Verification and validation in computational solid mechanics and the ASME Standards Committee

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Abstract

This paper is intended to serve as an introduction to the concepts of verification and validation as they apply to computational mechanics. The continuing formalization of the verification and validation processes by the American National Institute of Standards sanctioned bodies such as the American Society of Mechanical Engineers Standards Committee on Verification and Validation in Computational Solid Mechanics, and the American Institute of Aeronautics and Astronautics Computational Fluid Dynamics Standards Committee, is intended to provide decision makers, who increasingly rely on computational mechanics predictions for high risk endeavours, the ability to make informed decisions based not only on the computed 'answer', but also the rational approach used to obtain the answer and a quantifiable level of confidence in the correctness of the answer.

This paper begins by asking the question that verification and validation attempts to answer. Next, the processes of verification and validation are illustrated using simple and detailed figures, and an accompanying example of modelling an aircraft wing. Some thought on the future of standards as they might apply to verification and validation in computational mechanics are provided in the next section. The last section is suggested reading for those seeking a brief history of the American Society of Mechanical Engineers Standards Committee on Verification and Validation in Computational Solid Mechanics.
Keywords: verification, validation, computational mechanics, standards.

1 The critical question

How should confidence in modelling and simulation be critically assessed?

The processes of verification and validation (V&V) in computational mechanics are intended to provide, and quantify, confidence in numerical modelling and the results from the corresponding simulations. A convenient analogue for the V&V processes is the trial court process. Both processes collect evidence in an attempt to establishing the 'truth,' sufficient for a judgment to be made. Here the engineering reader is advised to think of truth in the philosophical sense, i.e. as a scientific statement that lies somewhere between the unattainable upper and lower limits that are truth and falsity (slightly paraphrasing H. Reichenbach as quoted by Karl Popper [3] on page 6). Having indicated that the word 'truth' is fuzzy, the reader should next note the phrase 'sufficient for a judgment to be made.' Again using the trial court analogy, for civil judgments only the preponderance of evident is required, while for more serious criminal case judgments, the evidence of the truth must be beyond a shadow of a doubt. In computational mechanics there exists a similar range of required evidence, e.g. if predictions about a Mars Lander are incorrect, important resources are wasted, but this loss is insignificant compared to human lives that could be lost if predictions of the earthquake response of a high rise building are similarly in error.

2 So what is verification and validation

These two words are typically used interchangeably, but the various entities in computational mechanics concerned with V&V are striving to associate distinct and different meanings to these two words. As usual, Pat Roache [1] says it best:

"Verification" – solving the equations right.
"Validation" – solving the right equations.

More formally, the AIAA V&V Guide [2] provides:

- *Verification is the assessment of the accuracy of the solution to a computational model by comparison with known solutions.*
- *Validation is the assessment of the accuracy of a computational simulation by comparison with experimental data.*

Somewhere between the above succinct and elegant definitions I offer the following layman's definitions:

- *Verification - getting (most of) the bugs out of the code.*
- *Validation - demonstrating the numerical model is capable of making (appropriate) predictions.*

3 A simple verification and validation diagram

Figure 1 shows a variation (the modifications are attributed to Bill Oberkampf of Sandia National Laboratory) on the so called Sargent Circle often used to illustrate the concepts of verification and validation in relation to a the numerical modelling effort. The overall circular shape of this diagram emphasizes that numerical modelling, and in particular, verification and validation are processes, i.e. the steps may need to be repeated if unsuccessful (resources permitting).

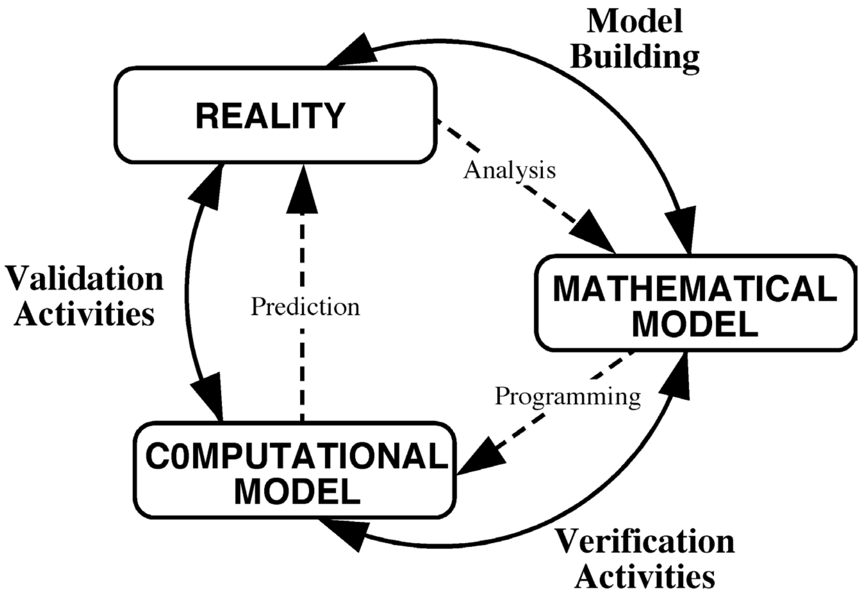

Figure 1: Variation on the Sargent Circle for illustrating the interaction of verification and validation in the numerical modelling process.

Understanding this diagram start with the box labelled 'Reality' which represents the physical system to be numerically modelled, e.g. a wing on an aircraft. From this box we move clockwise and being the model building activity which leads to a mathematical model. The mathematical model should be thought of as a system of partial differential equations, arrived at by considering what aspects of the reality need to be described, i.e. analysis. Continuing the airplane wing example, suppose we are attempting to predict the tip deflection under static loads, our analysis may indicate that a simple Bernoulli-Euler beam theory should be adequate.

Next we convert, via programming, the system of differential equations (mathematical model) into a numerical algorithm (code), which along with initial and boundary conditions, material properties and a description of the geometry form the "Computational Model." "Verification Activities" are the checks and sample problems we use to exercise the Computational Model to provide confidence that we have converted the mathematical model into a correct computational model. For the aircraft wing example, it is easy to imagine the complex cross sectional properties of an aircraft wing, Thus as part of the verification activity know analytical or benchmark problems, associated with

Bernoulli-Euler beam theory, would be exercised by the computational model until confidence was established that the code was error free, at least for the suite of verification problems.

Before we use the computational model, i.e. our example model of an aircraft wing, to make a prediction, i.e. the tip deflection, we seek some assurance (confidence) that the simple Bernoulli-Euler beam theory we selected to model the reality, is appropriate for such a complex structure; perhaps Timoshenko Beam Theory would have been more appropriate? To establish some confidence that our modelling is appropriate, we construct physical models of either sub-scale versions of the aircraft wing, or physical models with some of the characteristic of the wing. Comparison of our computational model predictions with the results of these physical tests are the Validation Activities.

When the above activities are completed, hopefully successfully but not necessarily, a prediction of the wing tip deflection can be made and the results, along with the documented V&V process, can be presented to decision makers. The decision makers can then make an informed choice about accepting or rejecting the prediction. The decision makers operate outside the V&V process, but add essential considerations, e.g. risks, budget, etc.

4 A not-so-simple verification and validation diagram

Figure 2 represents the ASME Verification & Validation Committee's current detailed view of the numerical modelling process that includes verification and validation. The basic ideas expressed in the Sargent Circle are still present in this diagram, but each process and activity has been further subdivided into its next level of detail. No detailed explanation of this diagram is provided here, as this is the subject of the ASME Verification & Validation Committee's guide.

5 Thoughts on future directions of V&V and standards

In presentations on verification & validation, and in particular what the ASME V&V Committee is attempting, the audience feedback I receive is very positive, and quite encouraging; I also assume those that think I am wasting my time do not bother to waste their time telling me so. The most common reaction is "I am glad someone is working on V&V standards." This is usually from an engineer that has tried to deal with answering the question, "How valid are those results?" either for personal satisfaction, or more typically, to answer this question as posed by management. The enthusiastic support for V&V standards is significantly diminished with the realization that we are probably many years away from even a Best Practices publication, yet alone any standards.

To understand this enthusiasm for V&V standards, I think it helps to look at what I believe are some important trends, related to computational mechanics, as an illustration of the need for V&V standards:

- Less Physical Testing – as the cost of computing declines, dramatically, relative to the cost of maintaining a high quality testing facility, there is increasing economic pressure to "just do some calculations."

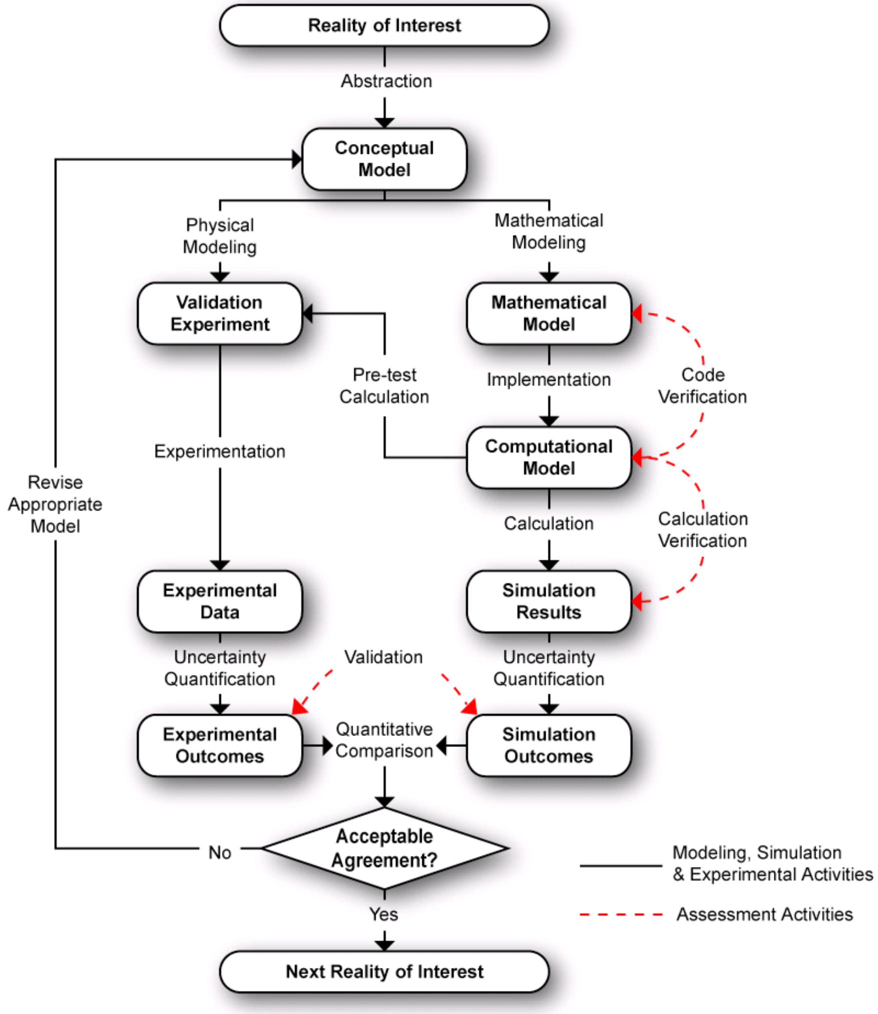

Figure 2: Detailed illustrating the interaction of verification and validation in the numerical modelling process.

- Increased Product Liability – in an increasing litigious society, failure to take reasonable precautions to ensure product safety can have serious economic consequences. Combine this need to do 'something,' with the above lack of quality testing facilities, and the result is "just do some calculations."
- Increased Self-Certification – Regulatory agencies typically put the burden of proof for certification on the manufacturer, e.g. auto companies for crash safety and biomedical device manufactures for

fault tolerant operation in vivo. For economic reasons, perhaps not all required test configurations are tested, and, in the latter example, limited access to testing 'facilities' for biomedical devices, both place an emphasis on "just do some calculations."

- From Developer/Analyst to Black-Box/User – Less than 20 years ago, most analyses were performed by the same person that wrote the analysis code, or worked in the same group with the code developer. Today, almost all analyses are performed using commercial software, where even a trusted user is not allowed to access the source code, for verification, or any other, purpose. The most ardent user is forced to 'know' the analysis package through its user documentation, which ranges from at best good to all too often nonexistent.

As more emphasis is placed on using computational mechanics to replace testing, and the corresponding computational results have greater economic, and safety, consequences, management will more frequently ask "How valid are those results?" and enlightened management will require an informed and quantitative answer.

As of this writing, it seems the path forward to V&V standards will involve dissecting computational mechanics into its basic parts and then writing Best Practices, and hopefully standards, for these basic parts. The immediate challenge is how to dissect such a topic where many of the parts are interrelated; the surgeon's task of separating Siamese twins comes to mind. A logical approach would be to select those areas of computational mechanics that can be isolated relatively easily, e.g. error estimation and constitutive modelling, and attempt Best Practices documents for those areas. But the emphasis in this approach will of necessity be on verification, as validation requires the whole of computational mechanics to perform adequately.

The most pressing need in V&V is validation, this is not to ignore verification, but for the reasons cited above, practical guidance, in nearly any form, on validation must be given a priority; certainly verification and validation can proceed in parallel. There seems to be three key areas in validation that guidance needs to be communicated to analysts, and their managers, immediately:

1. Precision Testing – what is required to specify and perform experiments that will be meaningful and useful for validation.
2. Validation Metrics – how do we quantify the comparisons between measurement and simulation results.
3. Role of Non-Determinism – neither the observed nor simulated behaviour is known with certainty, e.g. due to randomness in the physical system and modelling idealizations, this further complicates the validation process.

It is my belief that guidance in these three areas of validation needs to be presented in a form that provides for both education and guidance. Validation Metrics are an area of research and development and thus require education to disseminate the results. Most analysts will have some training in the area of Non-

Determinism, fewer will have the sophisticated working knowledge needed to make the required validation assessments.

The most dire need for validation education is in the area of experimental mechanics, and especially precision testing designed for validation. The demise of almost any form of laboratory training in universities produces analysts with strong theoretical, and numerical, skills but a complete lack of knowledge of experimental mechanics. The other side of the precision testing ‘coin’ are the diminishing number of practicing experimental mechanicians. Because of the traditional separation of computations from experiments, it is rare to find an experimentalist with an understanding of the requirements of precision testing for validation. This lack of knowledge, on both sides, needs to be bridged with a sharing of knowledge.

6 History of the ASME V&V Committee

The American Society of Mechanics Engineers (ASME) Standards Committee on Verification and Validation in Computational Solid Mechanics has its origin as a suggestion of the American Institute of Aeronautics and Astronautics (AIAA) Computational Fluid Dynamics (CFD) Committee on Standards. After publishing their “Guide for Verification and Validation of Computational Fluid Dynamics Simulations” in 1998 [2] the CFD Committee recommended a similar guide to be published by a corresponding group in solid mechanics. They also believed it would best for the computational mechanics community if this group were not part of AIAA, and thus represented an even broader view of the interests of the community.

After several attempts by the CFD Committee to interest other professional societies in such a verification & validation (V&V) guideline effort, they reversed their top-down approach, and looked for existing professional societies committee that might be appropriate for the task. In 1999 as the chair of the ASME, Applied Mechanics Division, Committee on Computing in Applied Mechanics (CONCAM), I was contacted by Hans Mair with an inquiry if CONCAM was the appropriate ASME committee to undertake the task of writing a V&V guide to complement the work of the AIAA CFD Standards Committee. Being naïve about standards, and knowing only a bit about ASME’s larger organization, I suggested a more appropriate place to form such a committee would be under the imprimatur of the United States Association of Computational Mechanics (USACM).

In August of 1999 a proposal was presented to the Executive Committee of USACM for the formation of a verification & validation specialty committee to explore the possibility of developing V&V guidelines for computational solid mechanics, which would complement the already completed work of the AIAA CFD Standards Committee. The first task of the USACM V&V Committee was to solicit members. The nucleus of the Committee included the aforementioned Hans Mair, Bill Oberkampf a member of the AIAA CFD Standards Committee and co-author of the AIAA V&V guide, and Mike Giltrud a long time supporter of verification and validation and colleague of Hans and myself. This group of four developed a list of prospective committee members with a goal of including a broad range of backgrounds. A special effort was made to recruit members with backgrounds in experimental mechanics and uncertainty quantification as these are key areas in computational mechanics validation efforts.

The USACM V&V Committee held its first meeting in November 1999 as part of the ASME International Mechanical Engineering Congress & Exhibition (IMECE) in Nashville Tennessee. Two near term objectives were established at that meeting:

1. Develop an "Organization & Membership Policy" (completed March 00)
2. Develop a formal request to form an ASME Standards Committee (completed June 00)

Both objectives were achieved in early 2000. In November 2000, representatives of the Committee were invited to make a presentation to the ASEM Board on Performance Test Codes (PTC) seeking to form a V&V standards committee under this Board of ASME's Council on Codes and Standards. The Board took final action approving the Committee on Verification & Validation in Computational Solid Mechanics, also known as PTC #60, in September 2001. The Committee has the following charter:

To develop standards for assessing the correctness and credibility of modelling and simulation in computational solid mechanics.

The Committee continues to operate under the supervision ASME Board on Performance Test Codes under the direction of the ASME Council on Codes and Standards which is a standards organization certified by the American National Standards Institute (ANSI).

7 Conclusions

Significant progress has been made in verification and validation in computational mechanics. Increasing recognition of the importance of V&V is evidenced by such items as the formation of another ASME V&V Standards Committee (PTC #61) with a focus on 'procedures for quantifying the accuracy of modelling and simulation in computational fluid dynamics and heat transfer,' and adoption by two respected journals in computational fluid dynamics of V&V related requirements for publication of computational and related experimental results.

While the publication of verification and validation guides by the AIAA CFD Standards Committee, and soon the ASME Committee on Verification and Validation in Computational Solid Mechanics, are necessary first steps, the next step of attempting to write best practice documents appears to be a greater challenge. These committees need the support of the computational mechanics community. The best type of support is involvement in the committee's activities. The members of these committees are volunteers who give generously of their time for the larger good of the community. The committee work is very rewarding on a personal and professional level, you will not regret becoming involved in this worthwhile effort.

References

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