Mid-Stage Validation as a Process Step in Simulation V&V

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Abstract

Physically accurate simulation is a requirement for initiatives such as late-stage prototyping, additive manufacturing and digital twinning. The use of mid-stage validation has been shown to be a valuable tool to measure solver accuracy prior to use in simulation. Factors such as simulation settings, element type, mesh size, choice of material model, the material model parameter conversion process, quality and suitability of material property data used can all be evaluated. These validations do not use real-life parts, but instead use carefully designed standardized geometries in a controlled physical test that probes the accuracy of the simulation. With this *a priori* knowledge, it is possible to make meaningful design decisions. Confidence is gained that the simulation replicates real-life physical behavior. We present three case studies using different solvers and materials, which illustrate the broad applicability of this technique. A quasi-static three-point bending experiment of an injection-molded parallel-ribbed plastic plate is performed and simulated using Abaqus software. A quasi-static bending/torsional experiment is performed on a 3D printed aluminum crank and simulated using ANSYS software. For both of these cases, digital image correlation (DIC) is used to measure the strain fields resulting from the complex stress state on the face of the part to quantify the simulation's fidelity. In the third study, a compression test on rubber is simulated with different hyperelastic material models using ANSYS. A comparison of the load v. displacement curves is used to quantify the simulation's fidelity. These studies illustrate the value of performing mid-stage validation at the start of any product development process where a new material, end-use application, load case or processing method is used.

1. Introduction

The use of computer simulation for design decision making is commonplace today, providing benefits such as wider examination of possible design options, geometric shape optimization and reduced late-stage prototype testing . There are even greater goals for this technology namely, digital twinning where the entire fully functional product exists in a digital environment. Achieving this goal requires that the physics of every aspect of the real product be correctly replicated in the simulation. While digital twinning can be achieved with moderate effort for some products, it can be a challenging task in general, due to product complexity and the non-linear multi-variate behaviour associated with most materials. It is clear nonetheless, that correct physical representation of the product is an essential requirement for simulation-driven design.

Achieving this goal is a complex matter involving many uncertainties and unknowns. Factors such as the ability of the solver to solve the equations correctly (verification), simulation settings, element type, mesh size, appropriateness of material model, the material model parameter conversion process, quality and suitability of material property data. Verification can be performed using benchmark problems in a virtual framework [1]. The balance of unknowns are best quantified using validation against an experimental test.

Validation needs to address a number of questions: relevance, fidelity, precision and accuracy. The question of what constitutes a suitable experiment is an important one. Ideally, it would be best to perform a simulation of a finished part, produce the prototype, test it and confirm that the simulation replicates reality, but this workflow has many problems.

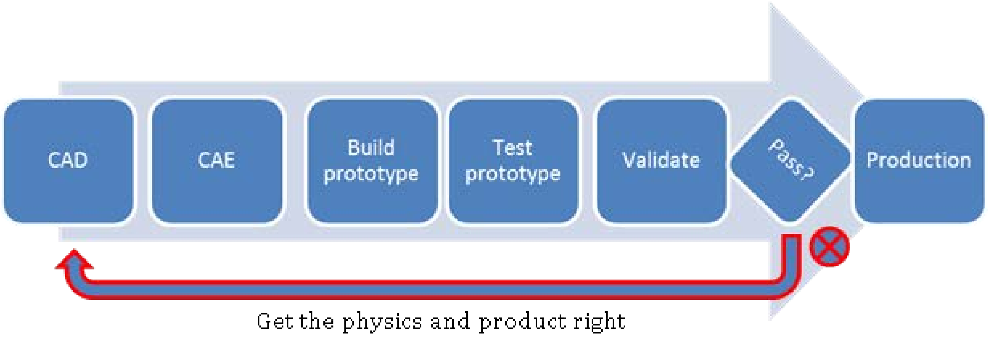

Figure 1: Validation with actual prototype.

The prototype is not ready until late in the design process so there is no guarantee that the simulation actually works except after the fact. While this data might help in the next simulation cycle, design factors and materials can change by then, rendering this type of validation irrelevant.

The simulation of prototype tests is challenging because it is often difficult or impossible to correctly set up the right boundary conditions and load cases in simulation. Quantified comparisons between simulation and experiment are not easily achieved resulting in lost time and possibly even incorrect conclusions. Discerning causes for the differences observed is not easy. That is not to say that comparing prototype test to simulation is unnecessary. On the contrary, significant benefit can be achieved with a post-mortem approach providing valuable knowledge about the ultimate success of the simulation.

Late stage validation of simulation comes with other drawbacks. It provides no confidence measure for iterations within the current design cycle. It is not compatible with light-weighting and additive manufacturing protocols which heavily exploit the ability of simulation to inform the final part shape. In these scenarios, an inaccurate simulation results in failed or overdesigned parts.

An alternate approach that validates simulation accuracy prior to commencing design of actual parts and assemblies is cheaper in the long run and can bring confidence and valuable insight to simulation-driven product development. The approach enables the application of light-weighting and additive manufacturing by ensuring that conceptualized parts behave like real-life parts. This paper concludes a multi-year study, drawing from previously released partial findings to build the case for mid-stage validation.

2. Method

The use of mid-stage validation has been shown to be a valuable tool to measure solver accuracy prior to use in simulation. Factors such as simulation settings, element type, mesh size, choice of material model, the material model parameter conversion process, quality and suitability of material property data used can all be evaluated. These validations do not use real-life parts, but instead use carefully designed standardized geometries in a controlled physical test that probes the accuracy of the simulation. The process takes a few days instead of the weeks or months typically associated with late-stage validation. The mid-stage validation is designed around four ideas:

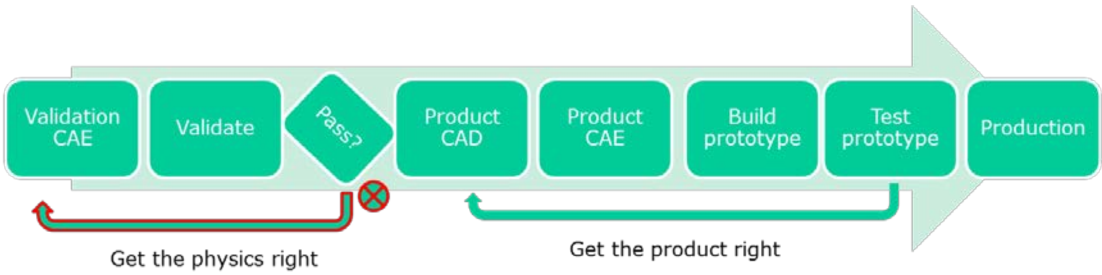

Figure 2: Mid-stage validation workflow.

Standardised geometry: While it may be attractive to validate against real-life parts, these sometimes do not lend themselves well to validation. They are often not available early in the design process or they cannot be tested with adequate precision to allow for a quantified comparison to the simulation. Instead, an alternate geometry can be created that contains features commonly seen in real life parts which when tested, will result in deformations and behaviours that are known to challenge the simulation. Importantly, these geometries must be easily made using the actual materials of interest. The design must facilitate the application of load cases that are correctly replicated in simulation. Sometimes, a standard test is available, which is greatly beneficial [2].

Complex load case: The measurement of material properties used for material model parameters aims to perform precise, highly specific measurements to get to the fundamentals of material behaviour. Real life applications typically involve complex multi-mode deformations. Computer simulations combined with the appropriate material model attempt to calculate these responses. A mid-stage validation requires a complex load case in order to adequately test the simulation. The load case should ideally have some characteristics similar to the real life situation.

Material Model: The material model should contain the right characteristics to adequately describe the material behaviour for the load case. Most simulation codes contain a number of material models and selecting the correct one is an important step. The calibration process to obtain the parameters of the material model can sometimes be done in a variety of ways and there is no guarantee as to which method yields the best result. It is vital that the material data used to develop the material parameters is obtained from the actual material that will be used in the product including the same manufacturing process. The measurement must be is scientifically accurate performed with adequate precision and traceability, that there is adequate statistical representation; and that the data cover the range of interest: strain, time, rate, temperature, for example.

Accuracy measures: Quantified comparisons allow for an assessment of the quality of the simulation. Simple comparisons include force v. time or displacement measures. The use of digital image correlation (DIC) presents an unprecedented opportunity for validation by allowing the comparison of surface strains at specific regions of interest. In our work, we have been able to create features in the standardized geometries that can be observed during the experiment to truly identify limitations in the simulations.

We have compiled the results of three case studies to illustrate the value of our approach. A fourth study on the validation of impact simulations with LS-Dyna was published but is not summarized here for brevity sake.

3. Case Study 1: 3D printed metal – linear elasticity with failure

The Cornell bike crank experiment [3] is part of a university lab course that teaches the importance of validation in finite element analysis. A bicycle-like crank geometry is subjected to a controlled static load case similar to the kind of force it might experience from a person using a bicycle. One end of the crank is rigidly fixed while the other end is subject to a static rotational force. Four crank geometries exist, each created to highlight stress states of varying complexity. The cranks are particularly designed to enable the calculation of deformation using classical analytical methods and can also be easily reproduced in ANSYS simulations. Experimental strains are measured using strain gauges placed at specific locations of the crank. Measured strains are compared to calculated and simulation values to provide a measure of simulation accuracy. The original classroom experiment was found to contain sources of experimental error which made it difficult to provide a reliable basis for validation. Borschoff et al [5] eliminated strain gauges from the experiment by switching to digital image correlation (DIC) methods, significantly improving the correlation accuracy to ANSYS. In their work, they showed that ANSYS correlated to real life within 10% for linear elastic simulations of metals, which is similar to the accuracy of ANSYS compared to hand calculations for this geometry.

For the additive manufacturing validation, one of the Cornell cranks was modified to enhance stress states in particular regions of the part. Cranks were printed in a single XY plane along with tensile bars through direct metal laser sintering of EOS Aluminum AlSi10Mg from EOS GmbH.

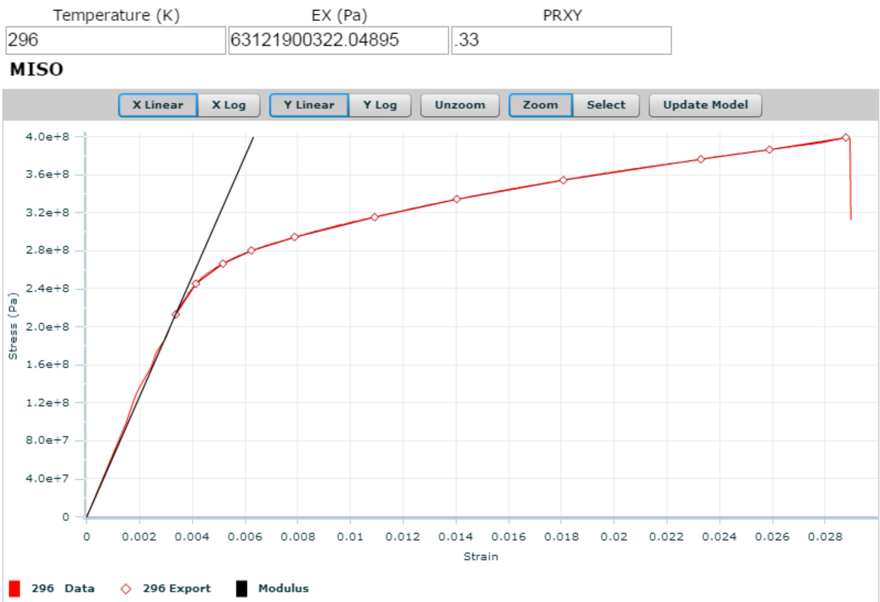

Figure 3: DIC validation of 3D printed bike crank (images are on same strain scale).

Stress-strain tests were performed on the 3D printed tensile bars. The failure strain was noted to be 400Mpa. Matereality's CAE Modeler for ANSYS was used to build a Multilinear Isotropic Hardening (MISO) material model model from the stress-strain data.

The linear elastic simulation showed remarkable spatial and quantitative correlation with the DIC experiment (Figure 4). During the experiment, the crank sustained a load of 1800 N before failing. Brittle failure occurred at the bottom left corner (A) of the crank (Figure 5) following which a subsequent failure occurred in the top right corner (B) as the moving part of the crank continued to break away from the fixed end.

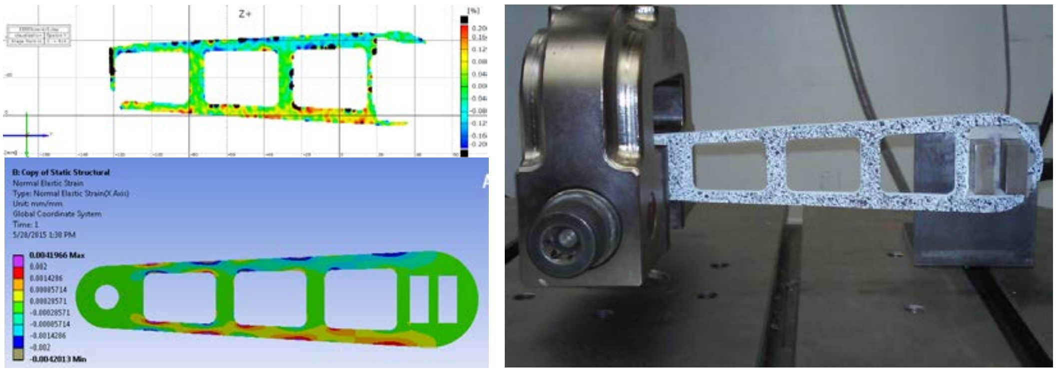

Figure 4: DIC validation of 3D printed bike crank (images are on same strain scale).

In the non-linear simulation, an application of the same load resulted in two high-stress locations which coincided with those observed in the experiment: 446 MPa for location A and 399 MPa for location B. The stress levels when compared to the measured fail strain from the tensile test, showed the simulation correctly predicting failure.

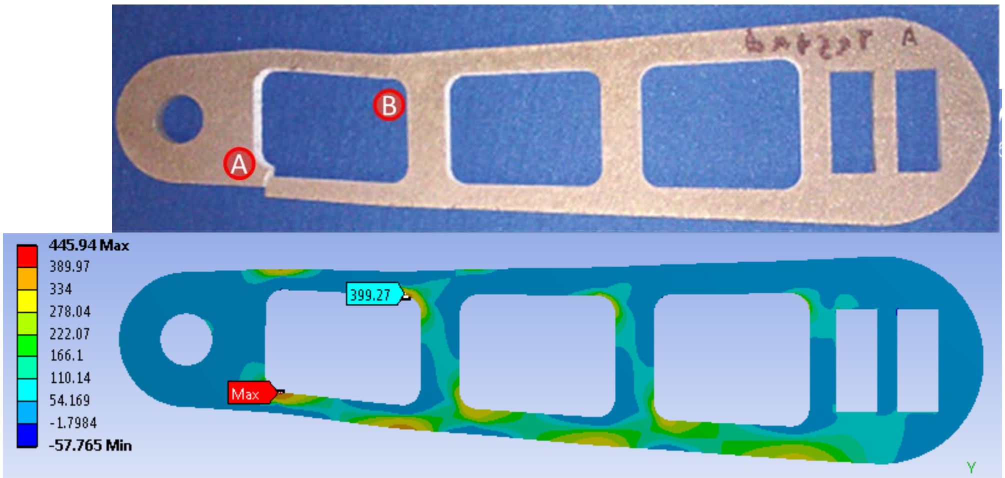

Figure 5: Failure correlation of 3D printed bike crank

In subsequent work, the results of this kind of validation have been used to lightweight and 3D print an aircraft component which was then shown to perform as predicted [5].

4. Case Study 2: Elasto-plasticity of ductile plastics

The simulation of ductile plastics is known to have fidelity issues due to material modeling limitations: the commonly used elasto-plastic material model is based on metals theory and has been shown to be deficient for describing the non-linear elastic behavior of plastics with accompanying plasticity [6]. In this case [7], an injection-molded polypropylene plate with large parallel fins was selected. It was chosen because it had flow complexity of the kind seen in typical injection-molded products, could be loaded in a manner that we could reproduce in simulation, while exposing regions where surface strain could be accurately measured by DIC. For the validation, we performed a three-point bend test on the plate and recorded the surface strain on the fin using DIC as well as the reaction force on the loading pin.

Tensile bars obtained from the polypropylene were used to measure the stress-strain properties and calibrate an Abaqus *ELASTIC, *PLASTIC material model. A simulation of the validation experiment was performed using Abaqus/Explicit to apply the force used in the validation experiment.

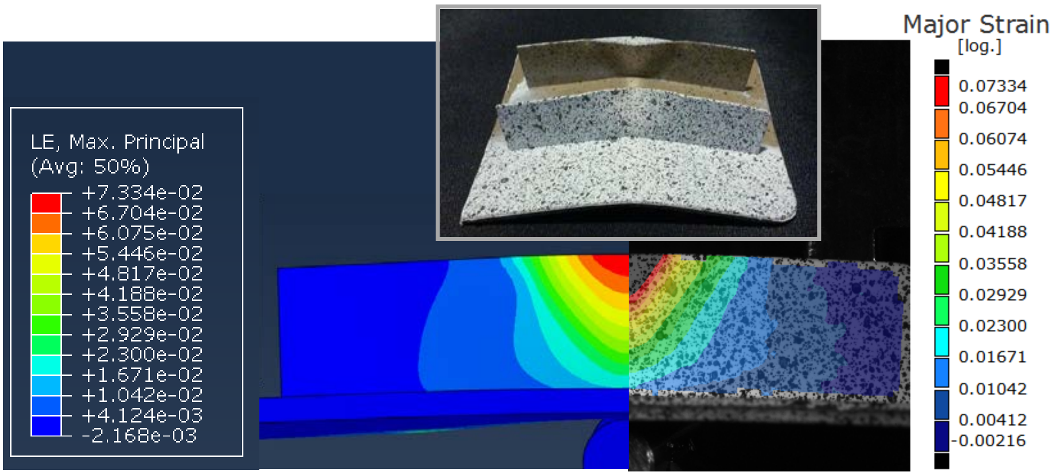

Figure 6: DIC surface strain comparison to Abaqus/Explicit at 2 mm displacement

At a loading pin displacement of 2 mm, the maximum local strain predicted by the simulation was 7.3% compared to 9.82% measured experimentally by DIC, amounting to a 26% variation. Plotting the maximum strain v. displacement for both the experiment and the simulation (Figure7), excellent agreement was observed up to 1.6 mm of pin displacement after which the simulation began to diverge dramatically from the experiment.

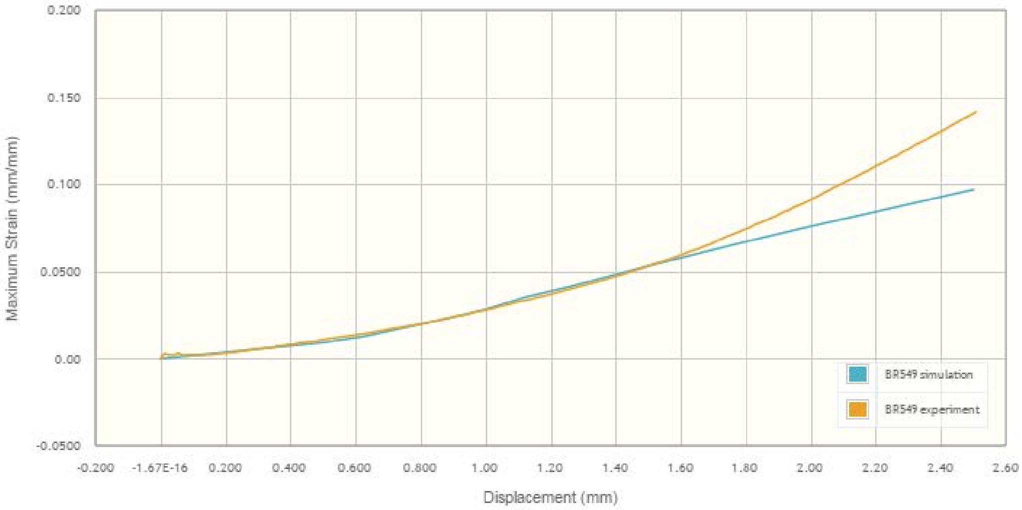

Figure 7: Local strain v. loading pin displacement for experiment and simulation

In contrast, the simulation reaction forces were highly accurate to a displacement of the loading pin of 2 mm (Figure 8). At this displacement, the reaction force on the loading pin was 860.3 N in the experiment and 860.0 N in simulation, with a variation of 0.03%. One possible reason for these deviations may be that the behaviors are beyond the capability of the elasto-plastic material model used in the simulation. Other possible reason could have been that the mesh refinement used was not sufficient to capture the complex bending shape in the fin.

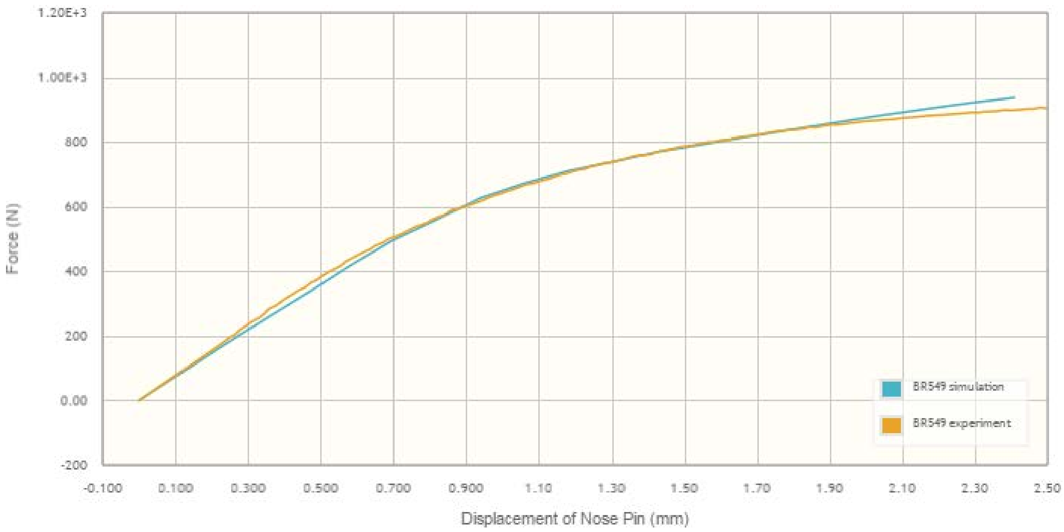

Figure 8: Reaction force v. loading pin displacement for experiment and simulation

5. Case Study 3: Rubber hyper-elasticity

Creating a mid-stage validation for hyperelastic material models is particularly useful. Unlike the elastic-plastic models from our previous studies on validation where the plastic curve is tabulated data from a tensile curve, many hyperelastic models are governed by an equation where the materials' modes of deformation are characterized through its coefficients. In order to simultaneously describe uniaxial, shear, and biaxial deformation modes for the model, the goodness of fit often suffers. In addition, when fitting a material model there may be variability in the coefficients depending on the seed values. Comparison of which of model better represents reality can be done quickly with validation.

In this case [8], the validation experiment is based on a compression test in conformance with ASTM D575 [9]. The test specifies a no-slip condition at the compression platens resulting in shear and uniaxial behaviour in addition to predominantly biaxial state in the compression button. Volumetric effects also exist. At large deformation, the rubber flows and the sides come into contact with the platen. This allows for the validation to be tested at large strains with significant element distortion, situations that often cause concern in real-life rubber simulations.

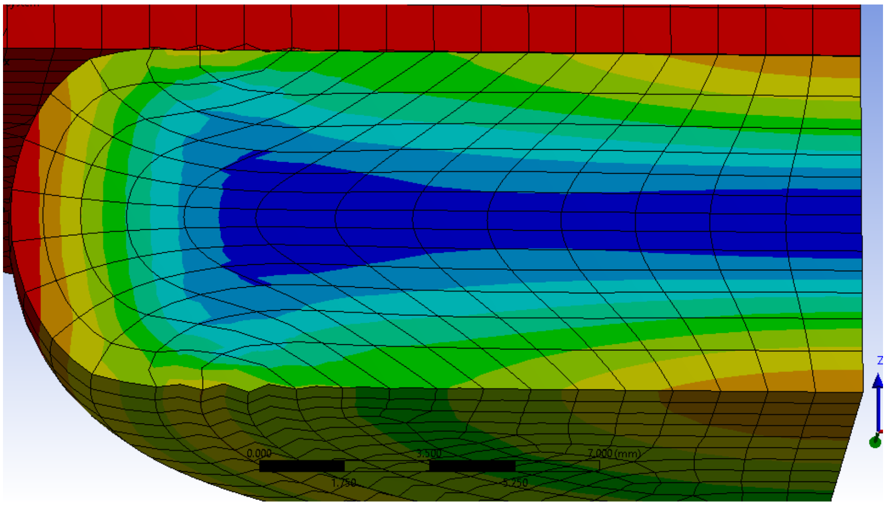

Figure 9: Simulation of compression test showing element distortion at large strain

For these compression tests, an ANSYS simulation was created. Mooney-Rivlin and Ogden hyperelastic material models were fit and validated against the experimental data [8]. There are also issues with contact, where the penetration of the rubber elements into the platen surface is greater than expected when the rough contacts were used. Mesh distortion was apparent after the first few milimeters of deformation in the model. The different material models varied in fidelity to the experimental curve. The Ogden model appeared to be off with a difference of 34% at 2mm displacement but was able to achieve the target displacement of 6.35 mm. The force deviation between simulation and test at 6.35 mm was 5%.

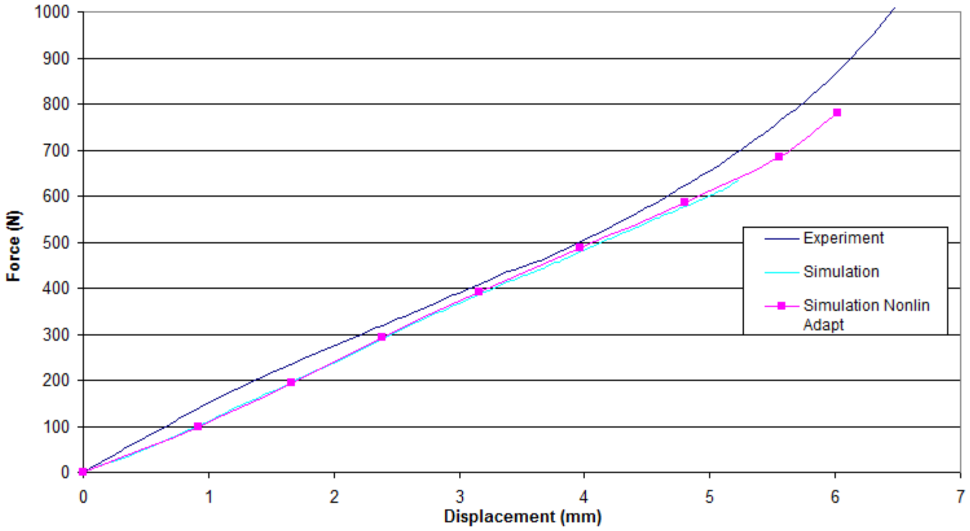

Figure 10: Ogden model validation with and without adaptive meshing

With the Ogden model as the notable exception, the simulation terminated prior to the target displacement as it was unable to resolve the force imbalance. Some of this is based on the skewness of the elements, and can be partially relieved by nonlinear adaptive meshing. The simulation with the adaptive mesh tested with the ANSYS-derived Mooney-Rivlin (M-R ANSYS) material model displaced an additional 0.78mm, the final deviation for the adaptive meshed simulation from the experiment was 10%.

4. Conclusions

Mid-stage validations with standardized geometries are beneficial in ensuring that the simulation is performing correctly prior to use in real-life applications. These validations are relatively easy to perform compared to late-stage validations against real life components, adding confidence to the design process and allowing for new generation concepts such as shape optimization and additive manufacturing to be implemented. In this process it is possible to probe questions about choice of solver, element type and size, meshing strategies and choice of material models. These decisions guide how the real-life components will be set up in the simulation.

Mid-stage validations are not part specific, meaning that the results can be useful for a variety of geometries that use the same material. Alternate material models, solvers or other simulation-side variables can be validated against the same experiment. A change to the material, processing or product environment (operating temperature or humidity, for example) would require the generation of new material data and a fresh validation experiment.

6. Acknowledgements

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