

Mechanical and thermo-mechanical response of a lead-core bearing device subjected to different loading conditions

Todor Zhelyazov^{1,*}, Rajesh Rupakhety², and Simon Olafsson²

¹Technical University of Sofia, 8 Kliment Ohridski blvd, Sofia 1000, Bulgaria

²University of Iceland, Earthquake Engineering Research Centre Austurvægur 2a, 800 Selfoss, Iceland

Abstract. The contribution is focused on the numerical modelling, simulation and analysis of a lead-core bearing device for passive seismic isolation. An accurate finite element model of a lead-core bearing device is presented. The model is designed to analyse both mechanical and thermo-mechanical responses of the seismic isolator to different loading conditions. Specifically, the mechanical behaviour in a typical identification test is simulated. The response of the lead-core bearing device to circular sinusoidal paths is analysed. The obtained shear displacement – shear force relationship is compared to experimental data found in literature sources. The hypothesis that heating of the lead-core during cyclic loading affects the degrading phenomena in the bearing device is taken into account. Constitutive laws are defined for each material: lead, rubber and steel. Both predefined constitutive laws (in the used general-purpose finite element code) and semi-analytical procedures aimed at a more accurate modelling of the constitutive relations are tested. The results obtained by finite element analysis are to be further used to calibrate a macroscopic model of the lead-core bearing device seen as a single-degree-of-freedom mechanical system.

1 Introduction

The lead-rubber bearing is one of the most promising developments in the field of base isolation [5, 6].

Base isolation devices have been increasingly used around the world, specifically in New Zealand, Japan, USA and Italy, in the construction of bridges, large structures and residential buildings.

The lead-core rubber bearing is inherently an elastomeric bearing that is modified by placing a lead plug down its centre.

The lead-plug yields relatively quickly under shear deformation and LCR bearing is then seen to have well-pronounced hysteresis response under cyclic loading paths.

When the lead-core bearing is subjected to repeated loading, the effects of heating of the lead plug should be taken into account because it has reportedly degrading effects on the mechanical properties of the isolator [7, 8, 9].

The lead-core bearing device is considered as a multiple component system. Material models are defined for all the compounding materials – rubber, lead and steel.

In the numerical simulations, the lead-core bearing device is subjected to a time-dependant kinematic excitation.

2.1 Rubber

A Neo-Hookean material model is employed to simulate the hyperelastic response of the rubber. The constitutive relations for rubber are derived from a strain energy potential of the following form:

$$W = \frac{G}{2} (\bar{I}_1 - 3) + \frac{1}{d} (J - 1)^2 \quad (1)$$

In equation (1) G stands for the initial shear modulus of the material and \bar{I}_1 is the first deviatoric strain invariant [5]:

$$\bar{I}_1 = J^{-2/3} \sum_{i=1}^3 \lambda_i^2 \quad (2)$$

where λ_i are principal stretches and $d=2/K$ with K -the initial bulk modulus of the material which for an isotropic material has the form:

$$K = \frac{E}{3(1-2\nu)} \quad (3)$$

In equation (3) ν is the Poisson's ratio.

J that is defined as the determinant of the deformation gradient:

2 Material models

* Corresponding author: todor.zhelyazov@tu-sofia.bg

$$J = \det(F_{ij}) \quad (4)$$

2.2 Lead-core

The lead-core is seen to have elastic-plastic behaviour with hardening after yielding [6, 7 8]. More precisely, bilinear isotropic hardening is used (i.e., the yield surface expands uniformly in all directions with plastic flow).

The yield criterion is generally defined as a scalar function of the stress and internal variables (ξ):

$$f(\sigma, \xi) = 0 \quad (5)$$

For isotropic hardening the yield criterion takes the form:

$$f(\sigma) - \sigma_y(\xi) = 0 \quad (6)$$

Alternatively, a fictitious 1-D model of the lead plug is defined. The boundary conditions for the fictitious model are taken from the transient numerical analysis. The fictitious configuration is used to implement a damage-based model for the lead core. Thus, the constitutive relations can be derived from the following state potential [9]:

$$\psi = \frac{1}{\rho} \left[\frac{1}{2} a_{ijkl} \varepsilon_{ij}^e \varepsilon_{kl}^e (1 - D) + R_\infty \left(r + \frac{1}{b} e^{(-br)} \right) + \frac{X_\infty \gamma}{3} \alpha_{ij} \alpha_{ij} \right] \quad (7)$$

In equation (6) ρ stands for the material density, a_{ijkl} is the elasticity tensor, ε_{ij}^e - elastic part of the strain tensor, D denotes the damage variable, R_∞ and b are material parameters characterizing isotropic hardening, X_∞ and γ which characterize kinematic hardening, α_{ij} is the stress tensor associated with the back stress X_{ij}^D .

The law of elasticity coupled with damage reads:

$$\sigma_{ij} = \rho \frac{\partial \psi}{\partial \varepsilon_{ij}} = a_{ijkl} \varepsilon_{kl}^e (1 - D) \quad (8)$$

Upon further customization of the finite element software, this procedure can be further optimized in order to reduce the computational resources and to minimize the computational time.

2.3 Steel

Generally speaking, the mechanical response of steel can be simulated by assuming isotropic or kinematic hardening after yielding. However, yield stress is not usually reached in the steel components of a lead-core bearing device. Taking into account these considerations, steel is assumed to have linear elastic response.

3 Finite element model and mesh generation

Solid 95 is used to mesh the steel shims, as well as for the upper and for the lower thick steel plates. This finite element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions.

Solid186 – a 3-D 20-node solid element that exhibits quadratic displacement behavior is used to mesh the volumes created for the rubber layers. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The finite element is chosen because of the supported mixed formulation capability for simulating deformations of fully incompressible hyperelastic materials.

In order to study the thermos-mechanical response of the lead core, the coupled field finite element: Solid226 a 3-D 20 node coupled-field solid has twenty nodes with up to five degrees of freedom per node is used.

In order to avoid spurious rigidity in the simulated mechanical response, the full integration option is suggested for the finite element analysis.

The employed finite element types are summarized in Table 1.

Table 2. Finite element types.

Finite element type:	Used for:
Solid 95	Steel elements
Solid 186	Rubber
Solid 226	Lead - core

Two test cases are studied. For each case an accurate and explicit 3-D model is built.

3.1 Test case 1

The generated finite element mesh is displayed in Figure 1.

The existing symmetries are taken into account and a half-model spaced is studied. Appropriate boundary conditions are defined on the plane of symmetry ($y=0$).

Nodes on the bottom surface ($z=-25$) are restrained, i.e., displacement along the x -, y - and z -directions of the nodal coordinate system are set to zero.

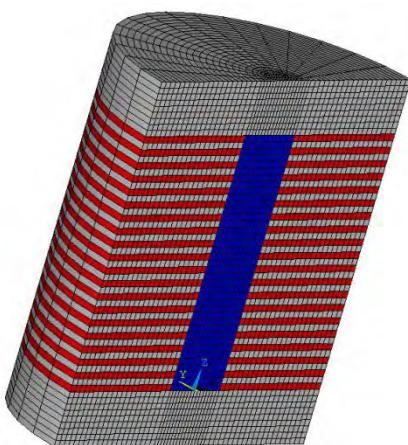


Figure 1. Finite element mesh. A half-model space: top and bottom thick steel plates, as well as steel shims – in grey, rubber layers – in red and lead plug – in blue.

The half-model space contains a total of 24624 finite elements: 14160 Solid95 finite elements, 6720 Solid186 finite elements and 3744 Solid226 finite elements.

3.2 Test case 2

Simulation of the mechanical response of a 356 x 356 mm lead-core rubber bearing that contains seven steel plates 3 mm in thickness each and six 16 mm rubber layers [11].

A total of 39866 finite elements are employed to mesh the quarter-space finite element model: 7658 Solid95 finite elements are used for the steel plates, 26256 Solid186 finite elements – for the rubber layers and 5952 Solid226 finite elements for the lead core.

Nodes on the bottom surface ($z=0$) are restrained, i.e., displacement along the x -, y - and z - directions of the nodal coordinate system are set to zero.

The finite element mesh is displayed in Figure 2.

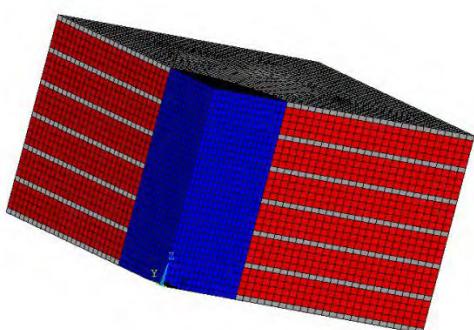


Figure 2. Finite element mesh. A quarter-model space: steel plates are plotted in grey, rubber layers – in red and lead plug – in blue.

4 Finite element analysis

Time dependant displacements are applied to nodes at the top surface (nodes for which $z=142$ mm for test case 1 and nodes for which $z=117$ for test case 2).

The time-dependant kinematic excitation is defined as an array that contains the discrete values of the displacements applied to node on the top surface of the bearing device.

To recover the experimental data in [11], the lead-core bearing device (Test case 2) is loaded by using sinusoidal paths of amplitude 120 mm and of frequency of 0.9Hz (Figure 3).

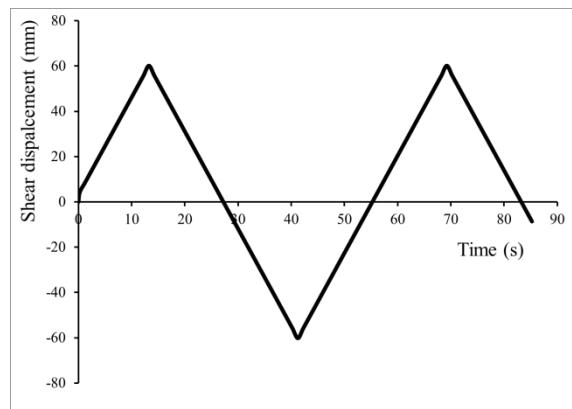


Figure 3. Displacements applied to nodes on the top surface to simulate a typical identification test.

A transient analysis is then performed.

4 Concluding remarks

The mechanical and the thermo-mechanical responses of a lead-core bearing device subjected to different loading conditions have been studied.

Explicit 3-D finite element models have been created for bearing devices of different geometries (test case 1 and test case 2).

Numerical simulations of the mechanical behaviour of the bearing devices to sinusoidal paths of the shear displacement accompanied by vertical load have been carried out.

A coupled-field analysis has been performed in order to study the reportedly degrading effect of the temperature on the mechanical performances of the bearing device subjected to cyclic loading.

References

- W. H. Robinson, and A.G.Tucker, Bulletin of the New Zealand National Society for Earthquake Engineering, pp.151-153 10, 3 (1977)
- R. Park and R. W. G. Blakeley, Structures Committee Summary 3, Road Research Unit, National Roads Board, New Zealand (1978)
- M. C. Constantinou, A. Whittaker, *Technical Report MCEER-07-0012*; Multidisciplinary Center for Earthquake Engineering Research, State University of New York at Buffalo: Buffalo, NY, USA (2008)
- I. V. Kalpakidis, M. C. Constantinou, J. Struct. Eng., pp. 1450–1461 135 (2009)

5. I. V. Kalpakidis, M. C. Constantinou, A. S. Whittaker, Eng. Struct. Dyn., pp. 1533–1549 **39** (2010)
6. Crisfield M. A., *Non-Linear Finite Element Analysis of Solids and Structures. Volume 2: Advanced Topics* (John Wiley & Sons, Chichester UK, 1979)
7. Hill R., *The Mathematical Theory of Plasticity* (New York: Oxford University Press, 1983)
8. Rice, J. R., Continuum mechanics and thermodynamics of plasticity in relation to microscale deformation mechanisms. *Constitutive Equations in Plasticity* (Ed. A. Argon. Cambridge, MA :MIT Press, 1975. 23-79).
9. J. L. Chaboche, International Journal of Plasticity **5**, 3 247-302 (1989)
10. Lemaitre J., *A Course on Damage Mechanics* (Springer, 1996)
11. R. I. Skinner, R. G. Tyler, A.J. Heine and W.H. Robinson, Bulletin of the New Zealand National Society for Earthquake Engineering, pp. 22-36 **13**, 1 (1980)