Modelling of bonded component tests – Comparing MAT_240 to state-of-the-art models

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1 Introduction

Modelling of adhesively bonded joints is still an active field of research, aiming for a more accurate description and simpler calibration processes without significant increase in computational costs. There are two different approaches typically applied to model adhesives depending on the size of the problem and required accuracy. For smaller problems where the computational cost is of less relevance, the adhesive line can be finely discretized and modelled with a mesoscopic material model. This mesoscopic model is characterized by a constitutive law describing the relation between stresses and strains in the material. One such model is the SIMLab Polymer Model (SPM), described by Morin et al. [1], which has been used in the current work. It was specifically made to capture the key phenomena present in polymeric materials, such as large elastic and plastic deformations, strong rate sensitivity, pressure sensitivity and possibility for softening. These features are also relevant for adhesives. Given that the model is accurate and properly calibrated, it could be used to simulate virtual experiments that could further be used to calibrate models used in large-scale analysis.

The second approach, typically applied to large-scale analysis, describes the adhesive layer using a cohesive zone model (CZM) or a constraint defined by a traction separation law. Models that are currently applied in the industry include MAT_138 and MAT_240 [2]. MAT_138 incorporates a simple triangular traction separation law, while MAT_240 is represented by a tri-linear traction separation law that also includes rate sensitivity. There are new models developed recently such as the one presented by Sønstabø et al. [3], which is a modified version of MAT_240 with more flexibility regarding the mixed mode response. Further, a Gurson based cohesive zone model (GCZM) was described by Said Schicchi and Caggiano [4], where the damage is based on growth of voids in the material. This model shares similarities with a lower-scale model, as the traction separation law is just a modified version of a Gurson based constitutive model.

A series of components, which consists of two hat profiles bonded together, were tested in 3-point bending. To simulate the component tests, the three models MAT_240, MAT_240 modified and GCZM were used to describe the adhesive behaviour. The two state-of-the-art models MAT_240 modified and GCZM were implemented as user materials in LS-DYNA. Calibration of the three models was done through a partial virtual laboratory, where the virtual experiments were based on the SPM. Simulation results of the component tests were compared to each other as well as test data, and then discussed with respect to suitability and accuracy.

2 Experimental setup

Component tests composed of two hat profiles; the top section is made with a rolled micro-alloyed steel sheet while the bottom one is made with a 6XXX aluminium sheet. These two hat profiles were adhesively bonded together using the adhesive SikaPower 498. These components were tested in 3-point bending. A progressive failure of the bonded line was observed in all repetitions, such that the behaviour of the adhesive line could be considered critical for the response of the component.

3 Modelling: Calibration procedure

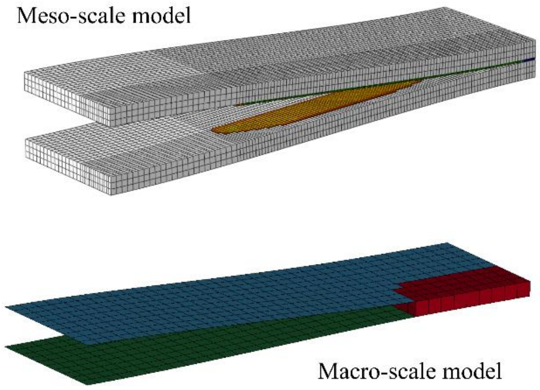

Fig.1: Finite element models of meso-scale and macro-scale simulations.

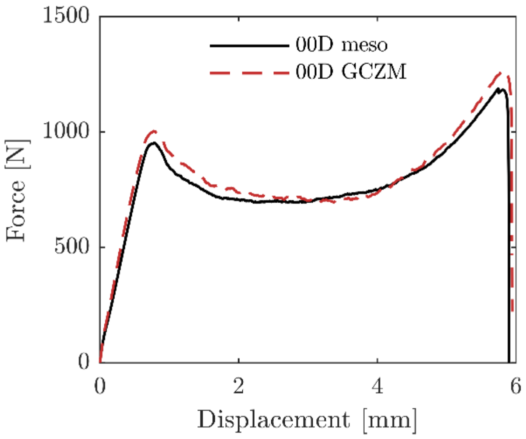

Fig.2: Smoothed force vs. displacement for 00d meso-scale model compared to macro-scale model using the GCZM.

Calibration of the cohesive zone models applied in this study was done using a partial virtual laboratory. In this virtual laboratory, the experiments required to calibrate the cohesive models are replaced by accurate numerical analyses using a mesoscopic model to describe the adhesive layer. The SPM [1] was employed to model the adhesive layer in this work. It was calibrated from three tension tests at different strain rates, one compression test and one notched tension test. These tests were required to calibrate the viscoplasticity, pressure sensitivity and critical damage of the model. It should be noted that the failure model employed in this work is a simple model with only one parameter that is directly dependent on the volumetric plastic deformation.

Three generic joint configurations were simulated using this model to serve as virtual experiments for calibration of macroscopic models. These configurations represent three global deformation modes applied to the three joints. The 00d configuration is loaded in global tension, leading to a peel-dominated load as seen in Figure 5. Further, the 90d configuration represents global shear deformation with almost pure shear load in the adhesive layer. Finally, the 45d configuration represents a mixed mode deformation mode globally. The philosophy behind the design of these virtual experiments was to retain a simple geometry and to use a representative width of the adhesive layer. Additionally, it was ensured that the adhesive line was long enough to avoid edges dominating the behaviour as well as allowing for significant crack propagation. It was found that both failure load and propagation were mesh dependent. Therefore, a mesh size corresponding to the mesh size used for calibrating the critical damage was chosen for the adhesive layer, meaning 3 elements through the thickness.

In order to determine the parameters for the macroscopic models, the simulation results from the detailed analyses were used as target curves for optimization using LS-OPT. Rough models of the generic joints were created, with a general mesh size of either 2mm or 4mm depending on the mesh size of the final application for the models. These models use shell elements to describe the adherents and solid elements with formulation 20 for the adhesive line. It should be noted that there is significant noise in the calibration models when using a 4mm mesh. Therefore, the focus is on the 2mm models in this work. Before performing the parameter identification, it was determined which parameters were already available from the mesoscopic models in order to reduce the number of parameters to calibrate. The parameters linked to rate sensitivity were neglected, as the intended application is a quasi-static problem. With that accounted for, the GCZM model only required 4 parameters to be calibrated, this is because it uses many of the parameters from the mesoscopic models. In comparison, MAT_240 has 8 parameters and MAT_240 modified requires 12 parameters. Results from the detailed model and the rough model using GCZM for the 00d configuration are compared in Figure 6.

4 Modelling: Component test simulation

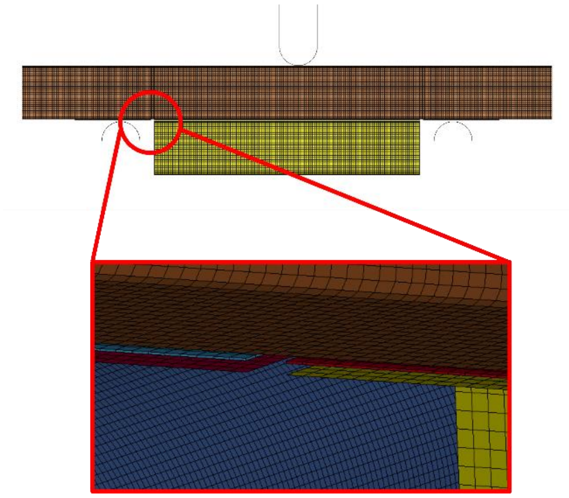

Fig.3: Finite element model of component test.

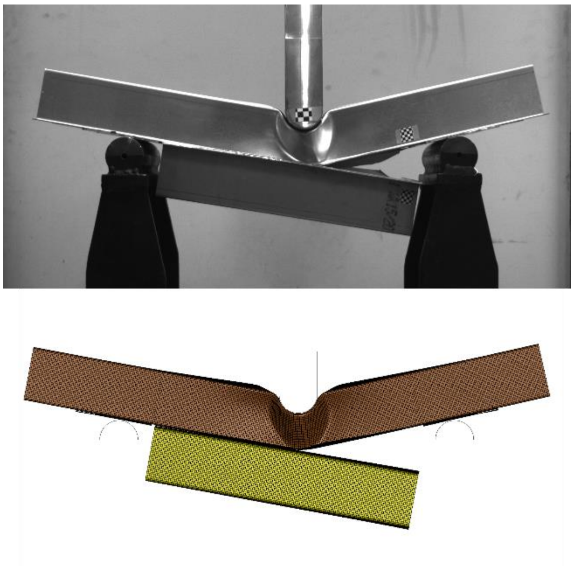

Fig.4: Comparison between experiment and numerical model in deformed configuration.

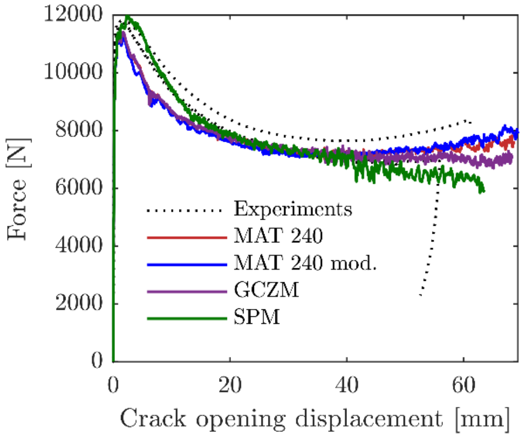

Fig.5: Force vs. COD for experiments and simulations.

The finite element model used to simulate the component tests is shown in Figure 7, using a general mesh size of 2mm and 1 element through the thickness of the adhesive layer. Solid elements with formulation 19 were used in the adhesive layer for the 3 runs using CZM, while formulation 1 was used for the SPM based simulation. The adhesive layer was connected to the metal adherents using a constrained offset formulation. To model the steel and aluminium parts, MAT_258 [5] was applied. Simple forming simulations were performed in order to estimate the initial history variables in the corners of the metal sheets. Due to the quasi-static conditions in the experiments, the simulations had to be mass-scaled with a factor of 10^7 to obtain reasonable simulation times. Additional mass scaling is necessary if SPM is used in the adhesive layer and compared to a CZM, which could be problematic for dynamic problems. All simulations were run with LS-DYNA version 9_3_0.

A comparison between the experiment and a simulation using GCZM is depicted in Figure 8. Qualitatively, the deformation state is similar in the experiment and the simulation, except for the crack propagating slightly more in the simulation. Force vs. machine displacement and force vs. COD for simulations and experiments are presented in Figures 9 and 10 respectively. The influence of which macroscopic model was used in the adhesive layer seems to be insignificant in terms of the overall response of the component. This is because all the macroscopic models initiate failure too early, thus underestimating the peak force. However, the crack seems to be propagating correctly after initiation.

Using SPM with one element through thickness, it was possible to initiate failure accurately and consequently also the peak force, but at a cost of decreasing the critical timestep significantly.
The consistent early failure in the macroscopic models for the component test suggests that there is an issue with the mesoscopic model used in the calibration process. This is likely to be linked to the simple failure model used, which is only indirectly dependent on the stress triaxiality. Further, there is no mesh regularization included in the formulation. Therefore, the failure mode should be similar to the one used for calibration in terms of both stress state and length scale in order to obtain accurate results. A similar length scale was employed in the generic joints, but the stress state is significantly different at the boundary where failure initiates. The results of the component test simulations using SPM suggests that using one element through the thickness alleviates this issue. Using one element through thickness smooths the strong gradients in the stress field at the boundary of the adhesive layer, such that it is more comparable to the stress state used for calibration.
Overall the accuracy of the simulations using a CZM is seen to be satisfactory considering the complexity of the problem. This indicates that using a virtual laboratory to calibrate these models is a viable approach, especially if the previous effects could be mitigated. With that in mind, it seems that the GCZM would be a preferred model as it requires only 4 parameters to calibrate, using this approach, and provides similar accuracy. Fewer parameters makes it easier to isolate and interpret the influence of each parameter as well as significantly reducing computational time in the calibration process.

5 Summary

This study was concerned with the accuracy and ease of calibration of three different cohesive zone models (CZM). The models were employed in simulations of a component test. The components consisted of two hat profiles of steel and aluminium bonded together using the crash-stable adhesive SikaPower 498. Results of the experiments indicated that a progressive failure was achieved for all repetitions and that the behaviour of the adhesive layer was critical for the overall response of the component.
In order to model the adhesive layer, a standard cohesive zone model (CZM) known as MAT_240 [2] in LS-DYNA was used as a baseline reference. Two state-of-the-art models described by Sønstabø et al. [3] and Said Schicchi and Caggiano [4] were implemented as user subroutines in LS-DYNA and used for comparison. All the CZM were calibrated using a partial virtual laboratory, where the virtual experiments were simulated using detailed numerical models based on the SIMLab Polymer Model (SPM) [1]. The component test simulation results were seen to be satisfactory for all CZM when compared to the experimental data, indicating that this calibration process presents a viable approach. However, there is still more work to be done to improve the accuracy of this method. Further, it is evident that the accuracy of these simulations is practically insensitive to what type of CZM is used, suggesting that the model which is easiest to calibrate would be recommended. Using the mentioned calibration method, the model described by Said Schicchi and Caggiano [4] was significantly easier to calibrate.

6 Literature

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