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On the validation of solid mechanics models using optical measurements and data decomposition

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ABSTRACT

Engineering simulation has a significant role in the process of design and analysis of most engineered products at all scales and is used to provide elegant, light-weight, optimized designs. A major step in achieving high confidence in computational models with good predictive capabilities is model validation. It is normal practice to validate simulation models by comparing their numerical results to experimental data. However, current validation practices tend to focus on identifying hot-spots in the data and checking that the experimental and modeling results have a satisfactory agreement in these critical zones. Often the comparison is restricted to a single or a few points where the maximum stress/strain is predicted by the model. The objective of the present paper is to demonstrate a step-by-step approach for performing model validation by combining full-field optical measurement methodologies with computational simulation techniques. Two important issues of the validation procedure are discussed, i.e. effective techniques to perform data compression using the principles of orthogonal decomposition, as well as methodologies to quantify the quality of simulations and make decisions about model validity. An I-beam with open holes under three-point bending loading is selected as an exemplar of the methodology. Orthogonal decomposition by Zernike shape descriptors is performed to compress large amounts of numerical and experimental data in selected regions of interest (ROI) by reducing its dimensionality while preserving information; and different comparison techniques including traditional error norms, a linear comparison methodology and a concordance coefficient correlation are used in order to make decisions about the validity of the simulation.

1. Introduction

Engineering simulation is used extensively in the process of design and analysis of engineered products at all scales to provide elegant designs optimized for cost, life and weight. Despite the development of easy-to-use finite element programs, it is still a complex task to create computational models that enable accurate representations of the physical reality; therefore the reliable prediction of design quantities (i.e. displacements, stresses, strains and the resulting safety factors) is difficult. This is particularly true for novel engineering structures, which may include new material systems with not completely understood mechanical behavior, combined with large-scale and increased structural complexity that may result

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in highly non-linear responses. Since the simulations are always simplifications of the real structural behavior, their ability to represent a complex physical reality at an affordable computing time and cost involves many assumptions about model parameters, which introduce uncertainty to the modeling process. To overcome the lack of credibility in simulations in cases where a high level of confidence in the design is required, the simple solution of conservative design is followed. However, this practice requires increased material usage, resulting in increased product cost and structures with large ecological footprints.

Major steps in achieving high confidence in the predictive capabilities of computational models are the model verification and validation. Verification is defined as 'the process of determining that a computational model accurately represents the underlying mathematical model and its solution' [1]. Software code developers mostly deal with the issue of verification, through the extensive comparison between numerical and analytical solutions, so as to prove that the model equations have been properly introduced and solved within the code. Whereas, validation is defined as 'the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model' [1]; this implies that the model should represent the real structural behavior with sufficient accuracy, therefore, it always needs reference to experimental tests.

Current validation practices tend to focus on identifying hot-spots in the data and checking that the experimental and modeling results have a satisfactory agreement in these critical zones. Often the comparison is restricted to a single or a few points where the maximum stress/strain is predicted by the model. This highly localized approach is the result of traditional strain measurement methodologies using strain gauges, but neglects the majority of the data generated by numerical analysis, carrying with it the risk that critical regions may be missed all together. For example, Jin et al. [2] used digital image correlation (DIC) to acquire a full-field map of strain in rectangular blocks of polyurethane foams subject to compression between steel plates; however, the quantitative comparison of simulation and experimental displacement fields was limited to selected sections in the specimen. Similarly, Spranghers et al. [3] made full-field measurements and used inverse methods to identify the plastic behavior of aluminum plates subject to free air explosions; but quantitative comparison between simulation data and experimental results was also limited to selected point locations, despite the availability of full field data.

Optical measurement technologies have reached a readiness level, due to recent developments, that enable displacement or strain data over large areas, or even the entire structure, to be reliably captured during an experimental test and thereafter visualized and analyzed. For example, Digital Image Correlation (DIC), Digital Speckle Pattern Interferometry (DSPI) and shearography are steadily replacing conventional measurement techniques such as strain gauges and extensometers [4]. Such developments provide the background for a more comprehensive approach to model validation, which could lead to optimized and less conservative designs. Although many companies have developed internal procedures for comparing simulation results to experimental data, there are no standard procedures for the validation of computational solid mechanics models used in engineering design. In the EU research project ADVISE [5], a methodology for validation of computational solid mechanics models based on full field data comparisons was developed [6]. In a subsequent European Union supporting action project VANESSA [7], the appropriateness of this validation procedure as part of a regulatory process for validation of computational solid mechanics models was examined.

In the present work, two important issues associated with the validation procedure are discussed, namely effective techniques to perform data compression using the principles of orthogonal decomposition, as well as methodologies to quantify the quality of simulations and make decisions about model validity. The three-point bending of an I-beam with open holes in the web was selected as an exemplar. Perforated I-beams are widely used in light-weight structures e.g. as aircraft wing spars, in steel building frames, as well as in many other engineering applications. The deformation of the I-beam was captured using a three-dimensional DIC optical system. At the same time, a detailed finite element model was developed to predict the stress, strain and displacement fields under three-point bending loads. The experimental and numerical data maps were compressed by applying Zernike decomposition. Subsequently the Zernike moment terms were compared in order to assess the validity of the simulation, by applying different techniques, including traditional error norms, as well as a linear comparison methodology and a concordance correlation coefficient. Advantages, difficulties, sensitivities and implementation issues related to the validation methodology have been revealed and further improvements of the methodology towards its whole field application are proposed.

2. Three point bending of perforated I-beam: testing and modeling

The three-point bending of an aluminum I-beam is shown schematically in Fig. 1. Despite its simple geometry, the perforated I-beam has many interesting structural analysis features, such as high stress concentrations around the holes, local plasticity in the contact areas and geometric – material non-linearity due to contact at the indenter and supports. The material properties of the aluminum beam are presented in Table 1. For the experimental purposes, an MTS testing machine capable of delivering up to 250 kN normal force was used and the beam was placed on two rigid cylindrical supports that were 450 mm apart. A steel rod was used to apply a nominally static vertical force at the mid-point of the beam. Additionally, a stereoscopic DIC system (Aramis 5 M [8]) was employed to measure displacements during the loading event, using images acquired at a frequency of 15 frames per second. Strain fields were calculated from the displacement measurements for a region of interest (ROI) on the beam web (260 mm $\times$ 60 mm), covering the contact location and the area around the holes, as shown in Fig. 2, with the aim of including all of the regions of stress concentration and the contact zones. Prior to testing, a