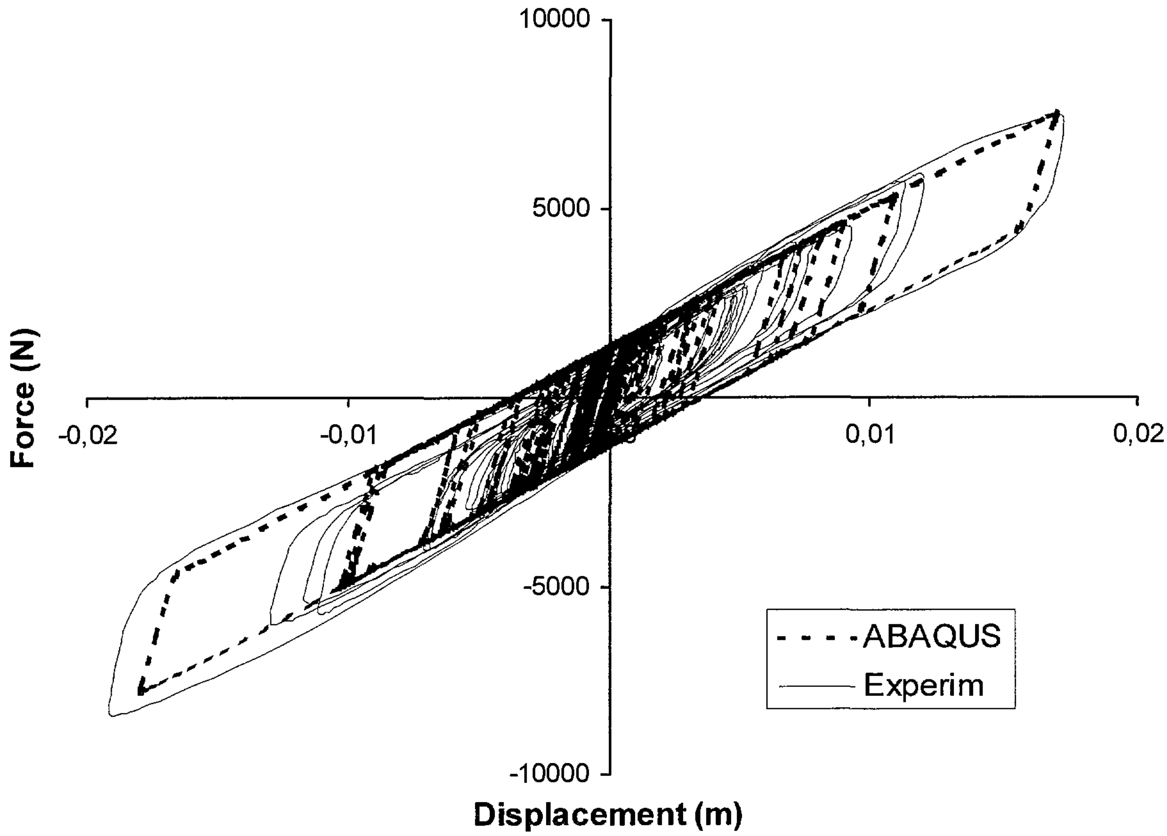

Figure 3.8: Comparison between measured and calculated hysteresis loops under the A1 acceleration time-history.

4. ANALYSIS OF ISOLATED BUILDINGS WITH SIMPLIFIED FEM OF HDRBS

Two Italian seismically isolated civil buildings subjected to on site experimental campaigns were jointly analysed by ENEA and ENEL. Aim of such analyses was the validation of the simplified finite element models of HDRBs described in section 3 in the case of real structures.

4.1 Description of the Buildings

4.1.1 TELECOM Italia building

The TELECOM Italia Center of the Marche Province was built at Ancona in 1991 and is the most important application of base isolation in Italy (Giuliani, 1989). It is formed by five large eight-storey buildings, connected among themselves. The resistant structures are reinforced concrete frames that are highly irregular (Figure 4.1). The buildings contain computers and other sophisticated hardware for which the protection from seismic actions is essential. The isolation system consists of HDRBs with hard rubber compound (shear modulus G = 0.8 MPa) and 'recess' attachment system (Bettinali et al., 1991); the devices, similar to those described in § 1.1.1, have a total rubber height of 144 mm and two different diameters (500 mm and 600 mm) corresponding, respectively, to 1,600 kN and 2,600 kN design vertical load (combination of the dead load of the structure with vertical seismic actions). The buildings have a first response frequency close to 0.6 Hz, with quite a high isolation ratio α, close to 7 (α being the ratio of the fixed-base structure frequency over the isolated one). During the design earthquake, the expected displacement is equal to 144 mm, corresponding to a bearing deformation of 100% shear strain. Somewhat beyond this displacement, a fail-safe system, formed by rubber bumpers, gradually stops the building motion.

The building analysed in the CRP was subjected to a wide-ranging experimental campaign including forced vibration and pull-back tests (Bettinali et al., 1991). Aim of the forced vibration tests, carried out by use of a mechanical vibrator placed on the roof, was to measure the fundamental response frequencies of the building superstructure. The pull-back tests, which consisted in providing an initial displacement to the isolation system by means of hydraulic actuators acting on the base of the building superstructure, aimed at observing the free-vibrations following the istantaneous release of the building itself. They were performed using collapsible devices provided with explosive bolts. These tests allowed for the measurement of the frequencies of the isolated structure (and the isolation ratio) and were suitable to characterise the mechanical properties of the isolation system.

4.1.2 The twin apartment houses at Squillace

The two buildings, one conventional and the other base-isolated, have identical geometrical and mechanical characteristics, apart the foundations and the isolation system (Forni et al., 1993). The buildings have four storeys, three above and one below ground. The resistant structure is a reinforced concrete frame, symmetrical with respect to the central transversal axis, while on the longitudinal axis the mass and stiffness centres are nearly coincident. The first interstorey is stiffer than the others, due to the presence of a shear reinforced concrete wall. The isolation devices are underneath the first floor, below them there is a rigid box structure acting as foundation, while a framed structure rests on them. They consist of 27 HDRBs with recess attachment system, 132 mm rubber height and two different diameters (400 mm and 500 mm), the largest for the internal columns, which carry a higher vertical load (1,190 kN), and the smallest for the exterior columns (770 kN). The bearings were fabricated using hard rubber compound (G = 0.8 MPa) and were designed to obtain an isolation frequency close to 0.8 Hz, with an isolation ratio of 8.3.

At the time of in-situ tests the frames of the two structures had been completed but the buildings were not complete; neither the roof nor the flooring were in place. In the conventional structure the external masonry walls and internal partitions were present, while the isolated structure had only the external walls. With the aim of characterising the dynamic properties of the buildings, forced vibration tests were carried out by use of a mechanical exciter placed on the roof of the two buildings, in an eccentric position. Excitations were provided in two normal directions (Forni et al., 1993).

4.2 Finite Element Analyses

Detailed FEM of the buildings described in the previous sections were implemented in the ABAQUS code (Figure 4.2). The numerical models of the buildings were calibrated based on the results of the on-site forced vibration tests (Figure 4.3), while the simplified MEP models were calibrated based on the results of laboratory tests on single HDRBs and the pull-back test on the TELECOM building (Figure 4.4).

After the validation of the superstructure and isolation system models, many artificial and natural earthquakes were applied to both the TELECOM and Squillace buildings with the aim of analysing the structure behaviour for different soil conditions, acceleration levels and isolation ratios, even in the case of absence of seismic isolation (Bettinali et al., 1996). Modal analysis (taking into account the first 9 modes) was used for the calculations at fixed-base, while direct integration (implicit method) was adopted for the runs concerning the base-isolated building. The analysis showed that the isolation system provides a reduction of a factor 4 to the accelerations (therefore to the inertial loads) acting at the top of the building during an earthquake which provides the maximum design displacement. Thus, not only the frame but also the contents are better protected from seismic actions.

4.3 Conclusions

The analyses on isolated buildings performed by Bettinali et al. (1996) confirmed the results obtained for the isolated mock-ups (§ 3): in spite of its simplicity, the simplified model of rubber bearing based on the coupling of a multilinear spring and an elastic-plastic beam can be successfully used in the non-linear dynamic analyses of isolated structures.

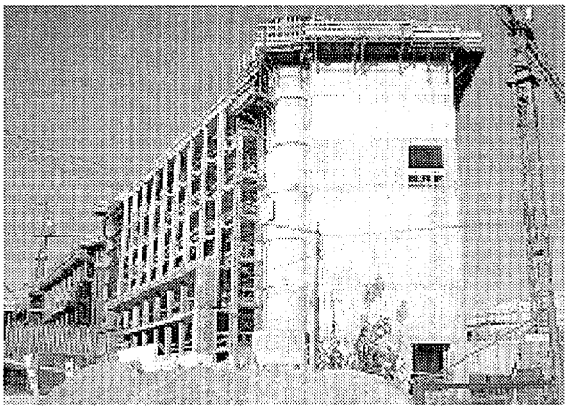

Figure 4.1: Base-isolated building of the TELECOM Italia Center.

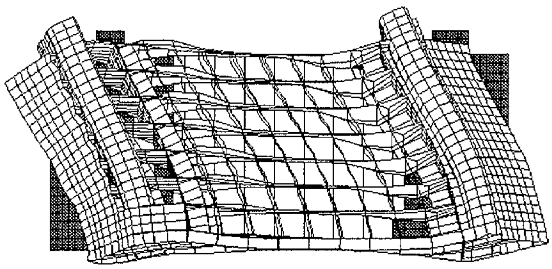

Figure 4.2: 4th modal shape of the TELECOM Italia building.

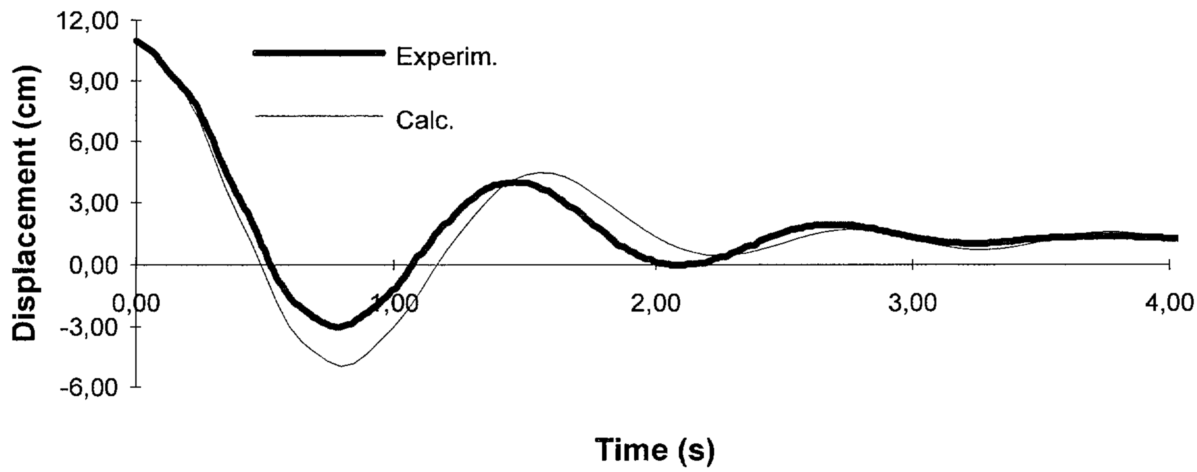

Figure 4.3: Experimental and calculated displacements during the pull-back test at 11 cm on the TELECOM Italia building.

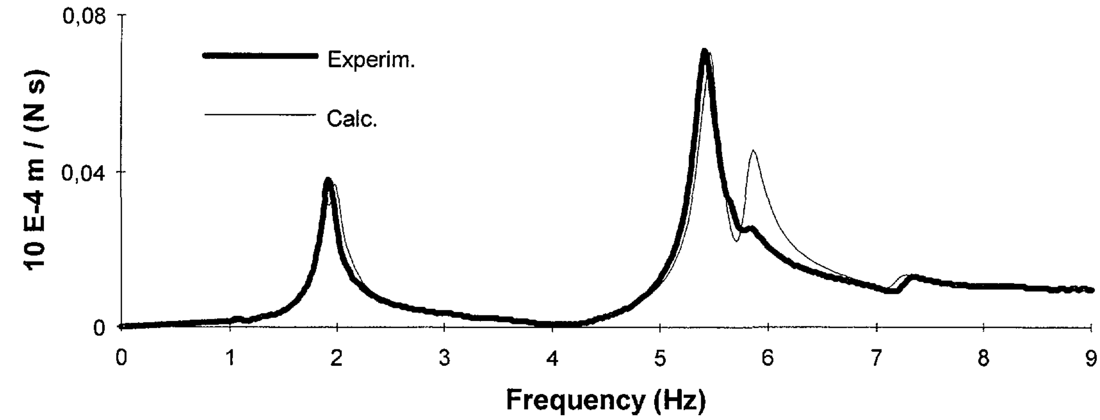

Figure 4.4: Measured and calculated transfer functions between velocity and excitation force in the longitudinal direction at the roof of the TELECOM Italia building.

5. PARALLEL ELASTOPLASTIC MODEL OF HDRBS

5.1 Model description

A parallel elasto-plastic model with exponential constitutive law for seismic isolator, able to represent the nonlinear behaviour has been developed by ENEL and ISMES (Dusi et al., 1999b). The model has been developed considering HDRBs, but it can be adequately applied to other types of isolation devices having a continuously decreasing stiffness with increasing displacement. An example of application of the model to LRBs is reported. The proposed model, implemented in an existing nonlinear finite element computer code, is particularly suited to compute the time history dynamic response of base isolated structures. Its reliability is checked by comparing the numerically computed and experimentally recorder motions of both single devices and different base isolated mock-ups subjected to different earthquake motions on shaking table.

The model proposed in this CRP, assumes a decreasing exponential constitutive law $G(\gamma)$ for the rubber compound; this behaviour has been implemented in the finite element ABAQUS code through a parallel scheme of elastoplastic elements. A peculiar feature of developed model is the capability to reproduce the complex behaviour of HDRBs using only very simple information concerning the rubber compound, without any need of experimental data relevant to tests on actual devices.

The nonlinear model is hysteretic with the following assumptions:

i) tangent modulus with decreasing exponential law, defined through 3 parameters related to the compound, i.e.:

G_∞	G value at design shear strain
G_0	G value at γ=0
b	exponent multiplier;

ii) overall bearing behaviour defined through 2 geometric data: normal area of bearing and total rubber thickness;

iii) no viscous effects, i.e. velocity does not affect the force-displacement relationship.

The assumed $G(\gamma)$ relationship can be expressed by the following two mathematical expressions, valid for a loading and unloading curve, respectively:

$$G_t(\gamma) = \frac{d\tau}{d\gamma} = G_\infty + ae^{-b(\gamma-\gamma_{\min})} \qquad (5.1)$$

$$G_t(\gamma) = \frac{d\tau}{d\gamma} = G_\infty + ae^{-b(\gamma_{max} - \gamma)} \qquad (5.2)$$

where:

$a = G_\infty - G_0$,

γ_{min} = starting strain value for increasing load phase

γ_{max} = starting strain value for decreasing load phase.

Hysteretic curves with continuously decreasing stiffness can be easily discretised using the parallel modelling concept. The above $G(\gamma)$ relationship has been reproduced by means of a set of elasto-plastic elements working in parallel; the parameters of each element in parallel must be calibrated to correctly reproduce the experimental bearing behaviour.

The parallel model previously described is able to reproduce the observed experimental behaviour of HDLRB as far as the maximum shear strain does not exceed a limit value around 100%. A more refined constitutive model was therefore set up to allow for the reproduction of the high shear strain behaviour. This was obtained by putting in parallel to the original model, a second one, whose $G_h(\gamma)$ function has the following expression:

$$G_h(\gamma) = c(e^{d|\gamma|} - 1) \qquad (5.3)$$

where parameters *c* and *d* define slope and curvature of exponential law.

5.2 Example of application

Figures 5.1 shows the comparisons between HDLRBs experimental hysteresis loops (obtained from quasi-static monoaxial tests) and numerical results.

In Figure 5.2 is reported the comparison between experimental and numerical hysteresis loops for a LRB having a diameter of 107 mm, a total rubber height of 15 mm and a lead plug of 12 mm diameter.

The numerical model of elastomeric bearings has been used to reproduce the dynamic behaviour of real base isolated structures subjected to seismic excitation. Different tests carried out using a shaking table have been considered for the validation of the model.

Among other tests, shaking table experiments have been conducted on the above mentioned (§3) Japanese isolated rigid mass. Comparison between recorded and numerical mass accelerations is reported in Figure 5.3. Finally, an example of application to a flexible mock-up, namely MISS (§3) is reported in Figure 5.4.

5.3 Conclusions

Comparisons between experimental tests and numerical analyses show that the numerical model with an exponential constitutive law, implemented through the parallel elastoplastic scheme, is able to reproduce the seismic behaviour of bearings with a high degree of accuracy. Hysteresis loops, multiaxial excitations and hardening effects are accurately reproduced.

The availability of a routine implementing the bearings behaviour inside a commercial available finite element code (ABAQUS) allows the user to perform time histories analyses of isolated structures, simply by defining an element having the same bearing dimension and whose material characteristics (related to the compound parameters) are given in a user subroutine.

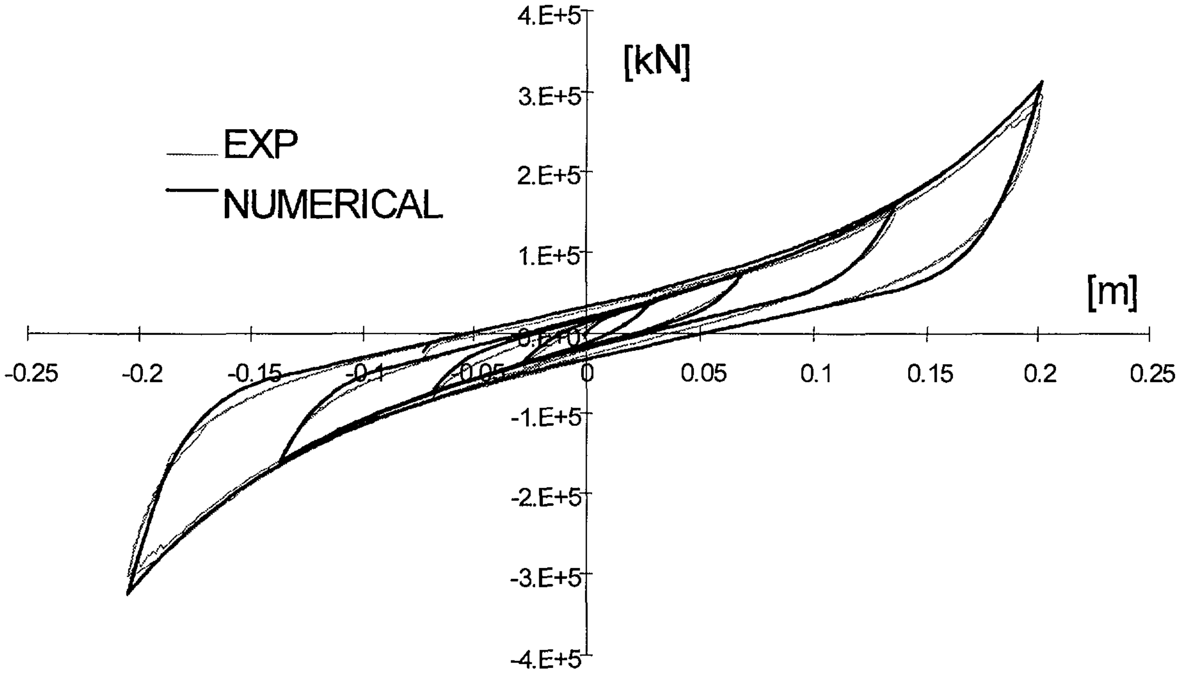

Figure 5.1: Experimental and numerical hysteresis loops for a rigid HDLRB (G = 0.8 MPa).

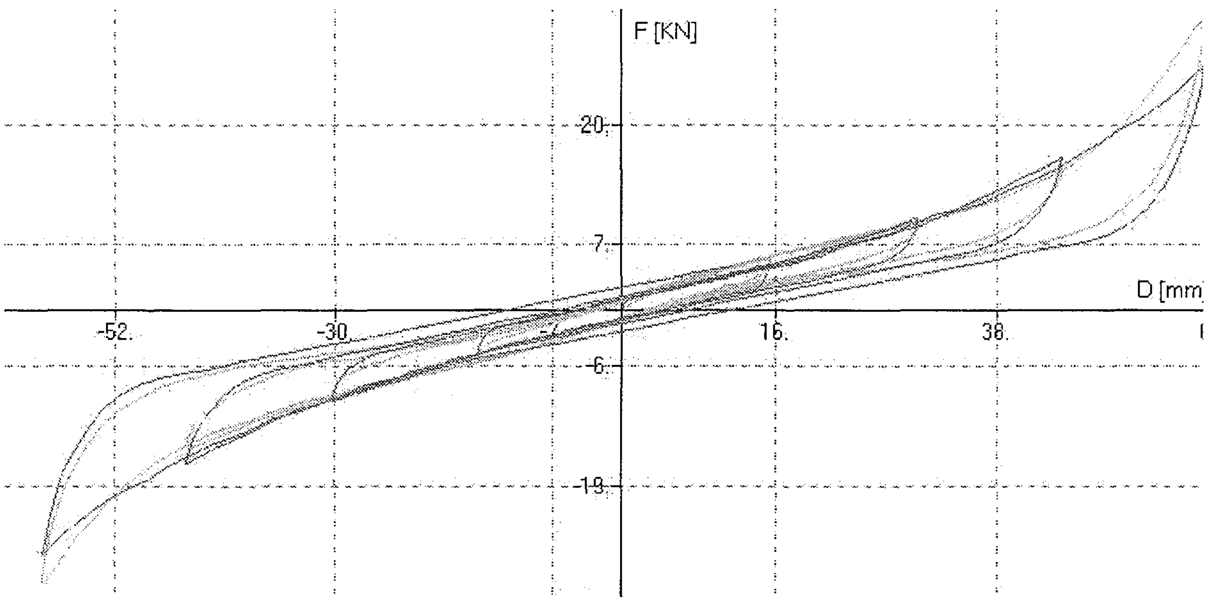

Figure 5.2: Experimental and numerical hysteresis loops for a LRB.

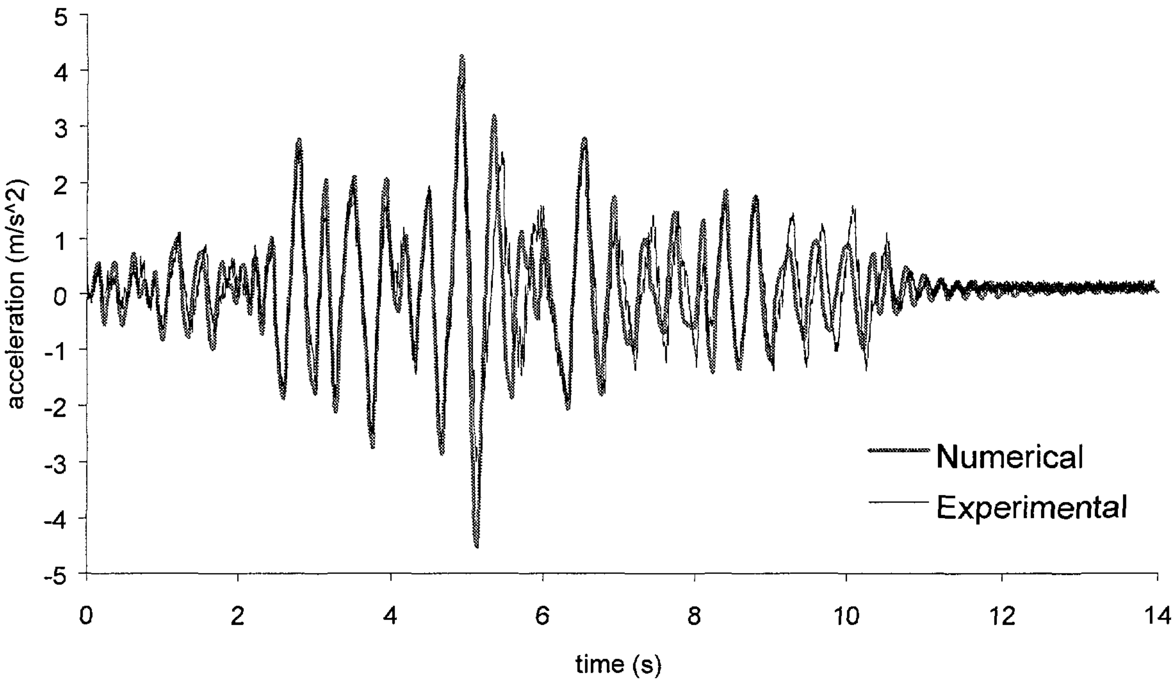

Figure 5.3: Experimental and numerical acceleration of a 179 kN isolated mock-up under the design earthquake record.

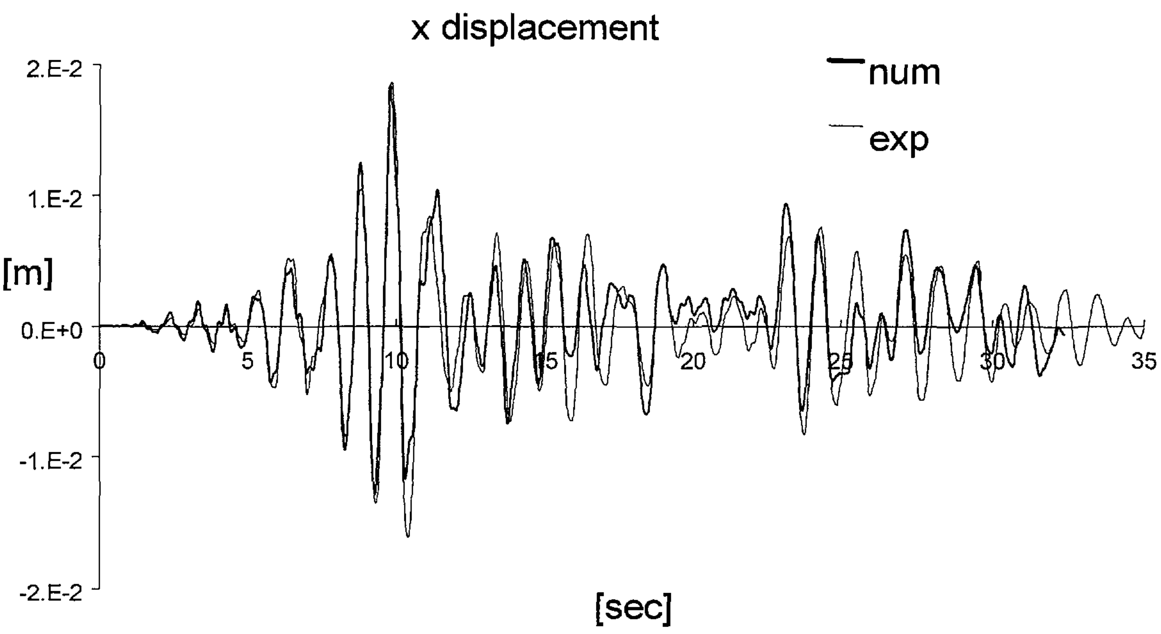

Figure 5.4: Experimental and numerical relative displacement (x component) of a steel frame isolated mock-up under the 1981 Calitri record.

6. BENCHMARK ON THE TORSION OF A ELASTOMERIC CYLINDER

6.1 Introduction

In order to asses the accuracy of both the FE model meshing and FE solver, a torsional benchmark problem was presented jointly by TARRC and ENEL. Prediction of the couple and axial load acting on the cylinder was obtained by ENEL from FE calculations using ABAQUS, and was compared to the analytical solutions for two types of material models, Mooney-Rivlin and Ogden. An extensive numerical work was performed by considering meshes with different refinements and different element types. The results, presented during the RCM Taormina by Fuller et al. (1998), showed an excellent agreement.

6.2 Description of the Activity

The analytical solution to the torsion of an elastomeric cylinder is suggested as a "benchmark" for the finite element analysis of elastomeric components. A general solution due to Rivlin is presented. It can be expressed for the two forms of the strain energy function commonly used to describe the stress-strain behaviour of elastomers — a function of either strain invariants or principal stretch ratio. Hence the accuracy of the FEA predictions, for either form of material model, can be assessed for two commercial FE Codes, namely MARC and ABAQUS. The response of a cylinder to torsional deformation is predicted. The comparison of the FE analysis with an analytical solution rather than experimental data means that the assessment of the FEA is not influenced by the effectiveness of the material model or the reliability of experimental data. Two material models that are available as default in the codes — a five term Mooney-Rivlin function and a three-term Ogden function — are used. The latter is included because of the availability in the literature of both material model data and an analytical solution to the torsion problem for that strain energy function due to Ogden and Chadwick. The FE 3-dimensional analysis for a coarse-mesh model with 500 elements (Figure 6.1) gives results generally within 5% of the analytical solutions for the couple required to deform the cylinder. For the axial load required to keep the height of the cylinder unchanged the errors are up to 10%. However, better levels of accuracy are obtained if the density of the mesh is increased. This is at the cost of much longer computing times.

The second part of the work evaluates two forms of strain energy function for describing the behaviour of high damping natural rubber compounds. The Ogden strain energy function is used to fit experimental data for a range of homogeneous deformations and it was observed that the quality of fit is not very good at small strains. Increasing the number of terms from 2 to 3 does not produce significant improvement. The use of sophisticated non-linear curve fitting algorithms may improve this. A second material model based on the assumption that the strain energy is a function of only one of the strain invariants (I_1) is proposed. It was found not only that a better quality of fit may be obtained but also that such a model can lead to much simpler material characterisation tests.

6.3 Conclusion

Rivlin's general solution to the torsional deformation of an elastomeric cylinder has been used as a "benchmark" problem to assess the accuracy of commercially available FE packages such as MARC and ABAQUS. The generality of the solution allows the prediction of the behaviour of the cylinder whether the stress-strain behaviour of the material is modelled as a function of strain invariants or modelled as a function of principal stretch ratios. The analytical solution thus provides a useful tool to assess the accuracy of the FE solvers.

The FE results using MARC and ABAQUS gave to an accuracy within 5% the couple that is required to twist one end of the cylinder with respect to the other through an angle of θ.

The degree of accuracy was reduced to 10% for the axial load required to keep the height of the cylinder constant. Refining the mesh density improved the accuracy at the cost of much increased computing time.

The use of the Ogden strain energy function to model the behaviour of high damping natural rubber compounds was found to suffer from the disadvantages that fitting the parameters to the experimental data using standard curve-fitting software is difficult, and that this form of function is not flexible enough to allow for the material non-linearity at small strains.

A strain energy function based on the assumption that the energy of deformation depends on I_1 only is proposed. The function is able to cater for material non-linearity both at small and large strains. If a material can be adequately characterised with this form of strain energy function only a simple uniaxial tension test is required to find its coefficients.

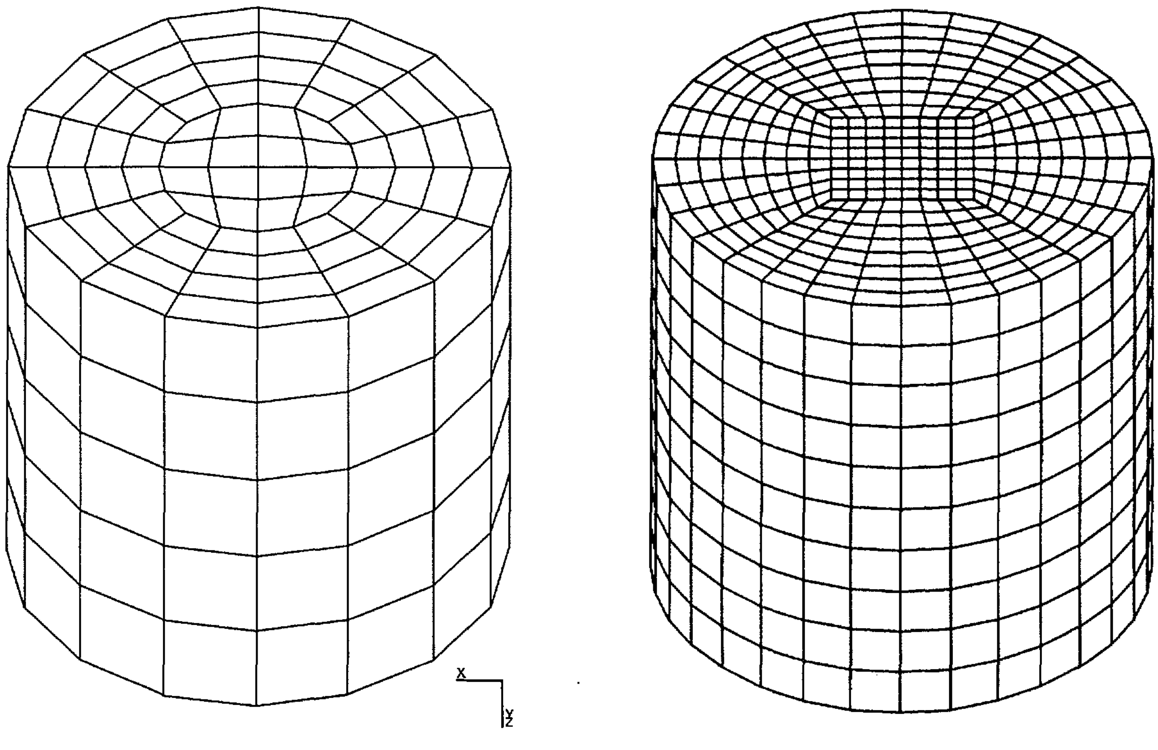

Figure 6.1: FEA models showing coarse-mesh (Models 1,2,5) and refined-mesh (Model 3).

GENERAL CONCLUSIONS

Italy, represented by ENEA, ENEL and ISMES, participated actively in this CRP by providing and analysing experimental test data on both isolation devices and isolated structures. Moreover, test data provided by the others countries were analysed jointly by ENEL and ENEA in order to improve the existing mathematical models and to validate the new models developed within this CRP. In particular, Finite Element (FE) analyses were carried out on U.S. scaled HDRBs that had been manufactured in Italy and tested by University of California at Berkeley; and on Natural Rubber Bearings (NRBs) and Lead Rubber Bearings (LRBs) manufactured in Japan for CRIEPI. The results concerning U.S HDRBs and Japanese NRBs were presented at the Research Coordination Meetings (RCMs) of St. Petersburg and Taormina, while information concerning Japanese LRBs was given at the Hertford RCM. Finally, the results concerning modified Japanese LRBs (with larger lead plug diameter) were presented at the Cheju RCM.

The compression and combined compression and shear behaviour of the bearings were analysed, using different FE models and different hyperelastic strain energy functions, by means of the ABAQUS code. Elastomers' constitutive models, available in the ABAQUS package to represent the non-linear and hysteretic behaviour of bearings, were used to solve the problem. Mooney-Rivlin and Ogden forms with different order of the strain energy function, and, alternatively, user-defined strain energy function, were used in modelling the rubber. Results from different meshes, with different discretisations and different types of elements (axisymmetric, axisymmetric with non axisymmetric deformation, shell and solid) were compared to the experimental data. The choices of the appropriate strain energy function, element selection and FE modelling were examined and their ability to model the behaviour of elastomeric bearings presented and discussed in the report provided to the Agency.

For the Japanese NRBs and LRBs both three-dimensional and axisymmetric finite-element models were developed and implemented in ABAQUS computer program by ENEL, while similar models were developed and implemented in the same code by ENEA for the U.S. HDRBs. Hyperelastic models of the rubber, defined according to the results of suitable tests on both scragged and unscragged rubber specimens, were also implemented in ABAQUS. Extensive numerical work was performed by considering meshes with different refinements and different element types. The numerical analyses, aimed at investigating the effects of the numerous variables of the problem, allowed for optimizing the type of material model, discretization and elements to be adopted, up to large strains.

For the Japanese NRBs, good agreement between numerical and experimental results was found by ENEL for horizontal stiffness (similar to the results of ENEA for the U.S. HDRBs); however, the agreement for compression tests was again satisfactory only when compressibility was taken into account. This confirmed the importance of volumetric tests on rubber specimens to correctly evaluate bearing vertical stiffness, especially in the case of large shape factors. Analysis of ENEL also confirmed that planar tests on specimens shall be performed to very large deformation, in order to allow for the definition of adequate hyperelastic models of the rubber. Moreover, it was found again that the unscragged rubber model should be used for reproducing bearing behavior to 50%–100% shear strain, while the scragged model should be used for larger deformations. Only slight differences were found between the results of 3D and axisymmetric models to 200%–300% shear strain, while 3D models shall be used for larger deformations.

Similar to the analysis performed for HDRBs and NRBs, also for LRBs, numerical analysis of ENEL was found adequate for horizontal stiffness, to 300% shear strain; however, at larger strains the numerical results showed hardening, contrary to test data. In addition, large discrepancy was found between the numerical results and test data for LRBs under compression with different offset strains: this must be attributed again to modeling rubber as incompressible in constitutive equations. Similar to the NRBs, for LRBs, the need was stressed for an improvement of the analyses, based on more precise data concerning the characterization of materials (natural rubber and lead), including effects of rubber compressibility. In addition, an attempt should be made to consider temperature effects on lead behavior.

In any case, the achieved results confirmed again the conclusions of previous studies that FEMs are useful tools for both the detailed design of elastomeric bearings and their qualification; for the latter, they allow for a considerable reduction of the number of tests to be performed (e.g. those concerning effects of parameters like temperature, aging, vertical load on horizontal stiffness, initial or arisen defects, etc.).

In order to asses the accuracy of both the FE model meshing and FE solver, a torsional benchmark problem was presented jointly by TARRC and ENEL. Prediction of the couple and axial load acting on the cylinder was obtained by ENEL from FE calculations using ABAQUS, and was compared to the analytical solutions for two types of material models, Mooney-Rivlin and Ogden. An extensive numerical work was performed by considering meshes with different refinements and different element types. The results, presented during the RCM Taormina, showed an excellent agreement.

Finally, ENEL developed a new non-linear simplified isolator model, with exponential constitutive law describing the rubber behavior. The main features of the model were presented at the Hertford RCM in 1998. The model was implemented as a "User Subroutine" in the ABAQUS FE code. The new model, based on three rubber parameters allows for a very accurate evaluation of the response of seismically isolated structures. Although it was developed for elastomeric bearings, the proposed model can be adequately applied to other types of isolation devices having a continuously decreasing stiffness with increasing displacement (e.g. rubber or helical springs coupled with metallic yielding elements, wire rope friction isolators, etc.). Results of the numerical analyses of isolated structures carried out with the new model were presented by ENEL at the Cheju RCM in 1999.

The activities performed within this CRP allowed a better understanding of the analysis methods for seismically isolated structures, by highlighting the most important items to be taken into account and by evaluating limitations and advantages of different approaches. A better knowledge of numerical methods to predict the response of both isolation devices and isolated structures has been achieved.

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