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CONTRIBUTION OF ITALY TO THE ACTIVITIES ON INTERCOMPARISON OF ANALYSIS METHODS FOR SEISMICALLY ISOLATED NUCLEAR STRUCTURES:

FINITE ELEMENT ANALYSIS OF LEAD RUBBER BEARINGS

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Abstract

This paper presents a summary of the results of nonlinear Finite Element (FE) analyses carried out by ENEL-Ricerca, Hydraulic & Structural Centre and ENEA-ERG-SIEC-SISM, on Lead Rubber Bearings (LRBs). Activities were carried out in the framework of the four years' Coordinated Research Programme (CRP) of the International Atomic Energy Agency (IAEA) on "Intercomparison of Analysis Methods for Seismically Isolated Nuclear Structures".
The bearing Finite Element Models (FEMs) are validated through comparisons of the numerical results with experimental test data. The reliability of FEMs for simulating the behaviour of rubber bearings is presented and discussed.

1. INTRODUCTION

The International Atomic Energy Agency (IAEA) has initiated a Co-ordinated Research Programme (CRP) on the implementation of base-isolation for nuclear structures. As part of the IAEA International Working Group of Fast Reactors (IWGFR) CRP, test data sets relevant to different rubber bearings has been provided for a benchmark problem. Numerical simulations of bearings test data have been carried out by the CRP participants in the first phase of the programme. ENEL-Research, Hydraulic & Structural Centre and ENEA-ERG-SIEC, besides supplying IAEA with experimental data on High Damping Rubber Bearings (Forni et al., 1996), have already performed numerical simulations of Italian HDRBs, USA bearings and Japanese Natural Rubber Bearings (NRBs) for the intercomparison studies, as reported by Dusi et al., 1997. The extensive numerical simulation aimed at investigating the effects of the numerous variables of the problem, has put into evidence which type of material model, discretization and elements have to be adopted in order to obtain a good correlation with the experimental results at very large strains.
In this paper a summary of the results of nonlinear Finite Element (FE) analyses carried out by ENEL and ENEA, on Japanese Lead Rubber Bearings is presented.
Central Research Institute of Electric Power Industry (CRIEPI), Japan, carried out a research project on the application of the seismic isolation technique to the Fast Breeder Reactor (FBR), during which rubber bearing tests as well as shaking table tests of base-isolated model structure were performed.
The LRBs, consisting essentially of a lead insert inside a laminated elastomeric bearing, are usually placed between the structure and its foundations. Their features provide high stiffness in the vertical direction, to support the dead load of the superstructure, and low stiffness in the horizontal plane, thus minimising amplification of ground acceleration, leading, however, to large horizontal

displacements during strong earthquakes.

Although the effectiveness of elastomeric and lead-rubber bearings has been investigated experimentally, very few analytical results has been presented. This is not surprising in view of the fact that lead rubber bearings combine three materials of different properties and behaviours. Most of the difficulties encountered in modelling the behaviour of LRBs result from the material nonlinearity of lead and material and geometric nonlinearities and incompressibility of the rubber part.

For the isolator considered in this paper, analyses have been performed up to very large (even 400%) shear strains, in order to evaluate the behaviour of the bearings in a range close to their failure or instability. Results from finite element analyses have been compared with the experimental ones.

2. BEARINGS CONSIDERED

The isolator considered in the following has been proposed by Japan for the benchmark exercise and is hereinafter referred to as "CRIEPI LRB".

2.1. Geometry and operating data

The bearing proposed by CRIEPI for intercomparison activities (Hirata, 1996) 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 150 tons. Geometry of "CRIEPI LRB" is reported in Figure 1.

2.2. Materials characterization

2.2.1. Rubber

Results of biaxial tests performed on rubber specimens were provided by CRIEPI (Hirata, 1996). The following constitutive equation was used in modelling the rubber (Seki et al., 1987):

$$\frac{\partial W}{\partial I_i} = a_i + b_i(I_i - 3) + c_i(I_i - 3)^2 + d_i(\exp e_i\,(I_i - 3)) \qquad (1)$$

where:

W is the strain energy function;

$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$;

$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2$;

$I_3 = \lambda_1^2\lambda_2^2\lambda_3^2$ ($I_3 = 1$ is assumed).

From biaxial tensile test data fitting, coefficients of the strain energy function (1), were determined by CRIEPI and were provided to the IAEA CRP participants (Figure 2).

The coefficients, determined under the assumption of incompressible material, are as follows:

i	a_i (kg/cm)	b_i (kg/cm)	c_i (kg/cm)	d_i (kg/cm)	e_i (kg/cm)
1	2.09	0.135	0.0024	1.75	-2.12
2	0.138	-0.0164	0.000644	-0.70	-6.44

2.2.2. Steel

The following mechanical properties have been assumed for steel:
Young modulus E = 1.97E06 kg/cm^2, Poisson ratio $\nu = 0.271$, while yield stress σ_y is equal to 2550 kg/cm^2.

2.2.3. Lead

As far as lead plug is concerned, provided a Young modulus E = 1.75E5 kg/cm^2, $\nu = 0.44$, and a yield stress equal to 20 kg/cm^2, the following relationship (Hirata, 1996) was used to model the post yielding behaviour:

$$\sigma_t = 4.0 * (1.0 + 0.096 \log_{10} \dot{e}_t) * e_t^{0.31} \tag{2}$$

where σ_t and e_t are the tensile true stress and true strain respectively and $\dot{e}_t$ is the true strain rate of lead.

2.3. Experimental tests on scaled bearings

Cycling compression tests, with different offset shear strain (0%, 50%, 100%, 200%) were performed under vertical loads up to twice the design value.
Combined compression and shear cyclic tests on bearings were executed with the design vertical load at 20%, 50%, 100%, 200%, 300% and 400% shear strain.
Results provided by CRIEPI are reported in Figures 3 and 4.

3. FINITE ELEMENT ANALYSES

The behaviour of the bearings under vertical load and shear strain was modelled by means of finite element analyses, using ABAQUS, version 5.7 (Hibbitt et al., 1997).

3.1. Material modelling

3.1.1. Rubber

The hyperelastic behaviour of rubber given by (1), has been implemented in the USER Subroutine UHYPER available in ABAQUS. This implementation of the hyperelastic model involved the definition of the hyperelastic energy function *W* and the definition of its first and second derivatives, by making use of the coefficients provided by CRIEPI.

3.1.2. Steel

Based on the values reported in § 2.2.2, an elasto-plastic model with isotropic hardening rule was adopted for steel.

3.1.3. Lead

In the analyses reported below, two different values of strain rate have been used in equation (2) to obtain the stress-strain curves.
By using for the strain rate the value 0.0001 (Lead Model I) and 0.01 (Lead Model II), the

experimental results relevant to the tested bearing were fitted. The plastic behaviour of lead was modelled in ABAQUS by means of a Mises criterion with isotropic hardening. Figure 5 shows the stress-strain curves used in the analyses.

3.2. Finite element discretization

The difficulties encountered dealing with the incompressibility of rubber-like materials were treated by means of a mixed FE formulation. Hybrid elements were used; in these elements the pressure stress is independently interpolated from the displacement field, making the numerical formulation of the variational problem well-behaved. An updated Lagrangian formulation was adopted.

In the present work, three different FE discretizations of the bearing were considered:

1. 3D FEMs were set up to analyse the proposed LRB. The geometry of the devices and the loading conditions make the problem symmetric. Therefore, for 3D cases, only one half of the bearing is modelled, by imposing appropriate boundary conditions on displacements and rotations of the nodes belonging to the plane of symmetry. According to Dusi et al., 1995 and Forni et al., 1995, rubber layers were modelled in ABAQUS with eight-node brick elements (C3D8H), which provide linear displacement and constant pressure interpolations. Steel plates and lead plug were discretized with eight-node elements, reduced integration, linear displacement (C3D8R) and linear triangular prism elements (C3D6);
2. taking into account that the isolator is axisymmetric in the geometry and that the asymmetric deformations can be modelled through Fourier component, axisymmetric FEMs were also considered, by making use of both first and second-order axisymmetric element with nonlinear asymmetric deformation. CAXA4H1 element types were used for rubber, steel shims and lead plug were discretized by means of CAXA41 elements for linear mesh, while CAXA8H1 (rubber layers) and CAXA81 (steel shims and lead plug) were adopted in the second order FE discretization;
3. following the approach proposed by Selvaraj et al., 1997, i.e. by considering that the behaviour of each rubber layer along with the steel plate is similar, a simple model, consisting of only one rubber layer, was used in the numerical analyses. The single layer model made use of solid elements (C3D8H). The model was simultaneously subjected to the bearing's design vertical load and to the shear deformations (up to 400%); results obtained from the numerical simulations has been scaled up by the total number of rubber layers, so as to allow a comparison with the full model. Rubber layer has been modelled using both solid and axisymmetric linear elements.

Different meshes of increasing density were set up for all the different discretizations previously described. Mesh convergence studies were performed in order to find the mesh density needed to achieve viable results. The results reported in this paper refer to meshes having a number of subdivisions along the radius varying from 6 to 10; 16 subdivisions along the external circumference were employed in setting up the models. In all the cases, each rubber layer had three elements through its thickness while each steel shim had only one element through the thickness. In Figures 6 - 7, examples of the FE solid and the axisymmetric FEMs used for the numerical analyses herein reported are shown. Typically, a linear 3D mesh consists of nearly 14000 nodes, while approximately 1800 and 5300 nodes are present in the models using axisymmetric linear and parabolic, respectively. In all cases, pre-processing of the geometry, boundary conditions, materials properties and loads were undertaken using GENESIS, a pre-processor for ABAQUS developed by ENEL-Ricerca, which allows for an easy automatic generation of the rather complicated ABAQUS input file on the basis of a few input data(Dusi et al, 1995).

Continuity at the interface between the lead plug and the rubber part of the bearing was assumed in the first step of the study. In the second phase, extensive numerical simulations have been carried out, using axysimmetric and 3D meshes, considering the effect of sliding at the lead-rubber interface. The contact problem was solved by means of slide line elements.

3.3. FE analyses

Appropriate boundary constraints were applied to the models to simulate the actual service conditions: each bearing was first compressed with the relevant compressive load and then sheared by keeping constant the vertical force until the target value of shear strain was reached.
In order to reproduce the experimental conditions of the bolted device, the FE models assume that the top and the bottom faces of the bearings are constrained to remain parallel. While the base plate nodes are fully constrained, every node of the top plate is tied, by means of *EQUATIONS, to a pilot node located at the centre of the device; either the vertical and the horizontal loads are then applied to this pilot node.

4. RESULTS AND DISCUSSION

Compression test was first analysed using both 3D and axisymmetric models previously described. No sliding effects were taken into account for these numerical simulations. The comparison between the experimental and numerical results, reported in Figure 8, 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. Figures 9 - 13 show the comparison between experimental data and numerical results. The agreement 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).
Results obtained using the same mesh and the two aforesaid stress-strain relationships for lead plug are reported in Figure 9.
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 discretization, (Figure 10), shows that, for the analysed bearing, mesh density has negligible effects in reproducing the shear behaviour of the isolator.
In Figure 11, results obtained using both linear 3D and axisymmetric (first and second order) elements are plotted together with the experimental curve. Numerical values are practically the same for 3D and 2D cases, in spite of a strong difference in the computational time required to run the analyses.
Results obtained using the simple model, consisting of a single rubber layer, well match those obtained from a 3D FEM (Figure 12), 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, Figure 13 reports a comparison between experimental data and numerical simulations obtained considering the effect of sliding at the rubber-lead interface. 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.

From the results obtained in the numerical simulations the following considerations may be drawn:
- compressibility should 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.

Analysis were carried out using ABAQUS 5.7, on an IBM-SP2 parallel computer (RISC 560); in Table I, a comparison among computational CPU time required for running combined compression and shear simulations using the meshes reported in Figures 6 and 7, is reported.

6. CONCLUSIONS

In this paper a summary of the results of nonlinear Finite Element (FE) analyses carried out by ENEL and ENEA, on Japanese Lead Rubber Bearings is presented.
The bearing FEMs are validated through comparisons of the numerical results with experimental test data. The reliability of FEMs for simulating the behaviour of rubber bearings is presented and discussed.
The results presented in this paper for Japanese LRBs, as well as those presented at the Taormina RCM for Japanese Natural Rubber Bearings (NRBs), stress the need for an improvement of the study, for both NRBs and LRBs, based on more precise data concerning the characterisation of material (natural rubber and lead).
The effect of rubber compressibility shall be included. At least an attempt shall be made to also include temperature effect on lead behaviour. This shall be done after a very detailed discussion on the reasons of differences (if any) between the results of the analyses carried out by the various participants using the present data.
In conclusion, the Italian position is that, according to the goals of a CRP, the analyses shall be continued to allow for the aforesaid improvement and better understanding of the parameters affecting the isolator behaviour.

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Combined Compression & Shear Tests

	Shear Strain	3D elements	Axisym. first order elements	Axisym. second order elements	Single Layer Model
Mesh1	25%	1h 10' 22"	6' 28"	27' 42"	
	50%	1h 27' 19"	7' 19"	29' 04"	
	100%	2h 23' 13"	8' 05"	31' 28"	21'
	200%	6h 01' 13"	12' 33"	51' 36"	
	300%	13h 13' 04"	21' 52"	1h 21' 28"	35'
	400%	16h 52' 37	43' 35"	2h 23' 08"	1' 11"

Table I. Comparison among computational CPU time required for running combined compression and shear simulations

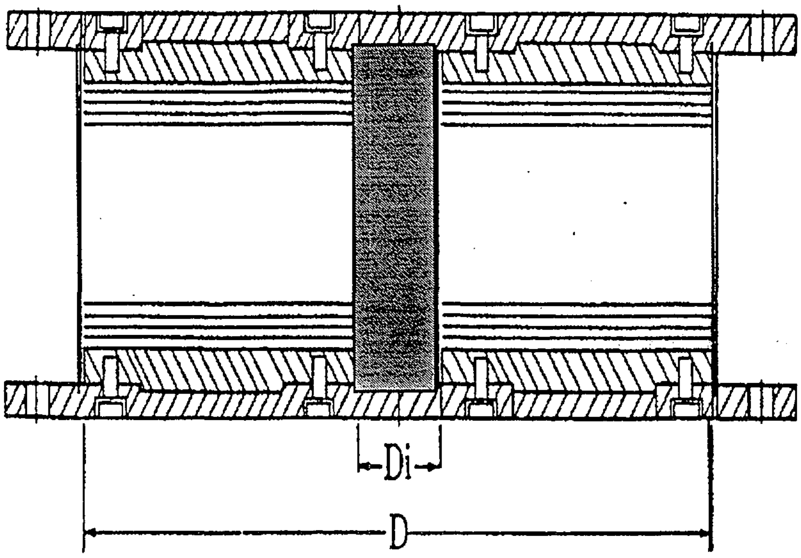

Figure 1. Sketch of the 1:1.83 scale prototype of the CRIEPI LRB

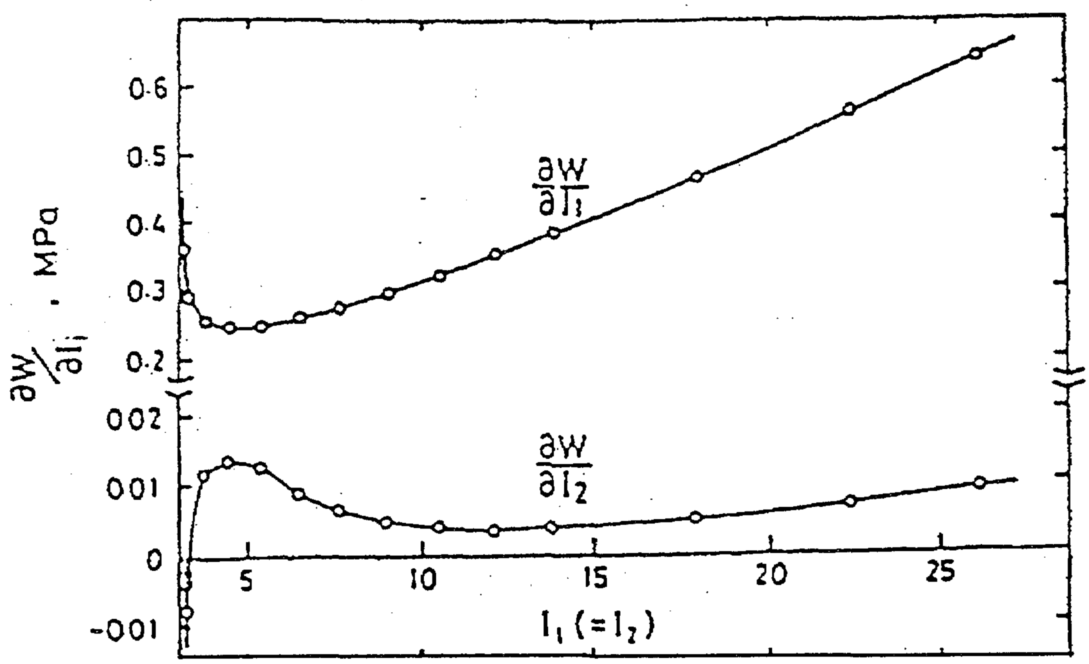

Figure 2. Strain energy density function

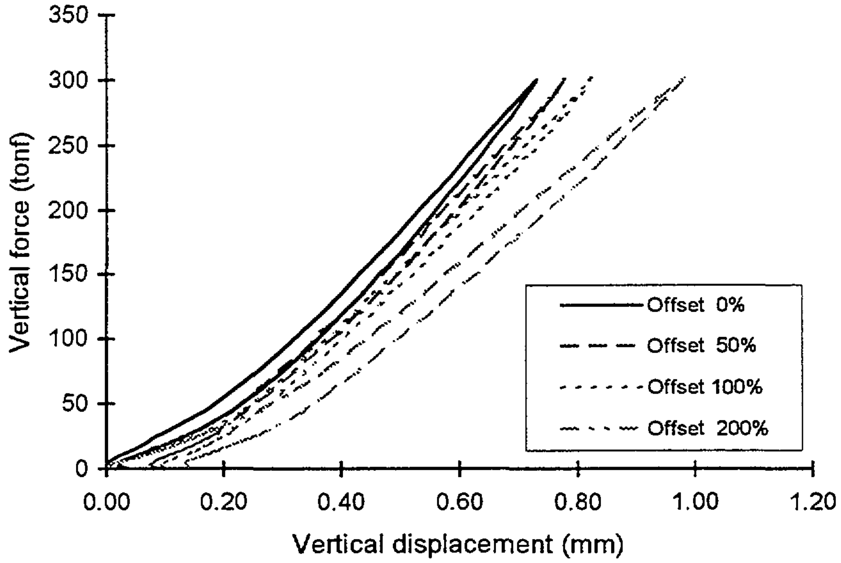

Figure 3. Compression test with different offsets shear strain on CRIEPI LRB

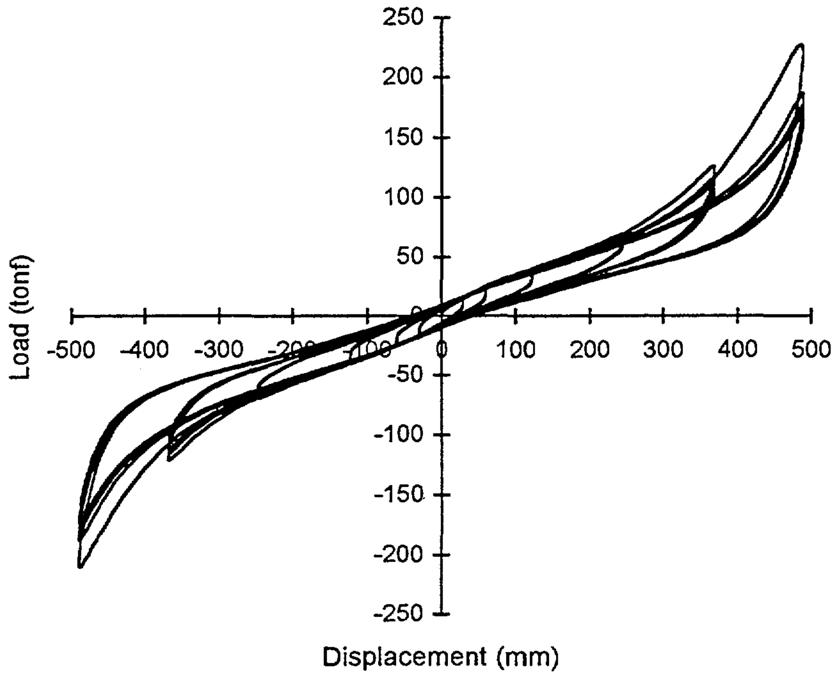

Figure 4. Combined compression & shear strain tests on CRIEPI LRB

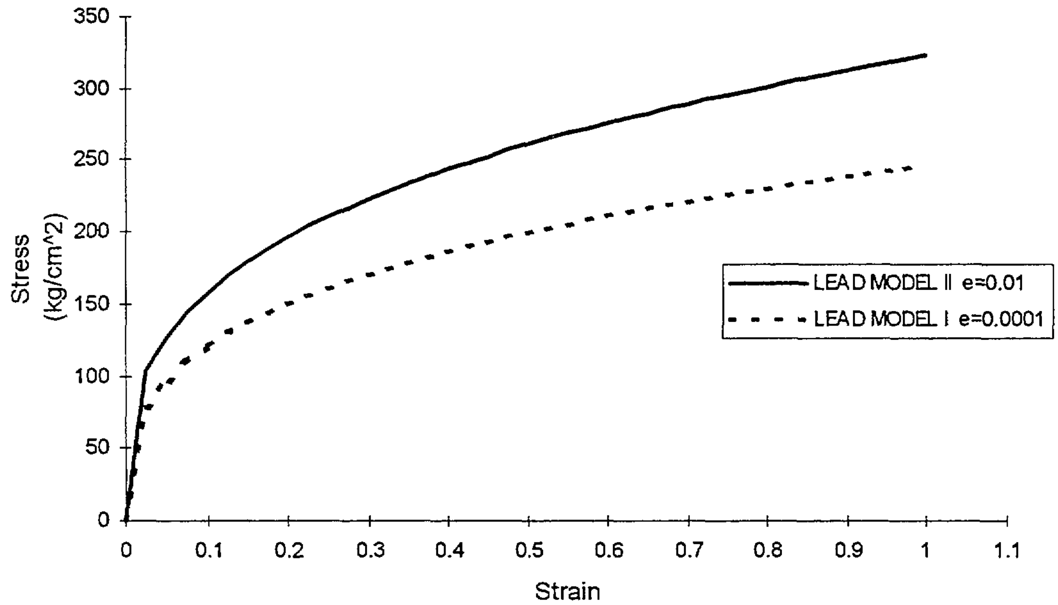

Figure 5. Stress-strain curves of lead plug

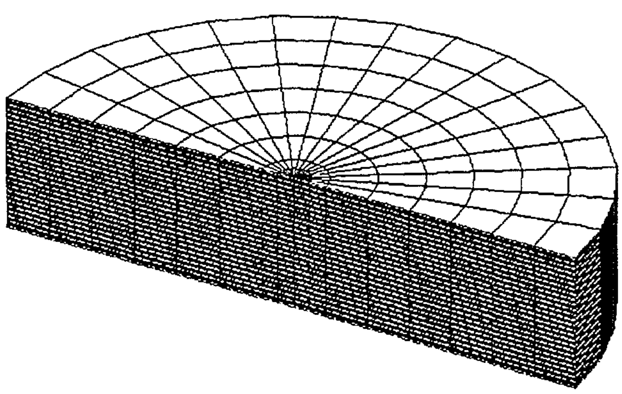

Figure 6. 3D mesh of CRIEPI LRB

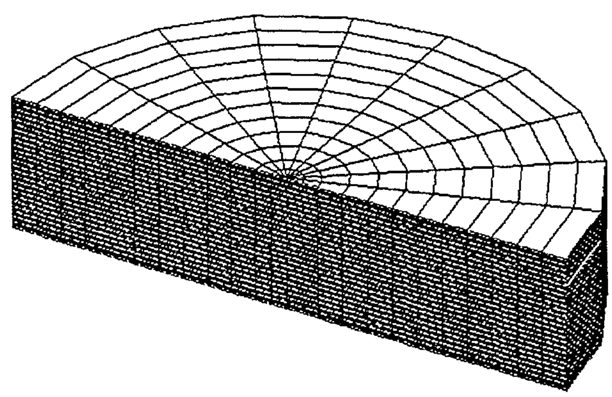

Figure 7. Asisymmetric mesh of CRIEPI LRB

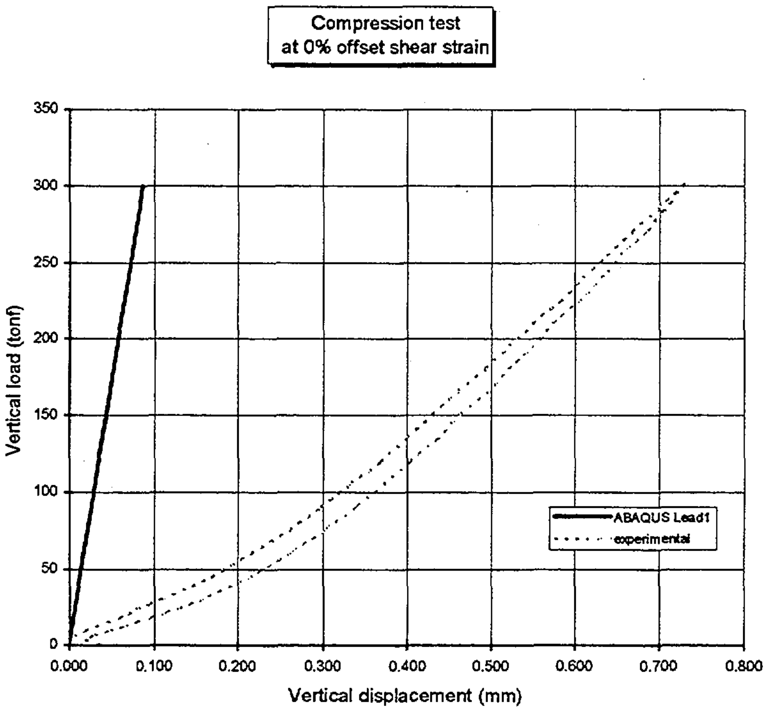

Figure 8. Comparison between experimental and numerical vertical stiffness at 0% offset shear strain

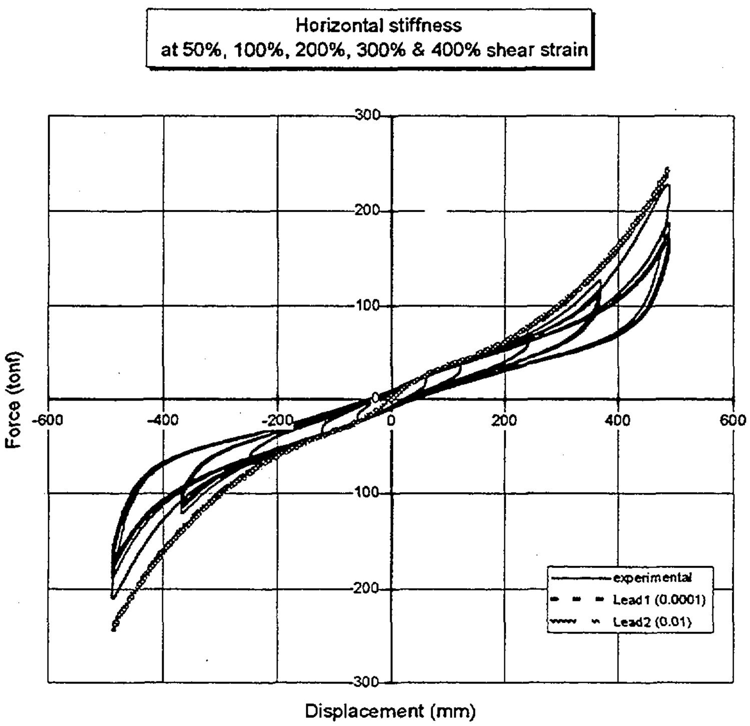

Figure 9. Comparison between experimental & numerical horizontal stiffness: results obtained using the same mesh and two different lead characterisations

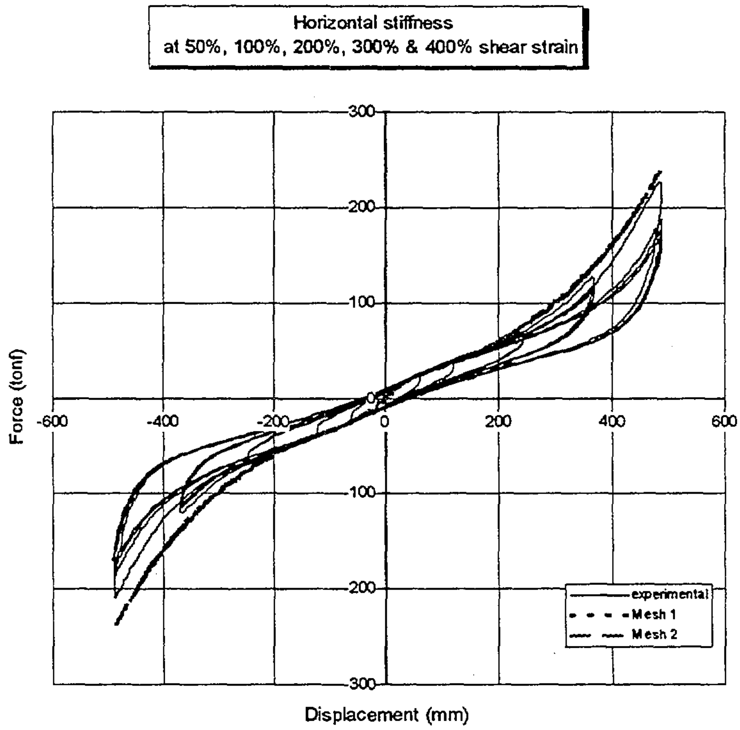

Figure 10. Comparison between experimental & numerical horizontal stiffness: results obtained using two different meshes

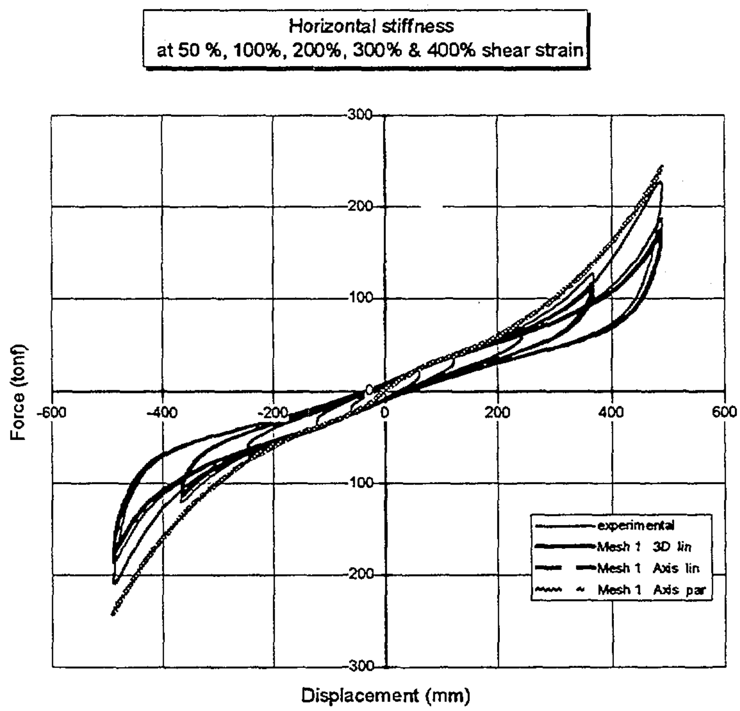

Figure 11. Experimental & numerical horizontal stiffness: results obtained using 3D and axysimmetric elements

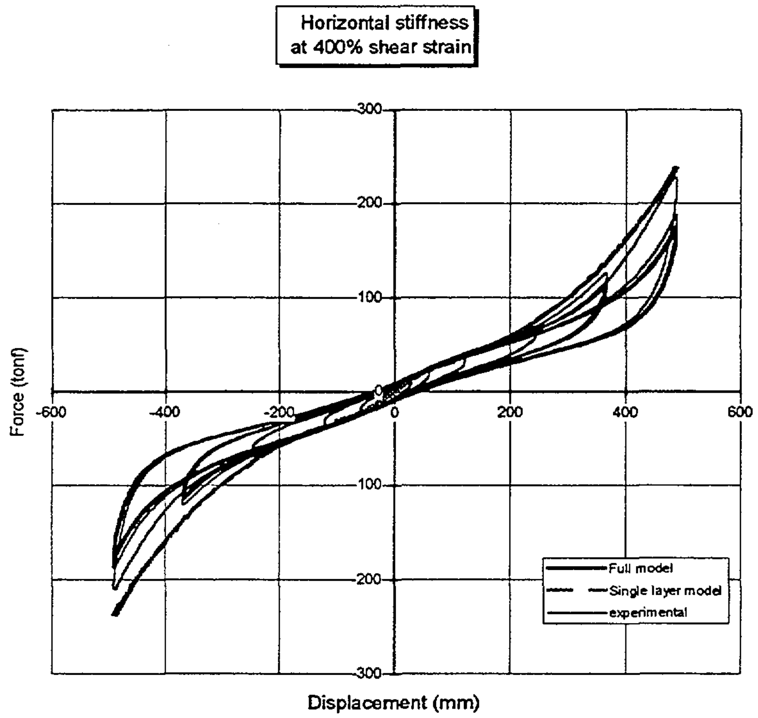

Figure 12. Experimental & numerical horizontal stiffness: results obtained using the single rubber layer model and 3D FEM

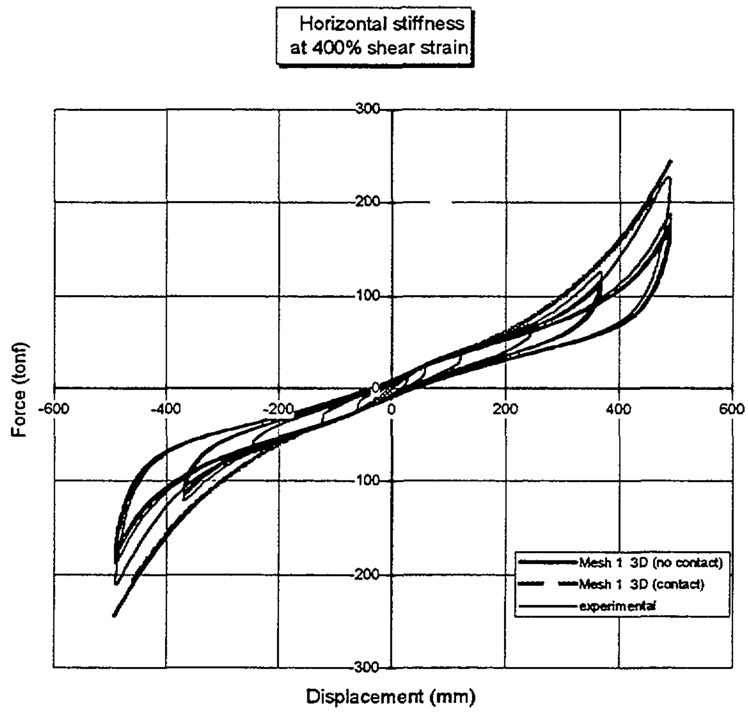

Figure 13. Experimental & numerical horizontal stiffness: results obtained considering the effect of sliding at the rubber-lead interface