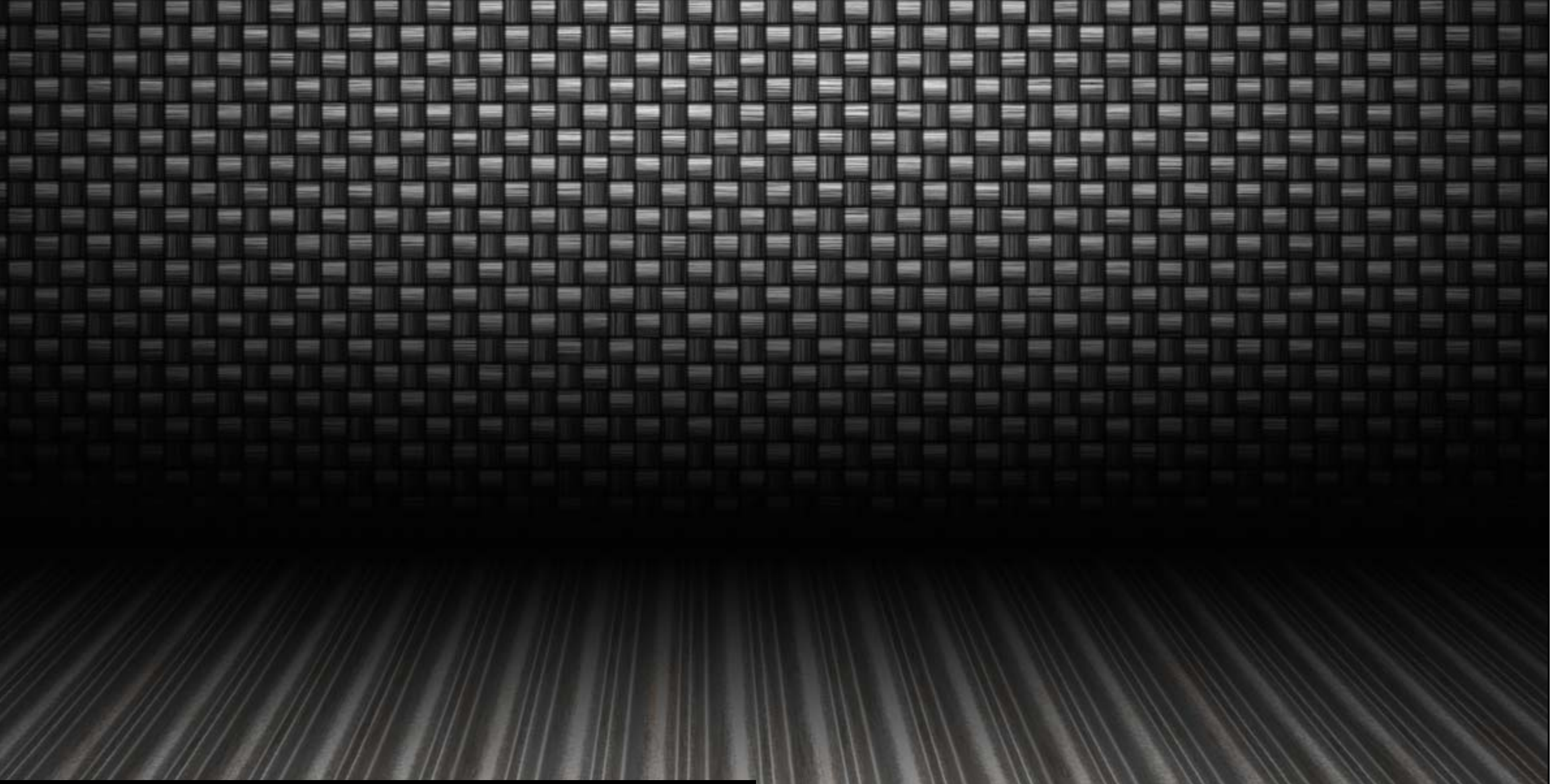

CASE STUDY // PROCESS ENGINEERING

SIMPLIFIED SIMULATION OF ALUMINUM-CFRP ADHESIVE JOINTS

optiSLang supports CAE-based simulation of hybrid adhesive joints by appropriate methods of model reduction using correlation models.

A detailed simulation of the non-linear behavior of adhesive joints is often not possible in regard to model complexity and computation time. If it becomes necessary in product development to simulate this non-linear behavior, reduced correlation models must be generated. As part of a funded research project, Brose Fahrzeugteile GmbH & Co. KG, CADFEM GmbH, Dynardo GmbH and the Chair of Engineering Design of the Erlangen-Nuremberg University investigated such correlation models (hereinafter referred to as meta-models) and their calibration regarding the capability of generating a sufficient prognosis of the nonlinear structural behavior of adhesive joints within reasonable computational effort and accuracy. After a successful calibration of appropriate meta-models, the economic use of numerical simulation and computer aided design methods for adhesive joints already becomes possible in an early stage of product development.

Compounds of aluminum and Carbon Fiber Reinforced Plastics (CFRP) achieve tremendous advantages for lightweight applications through the optimal utilization of the material properties. For example, this compound can be found in lightweight door modules (see Fig. 1) where aluminum parts like window lifter rails are applied to a door module made of CFRP.

Fig. 1: Light weight door module | © Brose Fahrzeugteile GmbH & Co. KG

The properties of such hybrid structures decisively depend on the joints between the component parts. This makes a sufficient load and material related design of these joints very essential. However, the anisotropic material behavior and a tendency towards delamination of the CFRP, as well as differing coefficients of thermal expansion of the joining structures make this aim hard to achieve. The fulfillment of requirements such as sufficient robustness towards varying thermal conditions or crash safety regarding the joints is only reachable if CAE-based procedures are implemented at an early stage of product development.

The basic steps of the derivation and calibration of correlation models of adhesive joints are shown in Fig. 2. Within the loading conditions of the joints, a design of experiment and a test setting is defined. At the same time, a parametric simulation model is created for the recalculation of all tests. The unknown or uncertain material parameters of the simulation model are calibrated on the test results. Thus, if an adequate prognosis capability is achieved, a large number of experimental set-ups can be virtually calculated to generate a sufficient data base for a predictive correlation model.

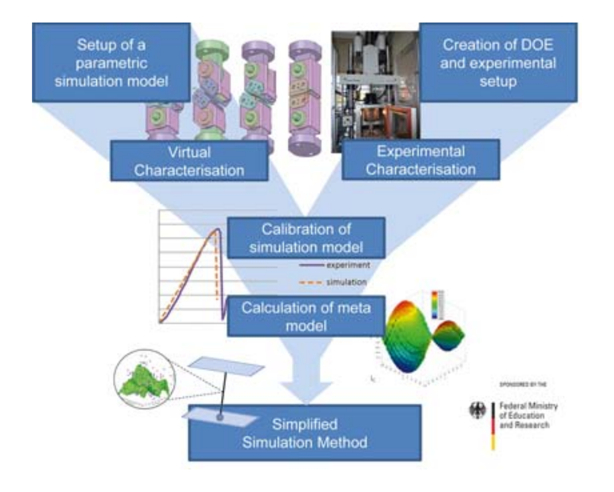

Fig. 2: Approach for the generation of a simplified simulation method

The reduced model is then used for modeling the adhesive joints on the contact elements. Thus, while having access to the data base of the meta-model, the modeling effort for a detailed simulation can be saved. The steps of generating a simplified simulation model, in particular the experimental and virtual characterization of the adhesive joints as well as the final validation of the simulation method, will be discussed more detailed in this article.

Experimental setup

To characterize the adhesive joints, a modified KS2-sample is used (see Fig. 3). In this case, a polyurethane adhesive joint of an aluminum and a CFRP plate is tested under the condition of production temperature, processing and hardening. The tearing experiment is carried out at a servo-hydraulically operated test facility (see Fig. 3). To carry out the high and low temperature tests, there is a temperature chamber integrated in the test facility. The force-displacement curves are recorded as the basis for later calibration with the simulation.

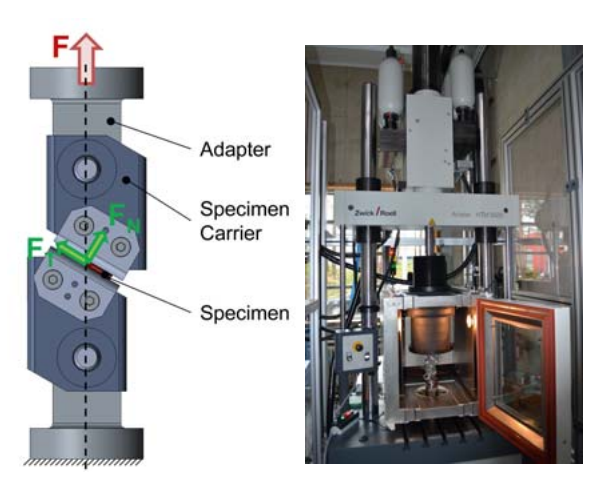

Fig. 3: Test design and facility

Parameter space to describe the possible operating conditions

Usually, the number of real experiments to be carried out should be minimized and, consequently, a minimalistic DOE has to be created. Here a linear D-optimal experimental design is chosen. Table 1 shows the parametrization and Fig. 4 (see next page) illustrates the sampling points in a 3-dimensional subspace.

Parameter		**Values**			
Joint Width (mm)	x_1/d	0,3	0,6	1	
Layer structure	x_3/LA	1	2		
Load angle (°)	x_4/α	0	45	60	90
haul-off speed (m/s)	x_5/v_α	0,001	0,1	2	
Temperature (°C)	x_6/T	-30	23 room temp.	80	

Table 1: Values of parametrization

As relevant parameters for simulating various load scenarios, the setting angle in regard to the direction of tension, the test speed and temperature, the thickness of the adhesive seam as well as different layer structures of the CFRP laminate are varied in the testing. Using the result variables of the thirty testing procedures of the experimental design, the most dominating major effects such as the acceptable force and displacement as well as the test speed and temperature can be identified.

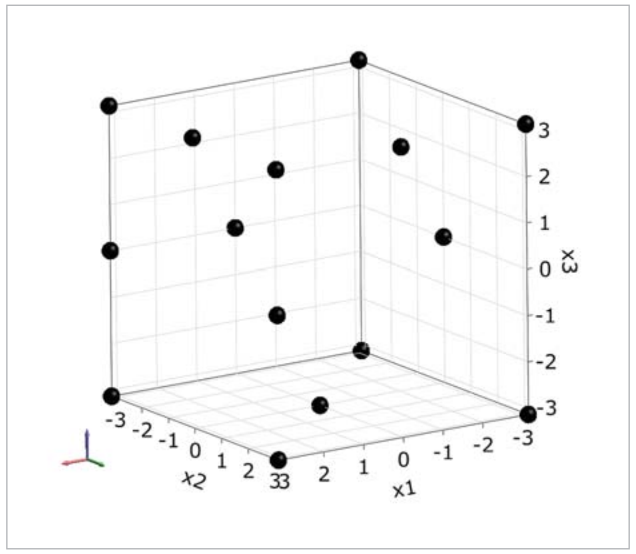

Fig. 4: Sampling points in a 3-dimensional subspace

Fig. 5 shows the Coefficient of Prognosis (CoP) and the Metamodel of Optimal Prognosis (MOP) for the maximum acceptable load and Fig. 6 represents the corresponding displacement derived from the thirty experimental procedures.

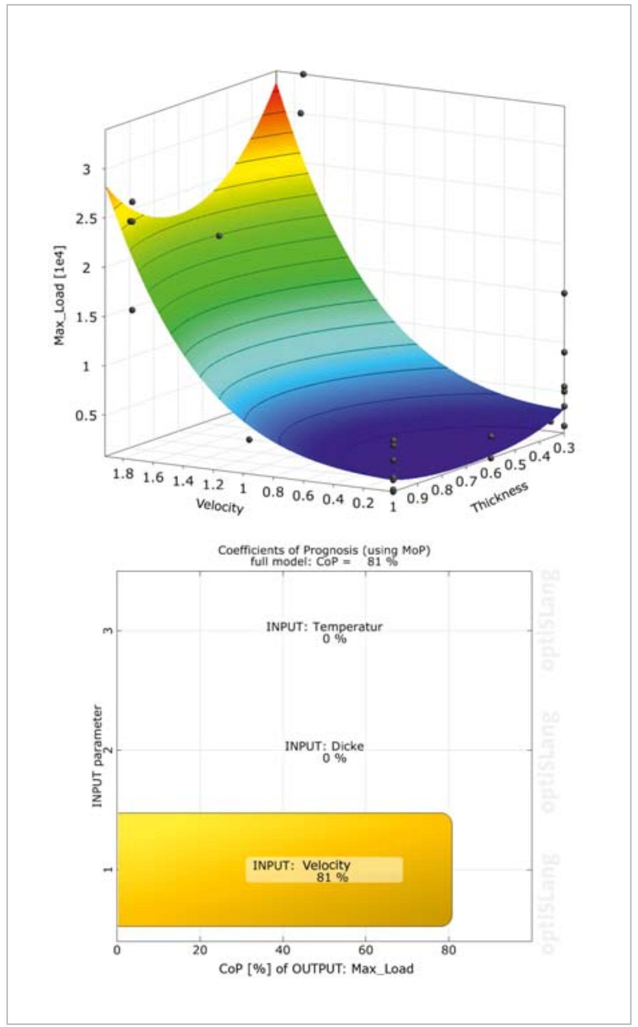

Fig. 5: MOP and CoP of maximum acceptable load

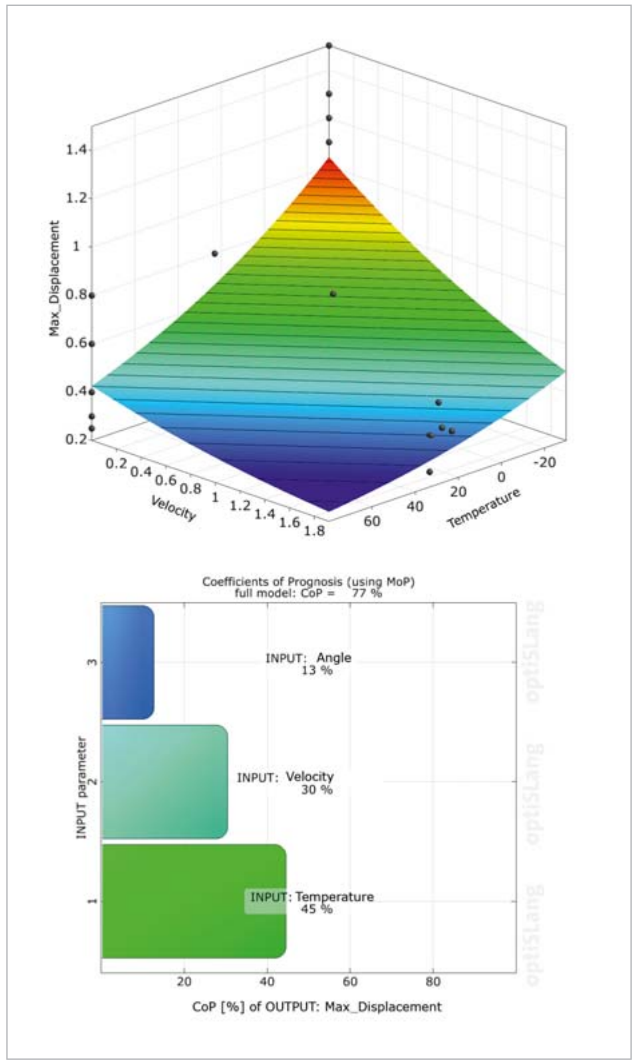

Fig. 6: MOP and CoP of the corresponding displacement

Detailed simulation

The results of the experiments serve as calibration points for the detailed simulation. Here, the failure modes that occur in practice have to be covered. Fig. 7 represents the failure of the adhesive joint on the aluminum surface, the cohesive failure within the adhesive layer and the delamination of the CFRP layer structure. The simulation model is designed as a parametric geometry model enabling the angle of the clamped specimen, along with the thickness of the adhesive layer to be varied. The possible variations of the angle ranges from 0 ° to 90 ° in regard to the tensile axis and the adhesive layer thicknesses can be varied from 0.3 to 1.0 mm. Regarding the adhesive layer, a viscoelastic material behavior is selected that also shows a different behavior when changing the temperature. For simulating the adhesive failure on the aluminum surface as well as the delamination in the CFRP layer structure, contact elements with cohesive zone approaches are used in the simulation model. The individual CFRP laminate layers, according to their thickness and fiber orientation, are each meshed with one layer of three-dimensional elements, as shown in Fig. 8. Adhesive and aluminum are also modeled with three-dimensional elements over the thickness and marked with the corresponding material properties. After an initializing step, the model is then driven with the defined speed until one of the described failures occur. The material parameters of the separating layers, the failure criteria and the damping parameters are based on assumptions in the first instance. They have to be determined by means of parameter identification.

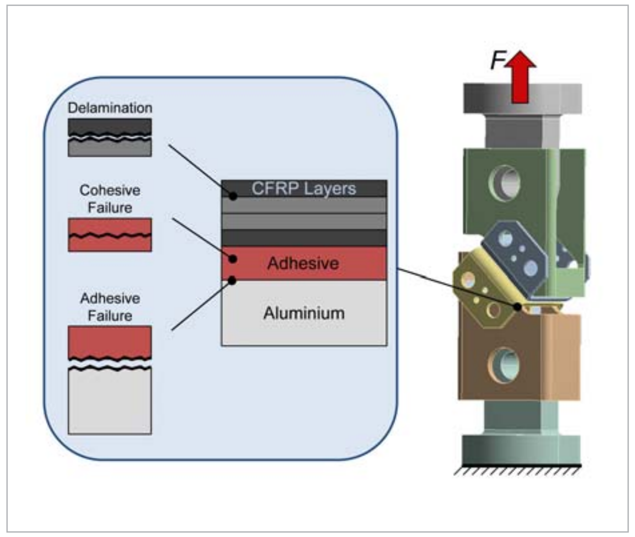

Fig. 7: Modes of failure of the adhesive joint

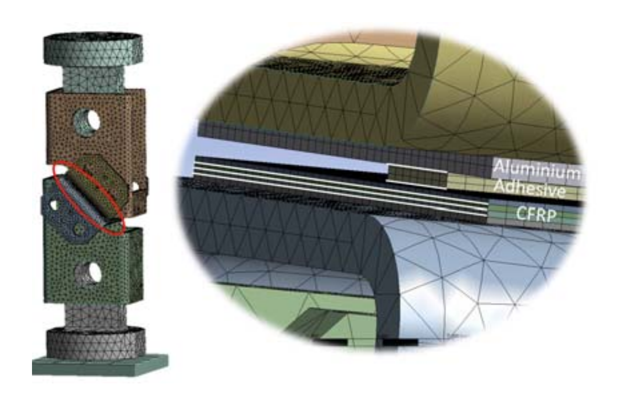

Fig. 8: Meshing of the adhesive joint

Model calibration

Important parameters to be calibrated comprise the maximum contact normal stress, the critical fracture energy density in normal direction (surface energy), the maximum equivalent tangential contact as well as the critical fracture energy density. A total of 25 parameters have to be identified in order to achieve an adequate correlation with the thirty test models. The unknown material parameters have to be calibrated in regard to the experimental results with the help of the numerical simulation model and an inverse approach. The identified material properties and the calibrated simulation model are then used to calculate a sufficient number of support points for the mathematical surrogate models.

Unfortunately, standard procedures such as the minimization of error squares, could not be successfully applied during the calibration. Due to the many unknown variables and the partially highly sensitive behavior of the simulation model, the parameter ranges were limited gradually. A fully automatic optimization method could not be applied for each adaptation step. Therefore, quasi-random experimental designs were used to scan the subspace and to identify appropriate parameter combinations. With the help of the Latin Hypercube Sampling and the parallel coordinate plot,

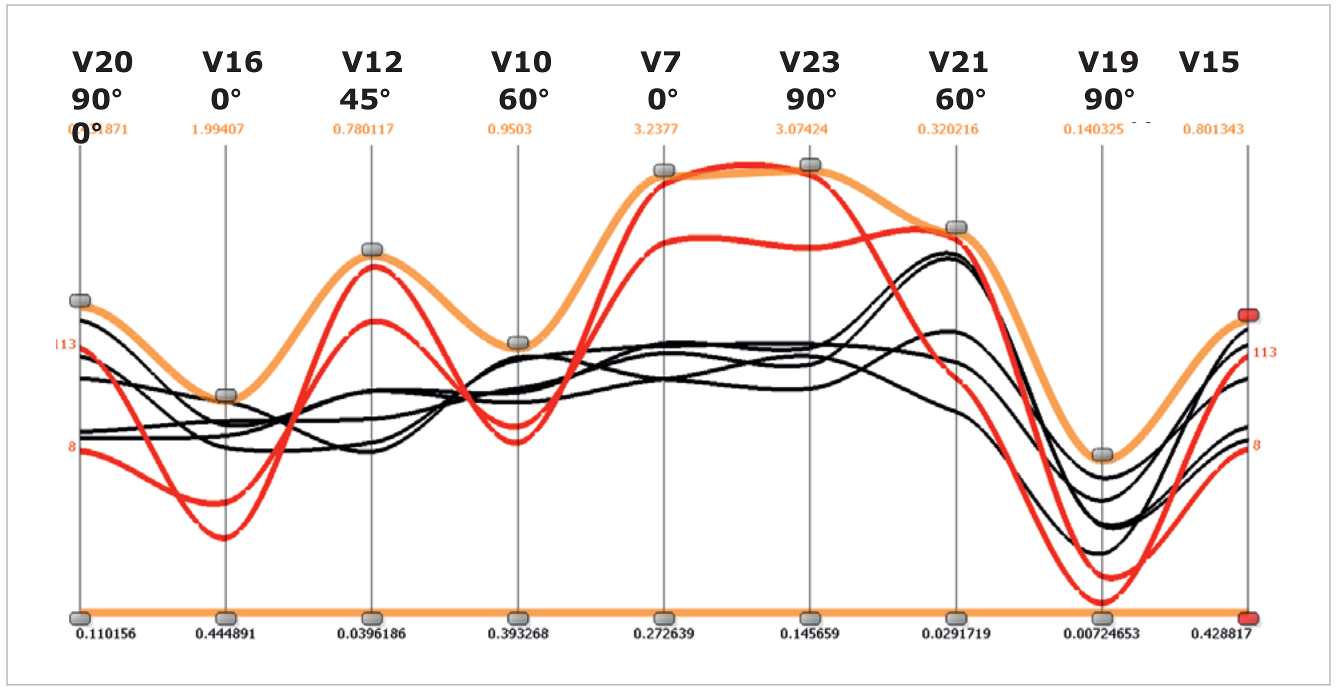

Fig. 9: Parallel coordinate plot

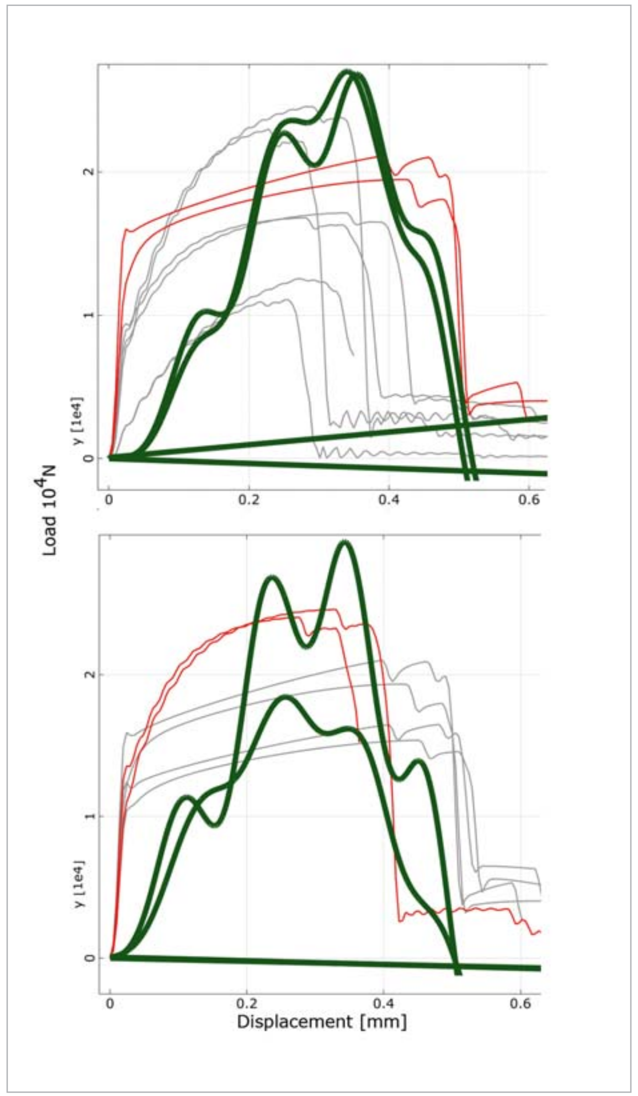

Fig. 10: Calibration of the detailed model to the experimental curves for a test with only tensile stress (top) and a test with mixed tensile and shear stress (bottom)

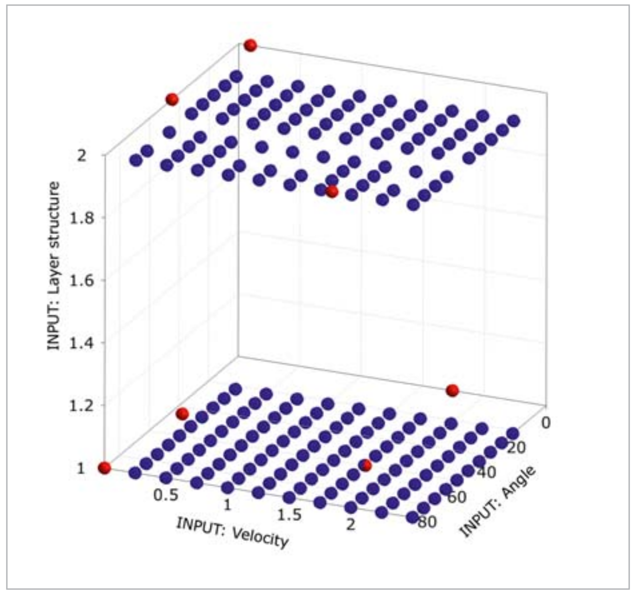

Fig. 11: Comparison between experimental parameters and the successfully calculated results of the simulation

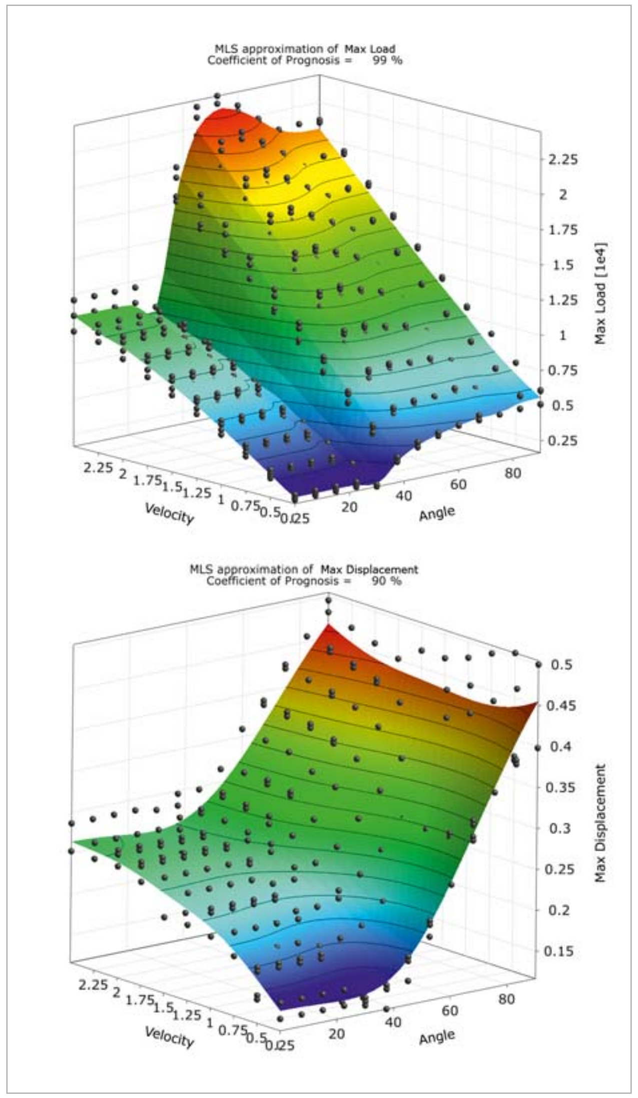

Fig. 12: Derived MOPs for max load and corresponding displacement

an incredibly efficient evaluation of the quality of each parameter combination according to various criteria was possible. Fig. 9 (see previous page) shows the limited range of the simulation results with a sufficient calibration.

Thus, a sufficient calibration between experiment and simulation was achieved and the associated surrogate models could be derived. Fig.10 shows the experimental data compared to the simulation results for the experiments at high loading velocity.

Generation of the meta-models

The matching in regard to displacement and maximum load between the experiments using the calibrated simulation models was 88 percent higher than the results of the experimental data with 77 and 81 percent, (see Fig. 5 and 6). After the verification of the calibrated parameter set was determined as being capable of a sufficient approximation of the test results, an adequate number of sampling points were calculated using additional virtual experiments. According to the application case, the temperature at 23 ° C and the adhesive thickness with 0.3 mm were considered constant. The remaining parameters regarding layer structure, speed and angle were entirely scanned by using a full factorial DOE scheme. Fig. 11 shows the comparison between experimental parameters and the successfully calculated results of the simulation.

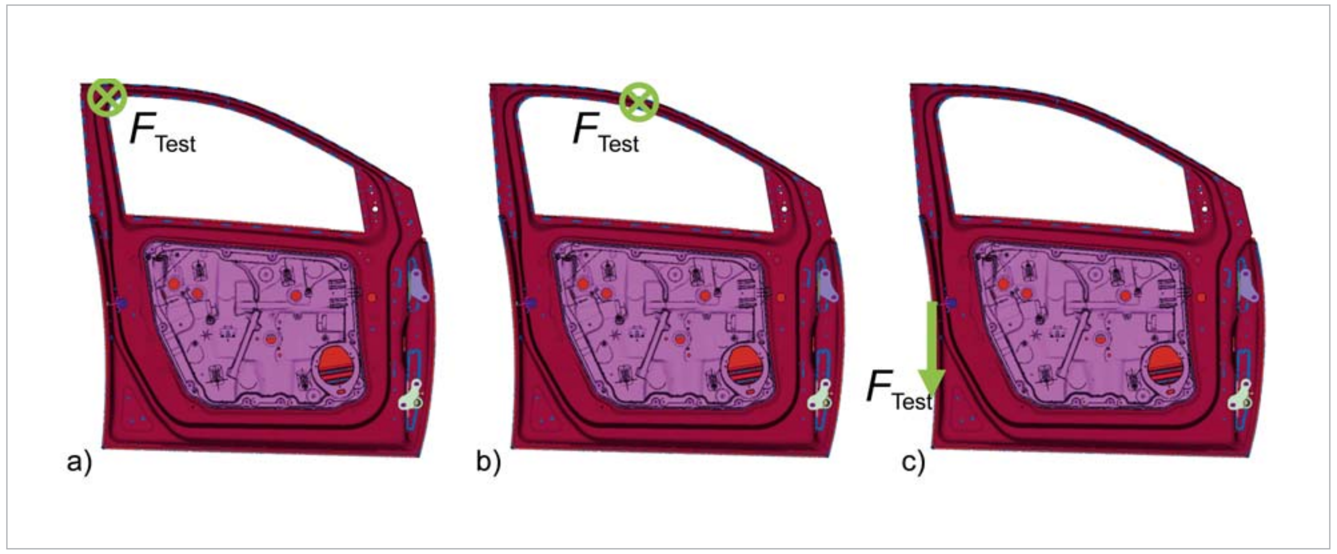

Fig. 13: Load cases for validation; frame rigidity (a and b); door lowering (c) | © Brose Fahrzeugteile GmbH & Co. KG

The calculated result values for each parameter combination enable the generation of meta-models for the maximum load with a prognosis quality (CoP) of 99% as well as for the associated displacement of 90% (see Fig. 12). The meta-models are integrated within a finite element in an implicit and explicit simulation tool. The created meta-model continuously describes the correlation between the stress situations and the contact behavior and can be accessed within the FE simulation.

Validation

The validity of the simplified simulation approach is examined by comparing it with the component tests of vehicle doors. The points of load application are located on the upper frame near the B-pillar and on the middle frame (see Fig. 13 a and b). In both load cases, the system stiffness significantly depends on the design of the joint. To take account of highly dynamic load cases, tests are carried out which are designed to simulate an accident scenario. Such side impact tests on vehicle doors are conducted and evaluated according to typical automotive specifications.

Summary

With the simplified simulation of adhesive joints based on meta-models, it is possible to significantly reduce the amount of calculation for the evaluation of product characteristics in early stages of development. The presented method is considered to be general and can also be applied to other types of compounds along with other adhesives or joining methods, such as riveting.

It should be noted that the generation of a predictive meta-model requires a minimum number of experiments for every variation window combined with a large number of simulated design points using a suitable simulation model. Important for the prognosis quality of the meta-models is the quality of the design and the setup of the experiments as well as the quality of the numerical model covering the main physical phenomena. The calibration, the verification of a sufficient prognosis quality, the design of virtual experiments and the derivation of meta-models can be automated by using optiSLang and, thus, combined with today's High Performance Computing capabilities, can be considered as relatively minor efforts in cost and time.

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