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VERIFICATION AND VALIDATION OF MODELS OF ELASTOMERIC SEISMIC ISOLATION BEARINGS

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ABSTRACT

User elements are developed for analysis of elastomeric seismic isolation bearings in OpenSees. These elements implement advanced numerical models of low damping rubber, lead-rubber, and high-damping rubber bearings, which can be used to analyze base-isolated nuclear structures subjected to extreme ground shaking. The formulation and implementation of the elements in OpenSees are discussed. The verification and validation of the user elements, which followed ASME best practices, are presented.

INTRODUCTION

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 system of interest here is an isolation system for a NPP that includes low damping rubber (LDR) and lead-rubber (LR) bearings. Verification and validation is a cyclic process that quantifies the error in a model due to different sources. Quantification of the error helps prioritize V+V activities and enables the assessment of the effect of a particular feature of the model on the behavior of the system.

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 describes 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 to a numerical model, and implementation of the numerical model in a computer program using a numerical 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 in addition to round-off errors and coding bugs.

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 experiments. The test data must be processed to remove measurement errors. If the computational results are within acceptable error per an established accuracy criteria, the model is deemed validated. If not, the model needs to be revised.

MODEL OF ELASTOMERIC BEARING

The physical model of an elastomeric bearing is formulated as a two node, twelve-degree of freedom system. The two nodes are connected by six springs, which represent the material models in the six basic directions. The six material models capture the behavior in the axial, shear (2), torsional and rotational (2) directions. The mathematical models and computational models of elastomeric bearings are discussed in detail in Kumar *et al.* (2014). The mathematical model of the elastomeric bearing is implemented in OpenSees and ABAQUS as user elements. A user element is the implementation of a numerical model in a computer program using a programming language. Two elements are created in each program for LDR and LR bearings. A user element of high damping rubber (HDR) bearings was also created in OpenSees. The HDR user element has the same axial formulation as LDR and LR bearings, but uses the model proposed by Grant *et al.* (2004) in shear. The V+V of the HDR user element is not discussed here. Table 1 defines the scope of the model and its intended use for V+V activities.

Table 1: Scope of the V+V for the model of elastomeric bearings

Feature	Description
Domain of interest	Seismic isolation of NPPs
Intended use of the model	Response-history analysis of a NPP under design and beyond design basis earthquake loadings
Response features of interest	1) Acceleration, velocity, displacement a) of the structure b) of secondary systems 2) displacement in the isolators 3) energy dissipation (damping) in the isolators a) due to heating in the lead core of LR bearings b) due to cavitation under tension
Accuracy requirements	To be developed after consultations with stakeholders

The features that are expected to have significant effects on the response of the base-isolated NPP is identified by constructing a Phenomena Identification and Ranking Table (PIRT). The PIRT for the models of elastomeric bearings is presented in Table 2. The confidence and importance levels assigned to the different components of the mathematical model in Table 2 are based on preliminary information available on the mathematical models of elastomeric bearings and the results of response-history analysis of seismically isolated NPP (Kumar, 2015; Kumar *et al.*, 2015).

Table 2: Phenomenon ranking and identification table for models of elastomeric bearings

Phenomenon	Importance to response of interest	Level of confidence in model
Coupled horizontal directions	High	High
Heating of lead core in LR bearing	High	High
Varying buckling capacity	High	Medium
Coupled horizontal and vertical response	Medium	Medium
Nonlinear tensile behavior	Medium	Low
Cavitation and post-cavitation	High	Low
Nonlinear compressive behavior	Low	Low
Post-buckling behavior	Low	Low

The PIRT helps to prioritize those physical processes that should be investigated experimentally for validation. Phenomena with medium or high importance to response quantities of interest and low level of confidence in modeling are given high priority. The phenomenological model that describes the behavior of an elastomeric bearing in cyclic tension is validated experimentally. The model development and the V+V plan for the elastomeric bearing models is presented in Figure 1.

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