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A case study to quantify prediction bounds caused by model-form uncertainty of a portal frame

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A B S T R A C T

Numerical simulations, irrespective of the discipline or application, are often plagued by arbitrary numerical and modeling choices. Arbitrary choices can originate from kinematic assumptions, for example the use of 1D beam, 2D shell, or 3D continuum elements, mesh discretization choices, boundary condition models, and the representation of contact and friction in the simulation. This work takes a step toward understanding the effect of arbitrary choices and model-form assumptions on the accuracy of numerical predictions. The application is the simulation of the first four resonant frequencies of a one-story aluminum portal frame structure under free–free boundary conditions. The main challenge of the portal frame structure resides in modeling the joint connections, for which different modeling assumptions are available. To study this model-form uncertainty, and compare it to other types of uncertainty, two finite element models are developed using solid elements, and with differing representations of the beam-to-column and column-to-base plate connections: (i) contact stiffness coefficients or (ii) tied nodes. Test-analysis correlation is performed to compare the lower and upper bounds of numerical predictions obtained from parametric studies of the joint modeling strategies to the range of experimentally obtained natural frequencies. The approach proposed is, first, to characterize the experimental variability of the joints by varying the bolt torque, method of bolt tightening, and the sequence in which the bolts are tightened. The second step is to convert what is learned from these experimental studies to models that "envelope" the range of observed bolt behavior. We show that this approach, that combines small-scale experiments, sensitivity analysis studies, and bounding-case models, successfully produces lower and upper bounds of resonant frequency predictions that match those measured experimentally on the frame structure. (*Approved for unlimited*, *public release*, *LA-UR*-13–27561).

1. Introduction

Computational modeling in physics and engineering has become accepted to study the behavior of complex phenomena, especially when experiments are hindered due to time, money or safety constraints. For example, numerical models offer

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a cost-effective alternative to investigate parametric studies of structural damage due to the cost and safety implications associated with full-scale destructive testing [1]. Further, when pursuing new concepts for design, computational models are useful to replace the traditional design, build and test paradigm. Numerical models have become commonplace to study the behavior of a wide range of structures, such as buildings, bridges, automobiles and wind turbines, as demonstrated by their inclusion in design standards [2–4]. While useful, it is emphasized that numerical models are developed using assumptions and simplifications, thus only being able to provide an approximation of reality. For this reason, the prediction uncertainty from numerical simulations must be quantified in order for simulation predictions to be effective in replacing or supplementing full-scale experiments.

Unavoidable sources of uncertainty exist when developing numerical models, such as experimental, parametric, numerical, and model-form (or structural) uncertainties. Reproducible and reliable experimental data are needed for use in calibration and validation assessments. However, experimental uncertainty is unavoidable, and can originate from variability of the manufactured product from design specifications, deviation of material properties from coupon properties used to represent the material behavior, and unique stress loading behaviors in critical sections of the structure [5]. Numerical uncertainty originates from the level of mesh discretization that is utilized in the model (or truncation error), round-off errors, numerical ill-conditioning, poor-quality interpolations and the lack-of-convergence of numerical solvers. In the case of truncation error, which is usually the dominant contributor, methods have been developed to produce error bounds for the resulting solution [6]. To ensure that the effect of mesh size on model output is minimal, it is typical to perform a mesh convergence study to identify the level of resolution that has an acceptably small effect on model predictions [7]. Parametric uncertainty is also commonly encountered when developing numerical models. This uncertainty represents, for example, the variability or unknown values of coefficients of a material constitutive model, energy restitution coefficients, or those of a contact condition between two surfaces. One approach is to treat these parameters as stochastic variables, for which probability laws are defined to create ranges of allowable values [8]. To identify parameters that exercise the most influence on model output, it is useful to use a phenomenon identification and ranking table, which can contribute to efficient parametric studies that include only the most influential parameters [9].

The last source of uncertainty discussed here, model-form uncertainty, is arguably more ambiguous than the experimental, numerical, and parametric uncertainties. Thus, attempts to quantify and realize the effect of model-form uncertainty have been far less encountered. Model-form uncertainty originates from assumptions or simplifications of known, or unknown, phenomena that must be represented in the numerical simulation. Assumption-making enables model building; it limits, however, the ability of the model to replicate reality [10]. When developing a model, its structural form is typically chosen based on theoretical considerations, goodness-of-fit to small-scale experiments, expert judgment, and computing constraints. This selection of a model form mitigates the lack-of-knowledge about the "best" modeling strategy that should be implemented; however, its effect on predictions often remains unknown. Some of the modeling assumptions that influence simulation results in structural dynamics include, but are not limited to: using a 1D, 2D, or 3D representation to model a component of the structure; the method through which contact and boundary conditions are represented; and the method through which external forces are applied. Due to the need for reliable simulation predictions, it is crucial to better understand the effect of model-form uncertainty on predictions.

When pursuing model-form uncertainty in structural dynamics, one area suggested as a topic of significance is the characterization of structural joints and connections [11]. After a decade-long research effort regarding the dynamics of jointed structures at Sandia National Laboratories, a recommendation is that more has to be achieved in order to quantify model-form uncertainty and "*assess the cumulative uncertainty of all elements playing a role in prediction*" [12]. Although much research has been conducted to understand the extent to which different joint modeling approaches accurately predict a dynamic response, more has yet to be discovered about how assumptions used in the development of these models affect numerical predictions. This work does not attempt to answer these questions for an arbitrary joint model. Instead, we propose a methodology that combines small-scale physical experiments, sensitivity analysis and the development of bounding-case models, and apply it to a relatively simple portal frame structure with bolted connections. Our goal is to estimate lower and upper bounds of resonant frequency predictions that are as consistent as possible with the experimental variability. This work builds on previous studies, which have already accounted for experimental, parametric and numerical uncertainties. The novelty is to consider and quantify model-form uncertainty. This comprehensive treatment of uncertainty is useful to understand the limitations imposed by simplifications applied to numerical models, which matters greatly if numerical simulations are expected to replace or supplement full-scale experiments.

The remainder of the paper is organized as follows. Design specifications and experimental setup of the portal frame are introduced in Section 2. Section 3 discusses the use of modal impact testing to measure the first four resonant frequencies. Experiments are conducted to characterize the variability that arises by changing the bolt torque, method of bolt tightening, and the sequence in which the bolts are tightened. Statistical Analysis-of-Variance (ANOVA) determines the sources of experimental variability that most significantly change the measurements. The most significant sensitivities learned from ANOVA are then used to guide the development of numerical models. Section 4 discusses the development of two competing Finite Element (FE) models implemented with the commercial software Abaqus™. Section 5 discusses test-analysis correlation between experimental measurements and numerical simulations, whereby the goal is to determine if the FE models provide ranges of predictions that are consistent with the ranges of measurements. Doing so leads to a better understanding of which model-form assumptions most significantly influence the predictions. Conclusions and recommendations for future work are given in Section 6.