Hydraulic and Civil Engineering Technology VIII
M. Yang et al. (Eds.)

doi:10.3233/ATDE230696

Modeling the Response of a Lead Core Rubber Bearing for Seismic Isolation

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Abstract. Lead core rubber bearings are among the commonly used devices for seismic isolation of buildings and structures. They are a part of the so-called base isolation meant to decouple the superstructure from the ground, thus modifying the structure's fundamental period and mitigating damage to structural and non-structural elements. Many insightful models have contributed to a better understanding of the lead core rubber bearings response considered as a separate unit or components of a seismically protected structure. However, the available models can still be enhanced. Furthermore, prediction of the dynamic structural response always offers, in most cases, unique problems; the incorporated models of the devices for seismic isolation play a crucial role in such a context. The article discusses an approach to predict the lead core rubber bearing response considered as a separate unit. To this end, the needed constitutive relations are defined on the material scale. The behavior of the isolator is then studied by transient finite element analysis. Both ready-to-use material models and original procedures (being developed) are considered. Additionally, some features of a data-driven algorithm designed to predict the response of a lead core rubber bearing are outlined.

Keywords. Lead core rubber bearing, finite element analysis, multilayer perceptron.

1. Introduction

Base isolation is a widely accepted technique often employed to mitigate the damage induced in structures and structural elements during an earthquake. The disastrous earthquakes that struck recently demonstrated that the resilience of buildings and structures is a sensitive problem that needs attention. First of all, the seismically protected built environment is a prerequisite to saving human lives. Some buildings and structures (e.g., hospitals, power plants, schools, bridges, etc.) require specific preventive attention to overcome the disasters' aftermath without interruption in addressing societal needs. It should also be emphasized that critical structures such as nuclear power plants must be equipped with seismic isolation to avoid massive environmental pollution that is among the potential consequences of a strong earthquake.

The main purpose of base isolation is to decouple the superstructure from the ground, thus minimizing the damage induced in structural elements during a strong

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ground motion. Lead core Rubber Bearings (LRBs) and Friction-Pendulum Systems (FPS) are the most commonly used devices for base isolation. The contribution discusses some aspects of the LRBs' behavior modeling, and friction-pendulum systems remain out of the scope. To the author's knowledge, LRBs have been used first in New Zealand [1, 2]. An LRB generally consists of rubber layers separated by steel shims; the rubber layers ensure the desired horizontal deformability and restoring capability of the device, whereas the steel shims provide resistance to vertical loads. The lead core, typically mounted in a central hole, enhances the energy dissipation capacity of the device when the structure is subjected to time-dependent horizontal loads. For example, under cyclic loading, the fast onset of the lead-core yielding results in well-pronounced hysteresis loops. Furthermore, previous research works report no or minor damage is detected in the lead core after a certain period of exploitation. A conceptual scheme of the LRB is shown in figure 1: rubber layers (1), steel shims (2), a lead core (3), and thick steel plates (4).

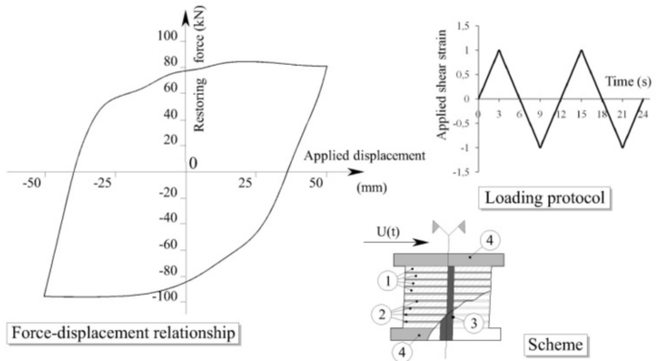

Figure 1. A force-displacement relationship, obtained by finite element analysis, a **t**ypical scheme of an LRB, and a tentative loading protocol.

The first models describing the LRB's mechanical response are the smooth bilinear model [3] and the Ramberg-Osgood model. These models postulate a skeleton curve and define the hysteresis variable evolution separately. The skeleton curve provides a relationship between the current horizontal displacement and the shear force generated in the bearing. Approaches referred to as "differential equation models" [4, 5] have also been proposed. More sophisticated relationships have been formulated to incorporate the contributions of multiple interacting failure/resistance mechanisms: modification of the behavior resulting from the temperature increase [6, 7], strength degradation [8, 9], and strain hardening [10].

The above-mentioned approaches are based on the approximation of the physical phenomena assumed to underlay the mechanical and thermo-mechanical behavior of the LRB. A recent trend is the implementation of machine learning techniques to derive relationships between crucial quantities (e.g., in-plane displacement and restoring force) based on available data without recurrence to the physics of the considered problem.

The contribution outlines an approach in which the constitutive relationships are postulated at the material level to define the involved competitive resisting mechanisms and predict the global response of the seismic isolator. Ready-to-use material models and original procedures (to be incorporated in the finite element analysis) are considered. Additionally, some elements of a machine learning algorithm, more precisely, a multilayer perceptron designed to predict the LRB's mechanical response to different loading conditions, are also presented.

2. The Finite Element Model

A transient dynamic analysis has been employed for the numerical simulations based on the defined boundary conditions, initial conditions, and material models. A rate-independent plasticity model is employed for the lead core, the steel shims, and the top and bottom steel plates, assuming isotropic hardening after yielding [11] and using appropriate material properties for different materials. The mechanical response of the rubber has been modeled using the Mooney-Rivlin model. As an alternative, the Neo-Hookean model can be employed.

Integration of numerical procedures taking into account the rise in the temperature that might occur during a strong ground motion when the LRB is "activated" is forthcoming.

The global response of an LRB in terms of the numerically obtained force-displacement relationship is depicted in figure 1. This result is produced in the simulation of a characterization test in which uni-directional time-dependent displacements are applied to the top surface of the LRB, whereas the bottom surface is fully fixed. The loading protocol is also presented in figure 1. In the subsequent stages of this research, alternative loading sequences, such as applied in-plane displacements on the top surface, will also be considered. Additionally, the LRB response to a seismic signal (time-history analysis using recorded acceleration time series) is a subject of ongoing research; however, it remains out of the scope of this contribution.

All the models mentioned above are ready-to-use procedures available in the employed general-purpose finite element code. Original procedures (to be integrated into the finite element analysis) are also being developed to get more insight into the dynamic behavior of the seismic isolator.

3. A Damage-based Model for the Lead-core

As an alternative constitutive relation for the lead core, a rate-independent model presuming a coupling between plasticity and damage can be employed. An original procedure is being developed based on the theory presented in [12]. The implementation of the procedure into the finite element analyses and simulations of the LRB response is forthcoming.

The total strain is split into elastic and plastic components:

$$\varepsilon = \varepsilon_e + \varepsilon_p \,. \tag{1}$$

Subscripts e and p denote the elastic and the plastic components of the strain tensor ε. Classically, the von Mises equivalent stress is defined by the following expression,

$$\sigma_{eq} = \sqrt{\frac{3}{2}\sigma_{ij}^{D}\sigma_{ij}^{D}} \,, \tag{2}$$

where σ_{ij}^{D} denotes the deviatoric part of the stress tensor. The yield criterion can be then formulated

$$f=\left(\sigma_{ij}^{D}-X\right)_{eq}-R-\sigma_y<0 \quad \rightarrow \quad \text{elastic response,}$$
$$f=\left(\sigma_{ij}^{D}-X\right)_{eq}-R-\sigma_y=0 \quad \rightarrow \quad \text{plastic flow,} \tag{3}$$

with $\left(\sigma_{ij}^{D}-X\right)_{eq}=\sqrt{\frac{3}{2}\left(\sigma_{ij}^{D}-X\right)\left(\sigma_{ij}^{D}-X\right)}$; X denotes the kinematic strain hardening, R - isotropic strain hardening, and σ_y is the material yield stress. The plastic strain rate is defined as follows

$$\frac{d\varepsilon_p}{dt}=\frac{d\sigma/dt}{X_\infty\gamma+b\left(R_\infty-R\right)-\gamma X sgn\left(\sigma-X\right)}, \tag{4}$$

X_∞ , γ , b , and R_∞ , are model parameters (to be identified through comparison against experimental data); $sign(\bullet)$ denotes the signum function: for a given variable q ,

$$sgn(q)=\begin{cases}-1 & if \quad q<0 \\ 0 & if \quad q=0 \\ 1 & if \quad q>0\end{cases}. \tag{5}$$

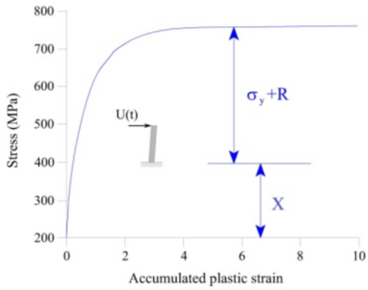

Figure 2. Stress evolution after yielding without damage accumulation.

Stress evolution in function of the accumulated plastic strain is shown in figure 2. The figure illustrates the decomposition of the stress developed after yielding into back stress, (labeled X), relative to kinematic hardening, and a component R , associated with isotropic hardening.

Damage accumulation is quantified by assuming an elastic-perfectly plastic material response. It is presumed that kinematic hardening and isotropic hardening have already occurred and have been already saturated. The damage variable, D , is computed as follows:

$$\frac{dD}{dt}=\frac{\sigma_s^2}{2ES}R_v\frac{d\varepsilon_p}{dt}. \tag{6}$$

In equation (6), σ_s and S are material characteristics that should be defined based on a comparison with experimental data. The latter is referred to as "the energy strength of damage," and E stands for the elasticity modulus of the undamaged material; R_v is the triaxiality ratio.

Furthermore, it is assumed that damage accumulation onset can be linked with the following threshold

$$\frac{dD}{dt} = 0 \text{ if } \varepsilon_p \le p_D, \qquad \frac{dD}{dt} > 0 \text{ if } \varepsilon_p > p_D. \tag{7}$$

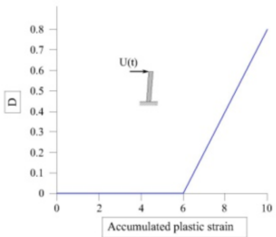

Figure 3. The damage variable evolution.

The damage threshold p_D should also be experimentally identified. A damage variable evolution obtained using a surrogate uni-directional model of the lead core is plotted in figure 3. This result contradicts the reported data that no damage accumulates in the lead core after an intensive sequence of horizontal loading, such as a strong ground motion. The conclusion can be drawn that damage accumulation in LRBs deserves additional research attention to adequately quantify the remaining resources after a given period of exploitation.

4. Data –driven Models

Data-driven models are generally used to extract dependencies between different quantities using deep learning techniques and abundant databases without reference to known relationships commonly employed to define the physics of the considered problems. Among the available data-driven models are Kriging, multilayer perception, and neural networks with a gated recurrent unit.

A tentative artificial neural network (ANN) is being developed. It contains one input layer, several hidden layers, and one output layer. The neurons in the hidden layers are provided with the widely used Rectified Linear Unit (ReLU) activation function, which results in the nonlinear overall behavior of the algorithm. Typically,

$$z_j^{(i)} = \eta\left[\left(W^{(i-1)}\right)^T \Omega + b_j^{(i)}\right], \qquad \eta(x) = \begin{cases} 0 & if \quad x \le 0 \\ x & if \quad x > 0 \end{cases}, \tag{8}$$

where $z_j^{(i)}$ denotes the j-th neuron belonging to the i-th hidden layer, $\eta(\bullet)$ is the activation function (ReLU), $W^{(i-1)}$ is an array containing the weights of the connections of the considered neuron with all the neurons from the previous layer, superscript T denotes the transpose operation, Ω is an array containing the outputs of the neurons from the previous layer transferred to $z_j^{(i)}$, and $b_j^{(i)}$ is the bias of $z_j^{(i)}$.

Initially, each neuron from the hidden layers takes inputs from all the neurons in the previous layers. By default, each neuron sends processed data to all the neurons in the subsequent layers. However, during training, some connections may be optimized. In other words, they can be assigned zero weights.

The hyperparameters are adjusted to optimize the overall behavior of the ANN. A backpropagation algorithm is employed for the ANN training. The employed loss function is identified with the mean squared error,

$$\psi = \frac{1}{N}\sum_{i=1}^{N}\left(z_i - \tilde{z}_i\right)^2 . \tag{9}$$

In equation (9), N is the number of neurons in the output layer, $\tilde{z}_i$ are the outputs, and z_i are the target values $\tilde{z}_i$ are compared with. In the context of the study presented herein, the following options to provide target values are being considered: (i) synthetic data obtained using analytical (closed-form) models; (ii) synthetic data obtained by finite element simulations; (iii) experimental data from previous studies.

The analytical model and the multilayer perceptron are being developed, envisaging their implementation into a model of a base-isolated structure.

5. Concluding Remarks

Features of the finite element model and results obtained by the performed transient analysis simulating a characterization test on an LRB for seismic isolation have been discussed. The presented results, in terms of the 'applied displacement-restoring force relationship' are obtained using ready-to-use models available in the employed general-purpose finite element code ANSYS Mechanical APDL.

Additionally, a damage-based model capable of reproducing the mechanical response of elastic-plastic material has been outlined. The implementation of a constitutive relationship presuming coupling between plasticity and damage allows for the accumulated damage quantitative assessment. Degradation of mechanical properties, if any, can be thus rationally assessed throughout the bearing device service life.

A machine learning algorithm under development designed to reproduce the LRB's response is also presented. Generally, data-driven models are expected to allow for a better investigation of the design space containing the crucial model parameters considered relevant in the analyses. Therefore, machine learning algorithms will possibly provide options for better calibration of the closed-form solutions through a more accurate identification of model parameters. Also, data-driven algorithms could be technically easier to implement into, say, finite element analysis of a base-isolated structure. It is clear that a detailed finite element model of each base isolation unit would be more time and resource-demanding. Also, data-driven algorithms could be technically easier to implement into a finite element analysis of a base-isolated structure. A detailed finite element model of the base isolation unit would be more time and resource-demanding.

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