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Cross-platform implementation, verification and validation of advanced mathematical models of elastomeric seismic isolation bearings

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ABSTRACT

Stable inelastic response of seismic isolation bearings is key to the successful performance of base isolated nuclear structures, buildings and bridges. Since full-scale isolated nuclear structures (and buildings) cannot be tested for extreme earthquakes on simulators because their payload capacities are orders of magnitude smaller than weights of structures, confirmation of adequate performance must be provided by analysis of numerical models and testing of individual bearings. As the consequences of isolator failure are high, for example, core damage in a nuclear power plant and collapse for a building, the numerical models of the key nonlinear components, namely, the isolators, must be verified and validated (V + V). Herein, advanced models of elastomeric seismic isolation bearings are implemented as user elements in the open-source code OpenSees, and the commercial codes ABAQUS and LS-DYNA. These advanced models are verified and validated following ASME best practice to predict response under extreme loadings. Sources of error in the computational models are quantified, and where possible, eliminated. Those isolator characteristics crucial to robust estimates of performance are identified. Experiments are performed to obtain data for validation. The isolator models are validated using data from experiments and values of model parameters are recommended.

1. Introduction

Analysis of elastomeric bearings for extreme loadings requires robust mathematical models that consider all of the properties that are expected to be critical under such loadings. Mathematical models have been proposed (e.g., [1–3]), including the advanced model of Kumar et al. [4]. These models capture the behaviour of elastomeric bearings with varying degree of sophistication. However, a robust model of elastomeric bearing capable of capturing response associated with extreme earthquake shaking is not available in any of the contemporary codes. The software codes used for the seismic analysis of base-isolated structures, including SAP2000 [5] and PERFORM-3D [6], provide simplified models of elastomeric (and sliding) bearings, as noted in Table 1. Previously, the open-source seismic analysis program OpenSees included more sophisticated isolator models (see Table 1) but could not capture the more complex characteristics described in Kumar et al. [4] (e.g., cavitation, interaction between axial compression and shear stiffness, change in hysteresis due to heating of the lead core).

The finite element programs (LS-DYNA [7] and ABAQUS [8]) can model complex isolator behaviors (see Table 1) using either discrete or continuum approaches. Of these two general-purpose FEA programs, only LS-DYNA provides a direct option to model an isolator based on its material and geometrical properties. The continuum approach is recommended when the behavior of an individual isolator is to be studied. For analysis of large base-isolated structures, the discrete model will generally have to be used. Implementation of a computationally efficient discrete model of an elastomeric bearing is required in multiple codes to enable analysis of the response of base-isolated structures under extreme earthquake shaking.

The credibility, reliability and consistency of advanced models of an elastomeric bearing implemented in different software codes need to be established to ensure confidence in their use. The models developed for the analysis of engineered systems are always approximations of the physical reality and are limited by knowledge of physical processes, available data, mathematical formulations and numerical tools of analysis. The degree of accuracy to which these models predict the response of a system is addressed by the process of Verification and Validation (V + V). The prediction of response of a physical event through engineering models consists of many steps, and each step is accompanied by sources of error. The magnitude of the error depends on the assumptions, tools and techniques used for the analysis. Mathematical models should always be verified and validated (V + V).

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Table 1
Modeling of elastomeric seismic isolators and software programs.

Properties	SAP2000	PERFORM3D	LS-DYNA	ABAQUS	OpenSees
Coupled horizontal directions	Yes	Yes	Yes	Yes	Yes
Coupled horizontal and vertical directions	No	No	No	No	No
Different tensile and compressive stiffness	No	Yes	Yes	Yes	Yes
Nonlinear tensile behavior	No	No	No	Yes	Yes
Cavitation and post-cavitation	No	No	No	No	No
Nonlinear compressive behavior	No	No	No	Yes	Yes
Varying buckling capacity	No	No	No	No	No
Heating of lead core	No	No	No	No	No

There is much literature that provide qualitative and quantitative guidelines on V + V (e.g., ASME [9] Oberkampf and Roy [10], Oberkampf et al. [11], Thacker et al. [12], Roache [13]) but these are focused towards mechanical and aerospace applications. Formal V + V is still not implemented for models in structural and earthquake engineering applications, where large-scale nonlinear systems are modeled with high uncertainty and variability in material and mechanical properties. The V + V for structural models is mostly limited to code-to-code verification. Here-in, an advanced model of an elastomeric bearing is V + V: the first such application in structural and earthquake engineering to a highly *nonlinear* component of a structure. Lack of examples is also an impediment to widespread adoption of formal V + V for structural and earthquake engineering applications. A presentation on how V + V of nonlinear numerical models of structural engineering components should be performed, including a formal treatment of sources and magnitudes of error is needed, and that is also presented in this paper.

The system of interest here is an isolation system for a building or a nuclear power plant (NPP), and includes models of low damping rubber (LDR) and lead-rubber (LR) bearings. Seismic isolation is used to protect mission-critical infrastructure from the effects of horizontal earthquake shaking. Mainstream seismic isolators in the United States are elastomeric bearings (with and without a central lead core) and spherical sliding bearings. These bearings are typically installed at the base of the structure, above a foundation and below a basemat. Fig. 1 presents a cut-away view of a seismically isolated NPP. In this view, the isolators are shown installed atop pedestals. The isolators are vertically stiff and horizontally flexible, providing isolation in the horizontal direction only. Fig. 2 is a cut-away view of a lead-rubber bearing: an elastomeric bearing constructed with alternating layers of natural rubber and steel shims, with a central lead plug to provide energy dissipation (damping).

2. Motivation

The stable inelastic response of seismic isolation bearings such as that shown in Fig. 2 is key to the successful performance of base-isolated nuclear structures (and buildings). Such structures are designed for earthquake shaking with return periods of between 2500 years (buildings) and 100,000 years (nuclear power plants). Since full-size isolated nuclear structures (and buildings) cannot be tested for extreme earthquakes on simulators because their maximum payloads are orders of magnitude smaller than the weights of buildings (1000 s of tons) and nuclear structures (100,000 s of tons), and maximum actuator displacements and velocities are smaller than those needed to simulate extreme earthquake shaking, confirmation of adequate performance must be provided by a combination of analysis of numerical models and dynamic testing of prototype bearings. Since the consequences of failure are extremely high, for example, core damage in a nuclear power plant and collapse for a building, the numerical models of the key nonlinear components in the structure, namely, the isolators, must be verified and validated (V + V).

Prior to the work described in this paper, there were no numerical models of elastomeric seismic isolators available in any finite element code capable of capturing all of the responses identified in the first column of Table 1. This paper describes the implementation of advanced user elements/materials in the open-source code OpenSees and in the commercial codes ABAQUS and LS-DYNA. Relevant information on V + V is presented. Models of elastomeric bearings are described and a V + V plan is developed and implemented for them. Modeling errors due to different sources are quantified and either minimized or eliminated. These V + V activities help an analyst establish confidence in the models and be aware of possible errors in calculated responses.

3. Background

The V + V process starts with the definition of the domain of interest, which is the physical system and associated environment for which the model is to be created. A conceptual model of the physical problem is formulated through a set of features that are expected to play a role in the physical event for which the model is to be used. A mechanics-based representation of the physical problem that is amenable to mathematical and computational modeling is created, which includes: (1) geometrical details of the model, (2) material definition, (3) initial and boundary conditions, (4) external loads, and (5) modeling and analysis approach. A mathematical description of the conceptual model is formulated through a set of equations and statements that describe the physical problem. The mathematical model uses parameters that are one of the major sources of uncertainty that affects its accuracy. A computational model is developed using the mathematical model to predict the system's response. The process involves spatial and temporal discretization of the mathematical model into a numerical model and its implementation in a computer program using an algorithm that solves the model through direct or iterative solution techniques. Domain discretization and solution techniques are the major sources of the error in the computational model; round-off errors and coding bugs are other sources. The process of model development and V + V plan is summarized in Fig. 3.

Verification addresses the accurate representation of a mathematical model through software implementation of a numerical model; a relationship to the physical reality is not of concern. Validation addresses the degree of accuracy to which the mathematical model represents the physical reality, which is represented by experimental data. ASME [9] provides a list of standard terms used in V + V. It defines verification and validation as:

***Verification*:** The process of determining that a computational model accurately represents the underlying mathematical model and its solution.

***Validation*:** The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

Verification activities are performed to improve the accuracy of the computational results. The system response obtained from analysis of verified models is compared with data obtained from validation