Characterization of a cohesive zone model for adhesives with *MAT_240 and curve mapping method in LS-OPT

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1 Abstract

The importance of adhesives in automotive structures exposed to high crash loads has increased over the years. To improve the structural sizing, it is necessary to predict the behavior of bonded joints under dynamic impact and crash loads. Cohesive zone models have proven to be suitable for numerically representing adhesive behavior in Finite-Element simulations. However, the manual determination of the model parameters requires experience with the material model and a corresponding amount of time to derive the various parameters. The present work aims at developing an optimization scheme with LS-OPT for the effective and automated identification of input parameters for the material card **`*MAT_240 (*COHESIVE_MIXED_MODE_ELASTOPLASTIC_RATE)`** [1] which is used to represent the behavior of the adhesive layer. The present work focuses on a curve mapping process with LS-OPT.

The investigated approach is based on the numerical simulation of the entire load-displacement curves of four different sample geometries. Of these, two sample types have nearly rigid joining partners. In the other two sample types the parts to be connected are made of sheet steel (which can be severely deformed during an experiment). The sample types were also chosen so that the adhesive layer in two sample types failed under peel load, while in the other two samples failure occurred under shear load.

First, a parameter optimization scheme based on two fracture mechanical tests for mode I and mode III loading is implemented. As a basis for the optimization, a sensitivity analysis is previously performed to determine the decisive parameters in fitting the numerical to the experimental results and reduce the optimization space. In the next step, an optimization loop for the fracture mechanical tests will be investigated. Therefore, the least square method for the curve mapping process is used for the parameter optimization of with LS-OPT. The determined optimized parameters strength and fracture energy are being used to optimize the material cards on coupon level afterwards. The cohesive zone parameters are being calibrated to the experimental results and the parameter space can be minimized using the Sequential Response Surface Method (SRSM).

2 Introduction

The increasing use of adhesively bonded joints in the automotive sector is caused by the flexible design and the effectiveness of joining different material combinations without damaging them or affecting their properties. Due to the high restrictions in the automotive sector regarding to emissions and safety, it is necessary to understand the material behavior of adhesive bonded structures in more detail, to achieve an improved crash performance. Tensile and shear stiffness and strength and fracture toughness (both in modes I, II, or mixed mode) are the most important properties. The numerical approach for complex adhesives is still challenging and the experimental characterization for simulation purpose is a cost-intensive task. Therefore, an effective numerical characterization of adhesive layers in Finite-Element simulations is indispensable. Several approaches exist to represent the behavior of adhesive layers numerically. One of the most commonly used approach is the use of cohesive zone formulations. [3]

The present paper presents an optimization scheme with LS-OPT for the calibration of relevant material parameters for a cohesive zone model with the material card **`*MAT_240`** [1]. The work is part of the DLR project “Fokusanwendungen, Fahrzeugstruktur, Antriebsstrang & Energiemanagement” (FFAE) [4] and focuses on a multi-step curve mapping process for adhesive layers.

3 Experimental tests

This chapter describes the experimental test campaign, the results of which serve as the basis for the optimization of the material card parameters for the two-component polyurethane adhesive BETAFORCE™ 2850L (BF2850L) from Dow. To guarantee a good adhesion, a cathodic coating of the joining partners is necessary. Four different sample geometries were investigated. Two sample types (M1 + M3 derived from fracture mechanics) have nearly rigid joining partners which are made of “Toolox 44” steel and are used for the measurement of mode I and mode III fracture toughness. The other two sample types (SLS + LTP) use deformable 2 mm thick steel sheets made of Docol 800. The sample types are chosen that the adhesive layer in two sample types (M1 + LTP) failed under peel load, while in the other two samples failure occurred under shear load. For a better understanding of the sample geometries, the numerical models are shown in figure 1.

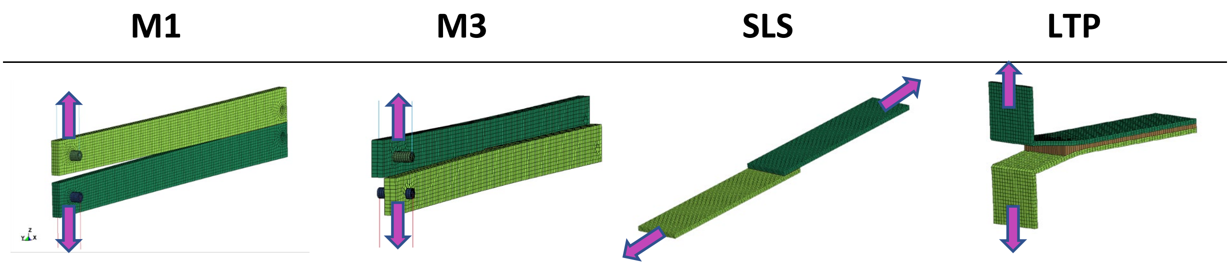


Fig.1: Numerical models for the four selected specimen types

First, the two fracture mechanics tests (M1 + M3) are performed to measure the fracture toughness in mode I and mode III of the adhesive respectively. It is here assumed that the mode II and mode III fracture toughness are equal. It is also assumed that the material behavior of the joining partners can be neglected because no significant deformation of the joining partners is expected. As a next step, two coupon level tests as Single Lap Shear (SLS) for shear loading and Long T-Peel (LTP) for peel loading are investigated. The specimens are tested under quasi-static conditions in a universal testing machine Zwick 1494. Figure 2 and figure 3 documents the experimental force-displacement curves.

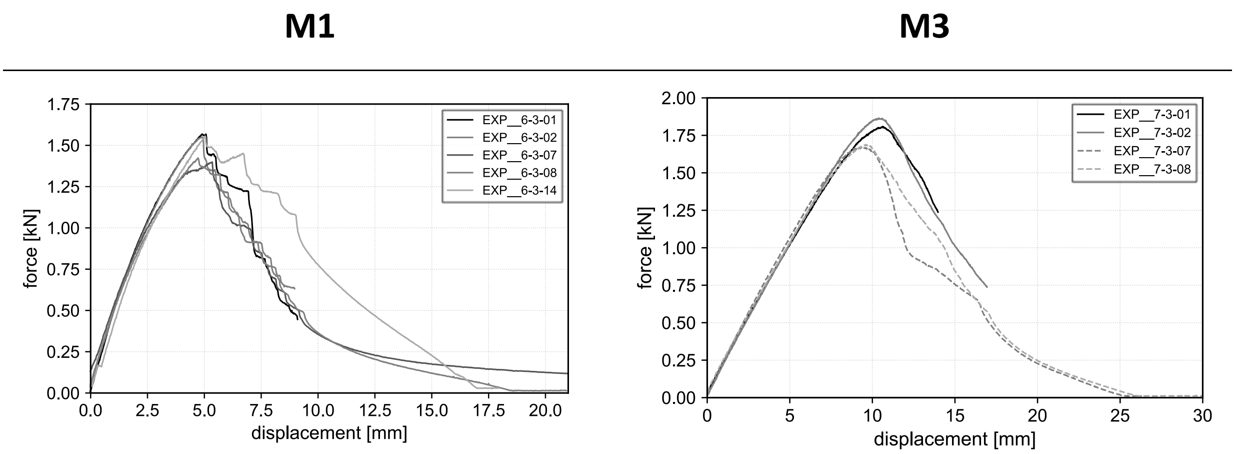


Fig.2: Experimental test curves for M1 and M3 tests

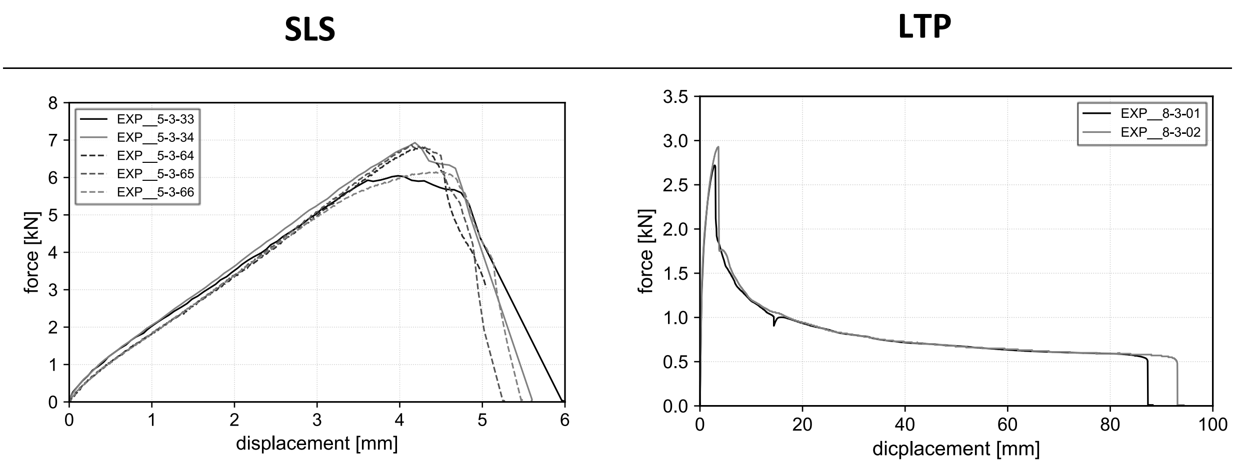
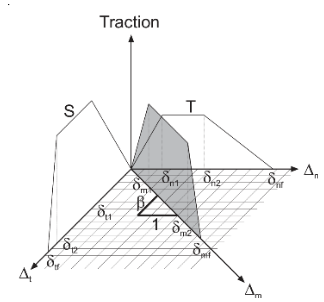


Fig.3: Experimental test curves for SLS and LTP tests

4 Material parameter identification

The following section presents the optimization of the input parameters for the material model **`*MAT_240`**. The numerical models of the specimen are briefly presented as well as the LS-OPT optimization scheme. Originally, **`*MAT_240`** was developed for the application of structural adhesives under mixed-mode loading. This work shows that **`*MAT_240`** can also be used for an adhesive with low modulus of elasticity and high elongation at failure. The behavior of the adhesive layer is represented by a tri-linear elastic and ideally plastic cohesive zone formulation with mixed-mode damage initiation criterion (see figure 4 (a)). The aim is to optimize the material parameters using the test campaign of section 3 to reproduce the experimental behavior of the adhesive layer. The material properties used in **`*MAT_240`** are shown in figure 4 (b). The parameters highlighted in green have to be calibrated in the optimization loop while the blue highlighted material parameters are kept constant.



(a)

Material Parameter to be calibrated
Constant Material Parameter

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*MAT_COHESIVE_MIXED_MODE_ELASTOPLASTIC_RATE_TITLE
MAT240_BF2850
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#    mid        ro     roflg   intfall      emod      gmod     thick    output
      300   1.25E-6     0.000       4.0     0.070     0.007     0.000    0.0020
$#  g1c_0   g1c_inf   edot_g1        t0        t1    edot_t       fg1
    0.013                         0.008                          0.50
$#  g2c_0   g2c_inf   edot_g2        s0        s1    edot_s       fg2
    0.037                         0.012                          0.10
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(b)

Fig.4: Mixed-mode traction-separation law of ***`*MAT_240`*** *(a) [1] and an example of material card* ***`*MAT_240`*** *for an adhesive layer (b)*

4.1 Finite Element models

The numerical models to identify the **`*MAT_240`** parameters are described in this section. The joining partners of FE models for mode I and mode III are discretized with fully-integrated solid elements with the formulation ELFORM 2. To save computational time, SLS and LTP specimens are modelled with thick shell elements and ELFORM 5. The cohesive layer is modeled with four-point cohesive elements using ELFORM 19 and an element size of 1.25 mm. For all FE models, **`*MAT_240`** is used for the cohesive layer. The material behavior of the M1, M3, SLS and LTP adherends is simulated with **`*MAT_024 (*MAT_PIECEWISE_LINEAR_PLASTICITY)`**. Force and displacement are evaluated as an output history data for each specimen type. The cohesive element thickness is fixed for a given adhesive layer thickness of 2.0 mm as measured in the experimental tests.

4.2 Iterative optimization with curve mapping in LS-OPT

LS-OPT is used as an optimization tool to optimize the input parameters of the above-mentioned material card to reproduce the experimental behavior of the tested specimens. The parameter optimization can be done by minimizing the error using the Mean Square Error method MSE [4] and by estimating the vertical distance between the simulation curves and the experimental reference curves. In the present work, the experimental curve representing the lower bound of the test results is chosen as reference curve to obtain a conservative material card. The basis of the present optimization is the selection of the design space according to the "Sequential Response Surface Method" (SRSM) with an adaptive domain reduction [4]. For this purpose, an upper and lower bound is chosen for each parameter, within which the optimum is expected at the beginning. The design space is minimized in each of the optimization loops until the region of interest for the optimum drops under an accuracy of 0.1 %.

4.2.1 Sensitivity analysis

First, a global sensitivity analysis is performed with a Design of Experiments (DOE) to exclude parameters with a low sensitivity (here under 5 %) and reduce the optimization effort. The sensitivities of each material parameter in the four different specimen types presented in chapter 3 are extracted. Different theories exist on which and how many parameter combinations of the experiments or simulations have to be used to extract the best information from a minimum number of permutations. In this work, a D-optimal method was chosen in order to gain the most information with the smallest number of permutations. Its advantages over classical experimental designs consists in the possibility to extend the model in further steps and in the consideration of constraints. The global sensitivities for the four sample types are determined via the "ANOVA" procedure implemented in LS-OPT and are shown in Table 1 [2].

Table 1: Global sensitivities for the different specimen types (all values in %); the colors indicate the parameters with the highest sensitivity

Specimen	G_{1c}	T_0	Fg_1	G_{2c}	S_0	Fg_2	E_{mod}	G_{mod}
M1	88.5	11.1	0.1	0.2	0.0	0.0	0.1	0.0
M3	0.0	0.1	0.1	32	0.4	0.1	0.6	66.8
SLS	2.2	4.7	2.6	7.7	7.9	4.8	3.6	66.5
LTP	48.7	32.5	1.2	2.6	6.0	1.1	4.4	3.6

4.2.2 Iterative optimization

Based on the previous DOE, a multi-step optimization loop is started. The basic idea is to derive the critical energy release rate from the fracture mechanical tests separately by using the curve matching algorithm and transfer the optimized parameters (G_{1c}, G_{2c}) into the simulation of the SLS and LTP tests. In a second optimization, the remaining parameters are optimized (G_{mod}, T_0 and S_0). The entire LS-OPT workflow is shown in figure 5. A maximum of eight iterations using a polynomial linear metamodel was performed using the global termination criterion of 0.1 % accuracy. At each level of the workflow, the parameter optimization is performed on basis of the entire force versus displacement curve in one step.

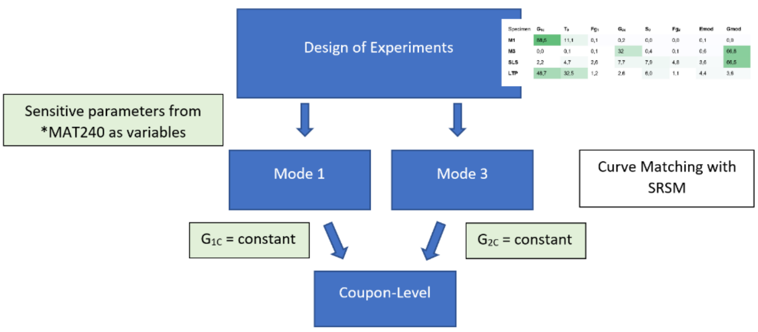

Fig.5: LS-OPT workflow for the optimization of material parameters for ***MAT_240***

Using the curve matching algorithm, the predicted and the calculated optimization process of the metamodel can be displayed over the iterations for the M3 curve (see figure 6). The SRSM reduces the range of investigated values in every iteration step. In the first iteration step (blue), the scatter range of the calculated curves from the simulation is still large, while the metamodel in iteration step 3 (green) already very precisely follows the given curve characteristics. The given termination criterion is reached at iteration step 5 (orange), so the optimization finished with the output of the optimal material parameters for the given curve.

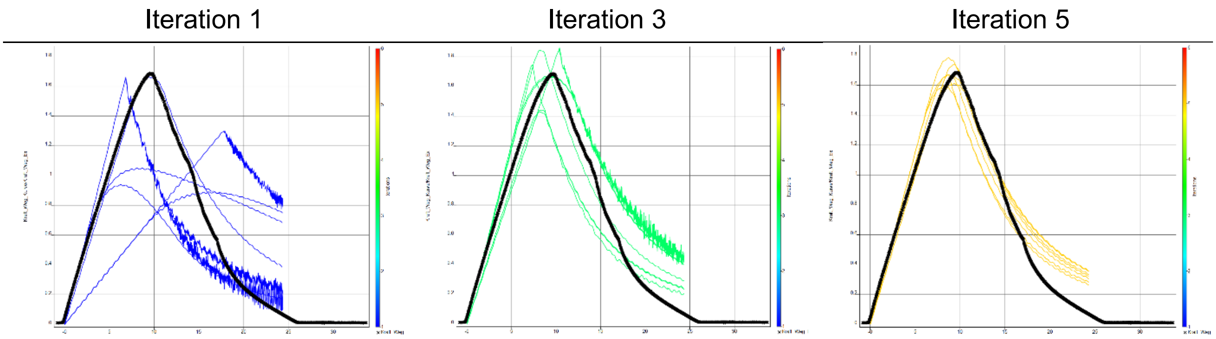

Fig.6: Force-displacement curves sorted by iterations with the SRSM method in comparison to the experimental curve (EXP__7-3-08 is shown black).

Figure 7 shows the comparison between the experimental force-displacement curves of the M1 and M3 tests and the simulation curves with optimized material cards. The optimized stiffness of the specimen is in good agreement with both experimental curves since it is uncoupled to any damage mechanisms in the specimen. Under mode I loading, the initiation and propagation of damage in the adhesive is strongly influenced by a larger number of parameters (E_{mod}, T_0, G_{1c}, FG_1). Starting damage initiation at a displacement of about 2.5 mm, the optimized curves deviates from the experimental curve. The optimized peak force for M3 (right) is approximately 8 % higher than in the experiment. Up to a displacement of 15 mm, the optimized M3 curve is in good agreement with the experimental curve. After this point, the curve fitting accuracy decreases. Based on the fracture mechanics investigations of the adhesive, the optimal critical energy release rates can be derived as G_{1c_opt} = 12.0 kN/mm and G_{2c_opt} = 37.0 kN/mm.

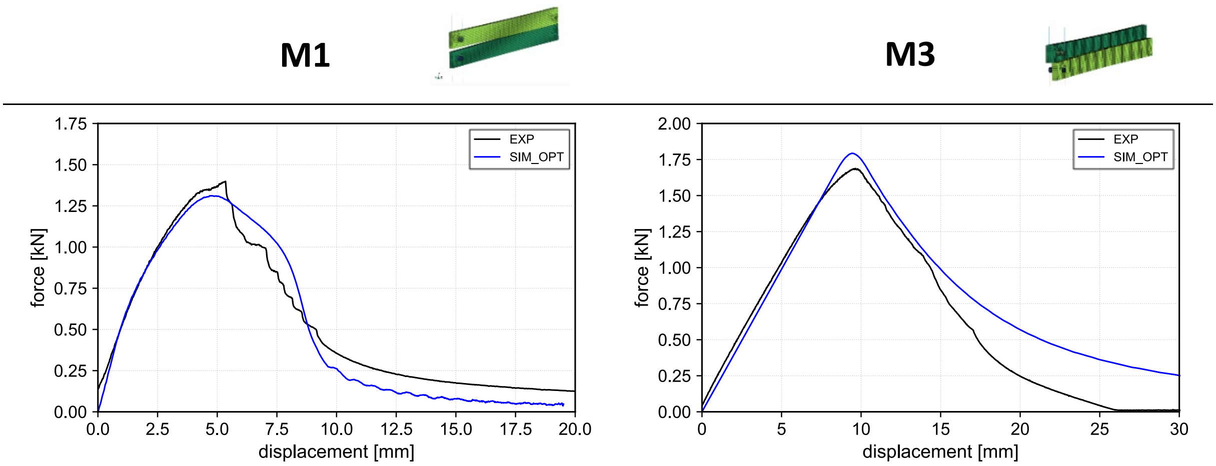

Fig.7: Force-displacement curves of the optimized material card for the fracture mechanical tests

The results of the multi-step optimization of SLS and LTP specimen types are shown in Table 2 and figure 8. For a better comparison, the single iteration curve (red) with variable G_{1c} or G_{2c} is shown. As expected, a variation of the parameters G_{1c} and T_0 for SLS does not show any influence on the shear loading dominated specimen. The stiffness of the SLS specimen (figure 8 left) in simulation is in good agreement with experimental measurements. It is visible that non-sensitive parameters are not further varied in the multi-step loop, since their influence on the global curve is very small in contrast to the critical energy release rate. However, some global non-sensitive parameters from chapter 4.2.1 have a greater influence for certain sections of the curve. For instance, the plateau in the SLS force-displacement curve is influenced by the shape parameter FG. In the following, a further optimization process is added (blue curve in figure 8) to investigate the influence of the non-sensitive parameters. Using this method, the numerical optimization of the plateau area achieves a better result.

For the LTP test (figure 8 right), a variation of the parameters G_{2c} and S_0 does not show any difference in the simulation results since the mode I loading is dominating. This is consistent with the sensitivity analysis mentioned before. For the LTP test, the second run is also performed but the effect on the optimized force-displacement curve remains negligible (see figure 8 on the right). The multi-step optimization leads to a more accurate prediction of the force peak compared to the single iteration. For both, the numerical model can not replicate the stiffness reduction measured between the displacement of 1 and 4 mm before crack initiation. An explanation for this could lie in the stress-strain curve derived from the literature for the sheet material of the joining partners, which inadequately describes the yield point and the real plasticization behavior.

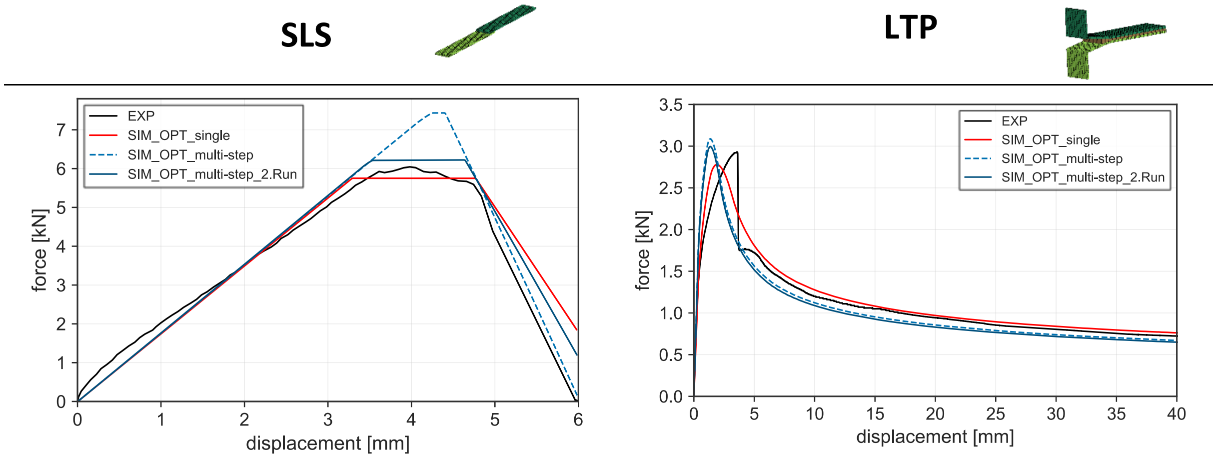

Fig.8: Force-displacement curves of the optimized material card based on the fracture mechanics and coupon tests

Table 2: Optimized material card for BF2850L

E_{mod} MPa	G_{1c} N/mm	T_0 MPa	FG_1 -	G_{mod} MPa	G_{2c} N/mm	S_0 MPa	FG_2 -
70.0	12	8	0.5	5.8	37	10	0.31

Table 2 syntheses the material parameters for the adhesive BF2850L resulting from the whole optimization process based on the experimental results of the M1, M3, SLS and LTP tests. Overall, the four force-displacement curves using the optimized material cards from the multi-step method are in good agreement with experimental results. However, numerical results on the coupon level show higher discrepancies. Suspected reasons for this are amongst others uncertainties within the selection of the curve data because of the large scatter range in the experimental setup. Factors such as the test procedures, manufacturing influences or the adhesive batch also determine the results of the experimental tests used as a target for the optimization process.

5 Summary and Outlook

This paper described an optimization method with LS-OPT to determine the input parameters for a material model `*MAT_240` and simulate the behavior of adhesive. The optimization workflow involved first a DOE sensitivity analysis to extract the parameters with the highest sensitivity and a subsequent multi-step curve fitting process. It was shown how to create a material card for adhesives with a cohesive zone model on the example of the adhesive BF2850L. The most important material parameters were identified based on the implemented curve mapping process. The challenge is also in the scatter of experimental curve data and its related curve selection for the optimization process.
Overall, modelling improvement for characterizing the joining partners material is needed to get more accurate numerical model approaches. In addition, further research work is needed to transfer the current method to a use on the structural level. Consideration should be given to whether a global curve adjustment is not the best solution for this material card calibration. The approach investigated here for the automated derivation of adhesive parameters is based on a one-shot comparison of the complete load-displacement curves of different specimen types. When comparing the sensitivities of the

parameters of specimens with basically similar load types, a shear load on the one side (M3 and SLS) and a peel load on the other side (M1 and LTP), there are significant differences in the determination of the parameter sensitivity. It is assumed that the material parameters have different effects for different curve sections.
As a further perspective, it is proposed to investigate whether limiting the parameter derivative to only a partial domain of the load-displacement curve leads to a further improvement of the results and a more comprehensible sensitivity evaluation. Furthermore, using the comparison of strains between the cohesive zone and the adhesive of the experimental test could help to better replicate the failure in the adhesive layer.

6 Literature

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