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Validation of computational solid mechanics models

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CEN WORKSHOP AGREEMENT

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English version

Validation of computational solid mechanics models

This CEN Workshop Agreement has been drafted and approved by a Workshop of representatives of interested parties, the constitution of which is indicated in the foreword of this Workshop Agreement.

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Foreword

This CEN Workshop Agreement has been drafted and approved by a Workshop of representatives of interested parties on 2014-06-11, the constitution of which was supported by CEN following the public call for participation made on 2013-02-27.

These organizations were drawn from the following economic sectors: Aerospace; Automotive; Instrument manufacturing; Nuclear power; Research institutes and Universities. The following individuals have contributed to and support the technical consensus represented by this CEN Workshop Agreement:

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The final review/endorsement round for this CWA was started on 2014-05-10 and was successfully closed on 2014-06-10. The final text of this CWA was submitted to CEN for publication on 2014-06-30.

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Comments or suggestions from the users of the CEN Workshop Agreement are welcome and should be addressed to the CEN-CENELEC Management Centre.

0. Introduction

0.1. Engineering simulation is an essential feature in the design and manufacture of all engineered products at all scales. In particular, simulation based on computational solid mechanics models permits designers to optimise the load-bearing components in devices, machines and structures so that a satisfactory level of reliability is achieved for an acceptable cost. The desire for a sustainable society stimulates designers to create elegant, light-weight designs in which embodied energy and material is minimised; however at the same time consumers demand “total reliability” that often can be achieved most easily by heavy, conservative designs in which additional material provides additional factors of safety. Removal of these safety factors to create light-weight and efficient designs requires a very high level of confidence in the engineering simulations. This confidence level should be acquired through rigorous, quantitative validation of the models employed for the simulations. Although many engineering companies and organisations have developed internal procedures for validating the computational models that are essential to their engineering design activities, there are no standards for the validation of computational solid mechanics models used in engineering design. Consequently, many engineering artefacts are designed using inadequately validated computational models which when this is recognised leads to conservative design, and when it is not recognised leads to unreliable design. The lack of standardisation inhibits the exchange of both data from simulations and of models used for simulation, which in turn slows down innovation, particularly in industries producing engineering systems that are composed of many sub-systems produced by different manufacturers. This CWA aims to address this short-fall.

0.2. The terms ‘model’ and ‘simulation’ are often used interchangeably in the engineering community. In this document the term ‘simulation’ is taken to mean ‘the imitation of behaviour or operation of a real-world system or process’ and it is assumed that a computational model is used to perform the simulation. A ‘computational solid mechanics model’ describes the response of a solid medium subject to loading, more specifically it relates the loading conditions, the material behaviour and the response of an object. The material behaviour is usually introduced in computational solid mechanics models using constitutive formulae which can be termed ‘constitutive models’.

0.3. Computational solid mechanics models are, in general, based on the finite element method[1] with some use of the boundary element method[2]. A large number of commercially available software packages provide end-users with varying degrees of modelling capability based on these methods. It is the norm for the suppliers of these packages to perform verification of the modelling method; in which verification is defined as *‘The process of determining that a computational model accurately represents the underlying mathematical model and its solution’*[3]. However, it is the responsibility of the user to perform adequate validation of each model developed with a package. 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'*[4]. A large number of benchmarks are provided by e.g. NAFEMS[5] to support vendors and users in verifying finite element packages; but support for the validation process is almost non-existent. The American Society of Mechanical Engineers has developed a Guide for Verification and Validation of Computational Solid Mechanics[4] which describes what is required but does not provide any methodology for performing a validation. The objective of this CEN Workshop Agreement is to fill this gap by providing a general approach to the validation of computational solid mechanics models used in engineering design and evaluation of structural integrity.

0.4. At the moment there are no directives or relevant national legislation and very little documentation in the form of standards or standardization related activities concerned with the validation of computational solid mechanics models. The United States Department of Defense issued a

[1] Zienkiewicz, O.C., & Taylor, R.L., The finite element method: basic formulation and linear problems, McGraw-Hill, New York, 1989.

[2] Banerjee, P.K., Butterfield, R., Boundary element methods in engineering science, McGraw-Hill Book Co., London, 1981.

[3] Computational Fluid Dynamics Committee on Standards, “Guide for Verification and Validation of Computational Fluid Dynamics Simulations,” American Institute of Aeronautics and Astronautics, AIAA G-077-1998, ISBN 1-56347-285-6, January 1998.

[4] ASME V&V 10-2006, Guide for verification & validation in computational solid mechanics, American Society of Mechanical Engineers, New York, 2006.

[5] National Agency for Finite Element Methods and Standards, www.nafems.org

glossary of terminology for modelling and simulation in 1998[6], while the American Society for Testing of Materials has published a "Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems"[7], which describes the principal approach for obtaining data for the validation process. There has been some activity in the scientific literature with Schwer[8] describing in outline the 'Guide for verification and validation in computational solid mechanics'[4]. He identified that verification can be achieved largely without reference to the real-world. Whereas, validation should be achieved by reference to experiments conducted specifically for this purpose.

0.5. The traditional approach to validation of computational solid mechanics models is to obtain experimental data from strain gauges bonded to a physical realisation of the model at locations of high stress indicated by the simulation. There are two major flaws with this approach: (i) the locations of highest stress may be elsewhere than predicted by the simulation and could lead to component failure; and (ii) no validation is performed in regions of apparently low stress where the design might be optimised by removal of material mass, so again increased stress in these regions could lead to component failure.

0.6. More comprehensive data-fields from experiments are available for validation via the use of optical techniques such as digital image correlation, photoelasticity, and thermoelastic stress analysis. These techniques provide data over a full field of view, and thus generate maps of displacement, strain or stress containing of the order of 10^6 data points, which is comparable to the number of nodes found in computational models. A point-by-point comparison of such data-rich maps from different sources and in different coordinate systems is computationally expensive, maybe impractical, and leads to a result that is not useful or at least cumbersome to interpret. Consequently, it is common practice to extract sections of experimental data from such maps for comparison to values predicted by simulations [e.g. 9, 10, 11] and, while this is an improvement on validation compared to using data from a small number of points at which strain gauges are located, it falls short of the comprehensive, quantitative validation that is sought to provide high levels of confidence in engineering design simulations.

0.7. The output from the validation process needs to be in a format that allows decision-makers to quantify their confidence in the computational models used in the design process. A key step in this quantification is establishing the uncertainty in the experimental data. The uncertainty in the data maps from experiment can be evaluated via the calibration of the optical system employed for their measurement[12,13,14]. More recently, the reliability of data collected in experiments involving variable amplitude loading has been considered, and statistical methods have been developed to quantify the associated uncertainties based on probability density functions[15]. Calibration provides traceability via a continuous chain of comparisons to an international standard, in this case for length, and also allows the measurement uncertainty to be established. Traceability is important in areas such as aerospace and nuclear power, which require certification of designs by regulatory

[6] DoD Modeling and Simulation Glossary, Under Secretary of Defense of Acquisition Technology, Washington DC., January 1998, available at www.dtic.mil/whs/directives/corres/pdf/500059m.pdf

[7] ASTM E2208 - 02(2010)e1 Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems, American Society for Testing of Materials, West Conshohocken, PA, 2010.

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[15] Baharin, MN., Nopiah, ZM., Abdullah, S., Khairir, MI., Lennie, A., The development of validation technique in variable amplitude loadings strain repetitive data collection, *Key Engineering Materials*, 462-463:337-342, 2011.

authorities. The establishment of measurement uncertainties is critical in making quantitative judgments about comparisons between datasets.

0.8. Recently, it has been proposed that a comparison of maps of strain and displacement data from computational models and experiments can be performed straightforwardly using shape descriptors[16]. Since these maps contain some level of redundant information, shape descriptors, which are rotation, scale and translation invariant, provide an effective means of comparison. Shape descriptors, including geometric moments, Fourier descriptors and wavelet descriptors are used in the field of image analysis for applications such as finger print recognition[17], face recognition[18], target recognition[19], and medical diagnostics [20]. They allow the decomposition of high resolution images into only a hundred or less unique moments, which are a faithful representation of the relevant features in the corresponding image. Recently[21], it has been demonstrated that a comparison of two sets of shape descriptors[22], describing the strain maps obtained from digital image correlation and computational modelling, can be used to update a finite element model[23] and improve its fidelity. These studies are innovative because they treat maps of strain as images and represent them with a small number of information-preserving moments which allows statistical measures to be applied effectively.

0.9. This CWA builds on the philosophy and recent advances described above to provide a methodology for validating computational solid mechanics models in a manner that is consistent with existing guidelines [4,6,7].

[16] Sebastian, C., Hack, E., Patterson, EA., An approach to the validation of computational solid mechanics models for strain analysis*, J. Strain Analysis*, 48(1):36-47, 2013.

[17] Ismail RA., Ramadan MA., Danf TE., and Samak AH., Multi-resolution Fourier-Wavelet descriptors for fingerprint recognition. *Int. Conf. on Computer Science and Information Technology,* 951- 955, 2008.

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1. Scope

1.1. This CEN Workshop Agreement (CWA) builds on the research outputs of two completed projects from the European Commission's Framework Programmes FP5 and FP7 with the aim of supporting their implementation in engineering industry and the related research community. The FP5 project SPOTS (Standardisation Project for Optical Techniques of Strain measurement) led to a unified calibration methodology for all optical systems capable of measuring strain fields on planar surfaces of engineering components subject to static and pseudo-static loading[12-14]. The SPOTS project provided an initial step in the process of validating computational solid mechanics models by creating a route for providing high quality data from experiments which is a pre-requisite in the validation process.

1.2. The FP7 project ADVISE[24] extended the research outputs from SPOTS in two important areas, i.e. developing an efficient quantitative method of comparing very large datasets[16,21] based on image decomposition and extending the calibration methodology to include dynamic and out-of-plane loading of engineering components.

1.3. This CWA includes both a protocol for validation of computational solid mechanics models using data-fields from calibrated instruments and a methodology for the calibration of optical systems for measurement of displacement and strain fields in static and dynamic loading. These procedures provide a general approach to the validation of computational solid mechanics models used in engineering design and the evaluation of structural integrity.

1.4. This CWA exploits a number of very powerful optical measurement techniques for acquiring displacement and strain data in engineering components subject to service loads[25], of which digital image correlation is becoming ubiquitous. These techniques generate high-density maps of displacement and strain containing of the order of 10^5 to 10^6 data values per view, which with careful experimental design could cover the majority of the surface of an engineering component. This CWA provides a procedure for the quantitative comparison of such data with corresponding data generated by engineering simulations based on computational solid mechanics models.

1.5. This CWA proposes the use of image decomposition to allow displacement and strain fields to be represented by feature vectors, which are invariant to rotation, scale and translation, and allow enormous data compression while preserving all of the relevant information[21]. A validation protocol is described, based on this data compression, that is efficient to apply, takes into account uncertainties, and gives a quantitative measure of the level of agreement between the datasets from experiment and simulation[16].

1.6. It is not the intention that this CWA should provide a definitive or prescriptive methodology for the validation of a computational solid mechanics model. Instead, an objective criterion and a set of associated tools are provided that can be incorporated into a plan or strategy for verification and validation, which is appropriate to the model and its intended uses. The ASME Guide for Verification and Validation in Computational Solid Mechanics[4] provides further guidance on such plans and strategies, so that the procedures described here can be seen as complementary to the ASME guide.

[24] ADVISE, *Advanced Dynamic Validations using Integrated Simulation and Experimentation*, Project No. SCP7-GA-2008-218595, see www.dynamicvalidation.org.

[25] Burguete, R.L., Lucas, M., Patterson, E.A., Quinn, S., *Advances in Experimental Mechanics VIII*, Applied Mechanics and Materials, vol. 70, Trans Tech Publications, Durnten-Zurich, Switzerland, 2011.