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On the origin of computational model sensitivity, error, and uncertainty in threaded fasteners

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ABSTRACT

Predicting the mechanical response of components requires simplifications and idealizations that affect the fidelity of the results and introduce errors. Some errors correspond to the limited knowledge of intrinsic physical attributes while others are introduced by the modeling framework and mathematical approximations. This paper studies the dependence of the force-displacement response of threaded fasteners on modeling attributes such as geometry, material, and friction resistance using finite element simulations. A systematic comparison of $1D$, $2.5D$ or $3D$ computational models demonstrates the influence of model properties and the limitations of the methodologies. Finally, the paper discusses the sources of model inputs and model form errors for threaded fasteners.

1. Introduction

Modeling the mechanical response of threaded fasteners often assumes simple $1D$ smooth geometry [1,2] without considering the complex phenomena that take place in between threads. Similarly, reliability analyses of assemblies with multiple mechanical components usually rely on reduced order models that do not convey detailed geometric attributes, material properties, or frictional effects. Instead, modeling large assemblies depends on equivalent constitutive behaviors of connectors (e.g., [3,4]), which many times are assumed to be linear and reversible [5]. This modeling approach can introduce large errors that are unacceptable in the analysis of high consequence applications. Since the computational burden rapidly increases with increasing component size, there is a need not only to ascertain more accurate physics-based reduced order models, but also to quantify the model form error and the sources of variability [5].

Prior research on threaded fasteners investigated torsional tightening (or loosening) [6,7], stress and strain distributions [8,9], and fatigue life [10,11], to mention a few of the most common aspects [12]. Nevertheless, few studies have focused on understanding and predicting the equivalent constitutive response of threaded fasteners. Furthermore, many of the existing studies employ simplified geometries (e.g., $2D$), linear elastic materials, and frictionless surfaces. Because most efforts focus on specific components, the conclusions from these publications cannot be generalized confidently to other scenarios. Therefore, there is a need to understand and generalize the relative impact of modeling assumptions and parameter errors on the force-displacement response of threaded fasteners.

A confident prediction of the mechanical response of threaded fastener needs to ascertain multiple sources of model uncertainty and sensitivity. Following the framework originated in the risk assessment community [13,14], uncertainty (either epistemic or aleatory) in computational models may originate in numerical approximations, model inputs, and model form. Thus, this work investigates model input and form uncertainties in threaded fasteners by performing finite element simulations with various input parameters and model simplifications. We emphasize that we seek to understand the mechanisms that control the mechanical response of fasteners rather than reproducing certain experiments with simulations.

2. Sources of variability and error in modeling fasteners

The mechanical response of fasteners is determined by complex phenomena arising from the interaction of many physical bodies. To systematically study the fidelity of threaded fasteners models, we propose a taxonomy for the major sources of sensitivity, error, and uncertainty that affect the force-displacement response (Fig. 1):

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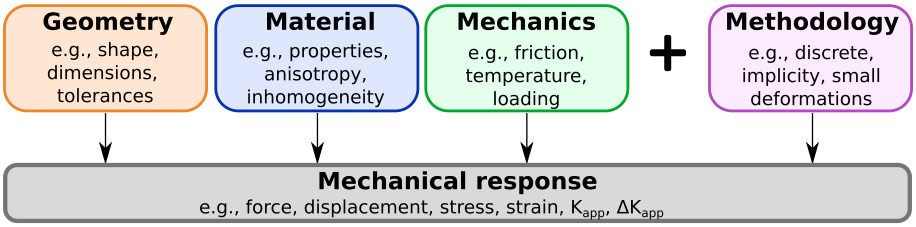

Fig. 1. Most significant sources of sensitivity, error, and uncertainty in modeling the mechanical response of threaded fasteners.

Geometry: Threaded fasteners are geometrically complex components with no axis of symmetry, which implies that only 3*D* models can yield exact results. Nevertheless, 2*D* simulations are still used to study threads (for example Ref. [15]). In addition, threads are manufactured with a wide range of quality, from inexpensive fasteners for disposable devises up to ultra-precise components for aerospace applications. As a result, geometrical attributes have a large variability among manufacturers, production batches, and applications; these may be mitigated with a statistical characterization of geometrical attributes.

Material: Manufacturing procedures have a notable effect on fastener material properties. Rolled threads present strong microstructural gradients [16] and texture while cut threads have discontinuous fibers with lower local strength [17,18]. Even the manufacturing speed changes the microstructure and influences the mechanical response [16]. Thus, the identification of fasteners with their chemical composition or alloy grade conveys a large error that neglects residual stresses, microstructures, and defects. Multi-scale material models can mitigate these errors by explicitly incorporating sources of mesoscale variability [19,20]. However, these strategies are computationally expensive, require a plethora of small-scale characterization, and represent a host of their own research challenges.

Mechanics: The mechanical response of fasteners is intimately related to the frictional interactions between the threads. These interactions are usually captured with Coulomb friction models and a range of friction coefficients between 0 and 0.5 [21,22]. Similarly, temperature changes or gradients, residual strains from installation, and loading direction also affect the response of fasteners. The coupling of these effects is an open problem and usually requires multi-scale and multi-physics approaches that are computationally and experimentally time-consuming.

Methodology: In addition to the intrinsic uncertainty of one particular fastener, computational models introduce acknowledged errors such as numerical rounding and spatial discretization errors, or unacknowledged errors such as coding mistakes. Recent efforts [23] have focused on identifying phases that introduce uncertainty and estimating the numerical error, but these sources of error are not the focus of this work.

Other sources of uncertainty may include loading history and environment assisted degradation (corrosion, radiation, etc) [24]. Although these aspects are beyond the scope of this work, as-produced and as-installed fasteners may degrade and alter their geometrical, material and mechanical attributes during the life of the component.

A final comment pertains to the impact of the sources of sensitivity, error, and uncertainty on different quantities of interest, which are application-specific. In the case of threaded fasteners, the focus may be on the prediction the force-displacement response, torque-tension relation, the fracture and fatigue integrity, or the degradation during service, to mention a few. Since modeling uncertainty may affect these quantities in different manners or degree, the propagation of errors should be carefully considered for each application.

This paper investigates the force-displacement response and stress and strain fields of threaded fasteners using 1*D*, 2.5*D* or 3*D* finite element models with different geometrical attributes (Sections 4.1–4.3). These assessments also include sensitivity analysis of friction coefficients and material properties (elastic or elasto-plastic). Next, the effects of torsional installation strains are analyzed in Section 4.4 and a comparison among models and experiments is presented in Section 4.5. Finally, Section 5 compares model inputs and model form errors, and discusses the results from various approaches.

3. Modeling approaches

This research investigates the relationships among a limited set of properties and models for *#0-40UNF* bolts [1] in Fig. 2. In what follows the nomenclature of Fig. 2 is used: a bolt consists of a head where load/torque is applied, a shank that connects the head with the threads, which engage with a substrate or a nut to form a stiff connector. Threads are characterized by number and pitch (e.g., 1/4–20 has a basic major diameter of 6.35 mm and 20 threads per 25.4 mm).

Regarding geometric variability, simulations employ 1*D* smooth models, 2.5*D* threaded models, and fully 3*D* threaded models, as shown in Fig. 3. Here, 1*D* model refers to 3-dimensional smooth specimens with squared cross section and 2.5*D* model refers to 3-dimensional symmetric threaded models with one element into the thickness. In addition, 2.5*D* asymmetric models consider threads that are displaced by half the pitch at each side of the substrate and different substrate lengths (Fig. 4). As previously shown by several researchers [25–27], the first five threads carry 90% of the load; thus, all cases include between four to five threads in contact between the bolt and the substrate.

The geometric characteristics of threads introduces difficulties in meshing 3*D* models with hexahedral elements, which are generally more accurate than tetrahedral finite elements. Therefore, 3*D* meshes are conformed by sections of hexahedral and tetrahedral elements, with tied contact to make a continuous mesh (see Fig. 3c). Hexahedral elements constitute most of the thread, where the highest stress and strain gradients occurs, while tetrahedral elements are employed for transitions with free surfaces and the inner core of the bolt.

Finite element simulations are conducted using the Sierra Finite Element software [28] with an implicit quasi-static solver. All meshes maintain similar element refinement to limit mesh size dependence, which does not strongly affect the force-displacement response [27]. Although a minor mesh dependence (about 10%) may exist on the peak stress and strain at the thread roots [8], this work assumes that the numeral uncertainty is negligible and focuses on the remaining sources of uncertainties. Certainly, the study by Rafatpanah [29] suggests that our mesh refinement is enough to yield mesh convergence of the shank stress.

The loading of the fastener consists of quasistatic normal displacement of the nodes on the top cross section of the bolt (dis-