ASME V&V 10.1-2012

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An Illustration of the Concepts of Verification and Validation in Computational Solid Mechanics

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AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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FOREWORD

From comments by the readership of the ASME Guide to Verification and Validation in Computational Solid Mechanics [1] (henceforth referred to as V&V 10), the ASME V&V 10 Committee on Verification and Validation in Computational Solid Mechanics recognized the need for another document that would provide a more detailed step-by-step description of a V&V application. The present document strives to fill that need by applying the general concepts of V&V to an illustrative example.

The authority of a standards document derives from the consensus achieved by the members of a standards committee (about 20 active members in V&V 10), whose interests span a broad range. Achieving such consensus is a long and difficult task, but the ultimate benefit to the computational mechanics community justifies the effort. Many compromises were made in the creation of the present illustrative example document. The main balance sought was to communicate to the reader on a basic level without distorting the many nuances associated with the exacting principles of verification and validation. The danger with being too basic is that the reader might take simplified concepts and statements out of the context of the illustrative example, and generalize them to situations not intended by the authors. The corresponding danger with being too exacting is that the reader might neither understand nor desire to understand the subtle points introduced by repeated qualification of terms (e.g., a "validated model" versus "a model validated for its intended use"). In most cases, the Committee favored clarity over completeness.

The scope of the document has evolved considerably since its inception. For example, the initial intent was to include as a lead-off example a one-experiment-to-one-calculation comparison without regard for uncertainties in either, since this is easiest to communicate and relate to readers and their possible past experience with validation. However, as a result of internal discussions and external reviews, the Committee came to accept that to maintain consistency with V&V 10, the recommended validation procedures must always account for uncertainties in both the calculations and the data that are compared. This led the Committee to restrict attention to validation requirements and metrics that depend directly on the underlying distributions characterizing the uncertainties in the calculations and data.

ASME V&V 10.1-2012 was approved by the V&V 10 Committee on December 2, 2011, the V&V Standards Committee on February 20, 2012, and the American National Standards Institute as an American National Standard on March 7, 2012.

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The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

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AN ILLUSTRATION OF THE CONCEPTS OF VERIFICATION AND VALIDATION IN COMPUTATIONAL SOLID MECHANICS

1 EXECUTIVE SUMMARY

This Standard describes a simple example of verification and validation (V&V) to illustrate some of the key concepts and procedures presented in V&V 10. The example is an elastic, tapered, cantilever, box beam under nonuniform static loading. The validation problem entails a uniform loading over half the length of the beam. The response of interest is the tip deflection. The validation test plan and the metrics and accuracy requirements for comparing the calculated responses with measurements are specified in the V&V Plan, which is developed in the first phase of the V&V program. In setting validation requirements and establishing a budget for the V&V program, the V&V Plan considers the level of risk in using the model for its intended purpose. Successfully meeting the V&V requirements means that the computational model for the tapered beam has been validated for the intended use discussed in this document, viz., predicting the response of a tapered beam tested in the laboratory.

To encompass as much of the general V&V process as possible in this example, a computational model was developed specifically for the tapered beam problem, even though it is more likely that a general-purpose finite-element code would be used in practice. The conceptual model is a Bernoulli–Euler beam for which the governing equations are solved with the finite-element method. The computational model was verified (checked for proper programming of the mathematical model and the solution procedure) by comparing computed values of tip displacement with an analytical solution to a relevant but simpler problem. A mesh refinement study initially revealed that the model did not converge at the expected theoretical rate. Further diagnosis revealed a programming error, correction of which led to the proper convergence rate. Knowing the allowable error due to lack of convergence then allowed an appropriate level of mesh refinement to be selected.

For validation (comparing with experimental results), 100 virtual trials of the same test were performed to quantify the distribution of results due to unintended variations in material properties, construction of the test specimens, and test execution. Other virtual tests were conducted to characterize uncertainties in selected model input parameters, namely rotational support stiffness and elastic modulus.

The following two validation approaches were considered:

(a) a case where uncertainty data were not available and obtained instead from subject matter experts.

(b) a case where uncertainty data were available from repeat tests and calculations.

In both cases the same metric was employed to demonstrate the use of uncertainty information in the model-test comparison. The validation metric is a measure of the relative error between the calculated and measured tip deflection of the beam.

The same model was used in both validation cases. In each case, the metric was compared to an accuracy requirement of 10%. In both cases the model was validated successfully. Had the validation been unsuccessful, it would have been necessary to correct any model deficiencies, collect additional or improved experimental data, or relax the validation requirement.

2 INTRODUCTION

This Standard is the first in a planned series of documents elaborating on the verification and validation topics addressed initially in the ASME V&V 10 Committee's seminal document, Guide to Verification and Validation in Computational Solid Mechanics (ASME V&V 10) [1]. V&V 10 was intentionally written as a high-level summary of the essential principles of verification and validation.

The present document provides a step-by-step illustration of the key concepts of verification and validation. It is intended as a primer that illustrates much of the methodology comprising verification and validation through a consistent example.

The example selected is a tapered cantilever beam under a distributed load. The deformation of the beam is modeled with traditional Bernoulli–Euler beam theory. The supported end of the beam is fixed against deflection but constrained by a rotational spring. This nonideal boundary condition, along with variation in the beam's elastic modulus, enables us to illustrate the treatment of uncertain model parameters.

The illustrative portion of the document begins with the Verification and Validation Plan (section 5). This plan is the recommended starting point for all verification and validation activities. The V&V Plan provides the

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framework for conducting the verification and validation assessment and provides an outline for the timing of activities and estimating required resources. The V&V Plan is developed as a team effort with participation by the customer (who provides the requirements), decision makers, experimentalists, modelers, and those who will perform the validation comparisons.

Having agreed on a V&V Plan, the next step is model development, which includes three types of models: conceptual, mathematical, and computational (section 6).

Developed on a parallel path with the mathematical and computational models are the validation experiments — the physical realizations of the reality of interest (tapered cantilever beam) that will eventually serve as the referent against which the computational model predictions are compared in the validation phase.

Once the computational model has been developed, an assessment of the agreement between the statement of the mathematical model and the results from the computational model is required. This activity is called verification and comprises two main parts: code and calculation verification (section 7). Code verification is typically performed by comparing the results from analytical solutions to the corresponding computational model results. Calculation verification is performed with successive grid refinements and estimations of the discretization error using techniques based on Richardson extrapolation [5].

Having verified that the computational model is mistake-free for the cases tested, and having established a level of mesh refinement that produces an acceptable discretization error, the predictive calculation of the validation experiments can proceed. In parallel, the validation experiments can be conducted and results recorded. The validation assessment is then made by comparing the outcomes of the model prediction and the validation experiment to determine whether the validation requirement has been satisfied.

The remainder of this document is organized as follows. The Purpose and Scope (section 3) describes which parts of the V&V process are, and are not, covered by the illustrative example. Next, the Background (section 4) provides a review of the verification and validation process and describes how the illustrative example fits into an overall validation hierarchy — a key element in the validation process. Sections 5 through 9 contain the illustrative example. The document ends with a brief Summary (section 10), which restates the key results from the illustrative example, and finally some Concluding Remarks (section 11) providing a look to the future of ASME V&V 10 verification and validation activities.

3 PURPOSE AND SCOPE

The purpose of this document is to illustrate, by detailed example, the most important aspects of V&V described in the Committee's framework document, Guide to Verification and Validation in Computational Solid Mechanics (V&V 10). V&V 10 intentionally omitted examples, as its purpose was to provide "a common language, a conceptual framework, and general guidance for implementing the process of computational model V&V," an already broad scope for a 27-page consensus document. The present document is the first in a series of more detailed and practical ones the Committee has planned to incrementally fill the gap between V&V 10 and a set of recommended practices.

To appeal to a broad range of mechanics backgrounds, a cantilever beam problem has been selected to illustrate the following aspects of V&V. The numbers in parentheses are references to sections and paragraphs in V&V 10 as follows:

(a) validation plan (para. 2.6)

(1) validation testing (para. 2.6.1)

(2) selection of response features (para. 2.6.2)

(3) accuracy requirements (para. 2.6.3)

(b) modeling development (section 3)

(1) conceptual model including intended use (para. 3.1)

(2) mathematical model (para. 3.2)

(3) computational model (para. 3.3)

(c) verification (section 4)

(1) code verification: comparisons using analytical solutions (para. 4.1)

(2) calculation verification: mesh convergence (para. 4.2)

(d) parameter estimation (para. 3.4.1)

(e) validation (section 5)

(1) validation experiments (paras. 5.1 and 5.2)

(2) comparison of experimental results and model prediction (para. 5.3)

(3) decision of model adequacy (para. 5.3.2)

(f) uncertainty quantification (para. 5.2)

(g) documentation (paras. 2.7, 4.3, and 5.4)

4 BACKGROUND

V&V is required to provide confidence that the results from computational models used to solve complex problems are sufficiently accurate and indeed solve the intended problem. The conceptual aspects of V&V are described in detail in V&V 10. V&V is used with increasing frequency in recognition that confidence in ever increasingly complex simulations can only be established through a formal, standardized process.

V&V includes assessment activities that are performed in the process of creating and applying computational models to address technical questions about the performance of physical systems. The overall process is summarized in Fig. 1, which is taken from V&V 10. The present document describes and provides examples of

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