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DESIGNING OF HYBRID JOINTS AT THE EARLY EMBODIMENT DESIGN STAGE

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Abstract

Increasing costs for fuel and an increasing ecological awareness of the companies have lead to a higher importance of lightweight constructions in the automotive industry. A possibility to make components more energy-efficient is to use aluminum/CFRP (carbon-fiber-reinforced plastics) hybrid structures. In today’s state of technology the design of reliable and safe hybrid joints is a big challenge that can be solved using simulation programs in the early embodiment design stage.

This paper shows the development of a new method to simulate and estimate the behavior of hybrid aluminum/CFRP hybrid joints in an effective and realistic way. In a first step the joints are explored in an experimental characterization. In a second step, detailed simulation models are created and uncertain parameters are adapted to the experiments using parameter identification methods. After that, the simulation models are used to create meta-models containing the behavior of the joints which in a last step are implemented in simplified abstraction models. This enables product developers to predict the realistic behavior of hybrid structures much faster than before.

Keywords: Early design phases, Simulation, New product development, Design methodology

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1 INTRODUCTION

Fiber-reinforced composites have become more and more important during the last years in the field of lightweight constructions. Especially in the automotive industry the demands on energy efficiency due to strict requirements, scarce resources and consequently for the increasing operating costs for automobiles can be fulfilled with material light-weight constructions.

The objective is to satisfy all the requirements concerning the product by using materials with low density. The result is that industry makes greater use of carbon-fiber-reinforced plastics (CFRP) for example. In comparison to conventional metallic materials they show high stiffness and strength at low weight as well as a better corrosion resistance.

From the environmental viewpoint they are attractive, as they are very durable and show just little maintenance. And as less mass means better fuel efficiency, it is worth to make greater use of fiber-reinforced composite materials. Nevertheless fiber-reinforced composites are not used in all situations even if they would be a good choice. This paper will show some reasons for that and how to overcome the challenges coming along.

2 THE DESIGN OF ALUMINIUM/COMPOSITE HYBRID STRUCTURES

2.1 Challenges in the Design of Hybrid Structures

In a lot of circumstances it is not possible to use just composites, which means that many different situations arise where on the one side metallic materials and on the other side fiber-reinforced composites must be used. Reasons can be the mechanical or thermal properties, expensive production or materials costs as well as the availability of the material. For modern light-weight constructions often a hybrid structure with a multi-material design made of aluminum and CFRP can be found, as aluminum is a proven material that offers a good lightweight potential at moderate costs.

The connection of both materials confront product developers with problems that are not solved in an optimal way so far, respectively whose study and evaluation is too expensive and time-consuming.

Typical challenges for joints in aluminum/ CFRP hybrid structures are

- complex material behavior in the CFRP material as well as delamination
- a different coefficient of thermal expansion in both materials respectively different strain due to a change in temperature
- different load scenarios (static and dynamic) that joints must withstand
- corrosion

Nevertheless it is necessary to have a closer look at it, as the mechanical properties of such aluminum/ CFRP structures are depending significantly on the connections between the components, as an optimal transmission of the force within the hybrid structure is just possible, if the stress can be transferred directly to the fibers of the CFRP. It is therefore crucial, that a hybrid joint is designed according to the applied load and the material.

2.2 The Necessity of Simulation at the Early Embodiment Design Stage

Although the behavior of the connections between CFRP and aluminum can be tested experimentally, this comes along with high costs and much time that is needed. Additionally, just certain operating points can be explored which do not deliver all properties of the overall model.

That is why the actual behavior of the hybrid joints cannot be predicted accurately enough. Also the suitability of different joint methods in general (adhesive bonding, riveting) can hardly be classified in the early embodiment design stage, which at the end often result in solutions that are not optimal or that even prevent the use of effective aluminum/ CFRP structures. For this reason, the development process must be supported by simulation.

By the use of simulation tools the knowledge about the behavior of the system in the joints increases and contributes to a systematic improvement of the hybrid structure.

In the first steps, simulations are typically used to compare different variants. The objective is a qualitative statement about the field of application of the chosen approach.

In the next step the chosen concept can be developed in detail to ensure its functionality. In these steps it is important to make comparisons with experiments to ensure that all simulations show the same effects occurring in reality to guarantee the expected accuracy. If a simulation model has been proven to represent the physical behavior of the real experiment, prototypes can be replaced by simulation and costs as well as time can be reduced considerably. Furthermore, the simulation provides information about the interesting outputs at all locations and at any time step. Explorations of variants are virtually possible and deliver information about the interactions and the sensitivities in the model at a minimum of costs and in a comparatively short time.

Furthermore, tolerance analyses can be performed by using variant studies, to explore and evaluate the scatter of the important output parameters due to the scattering input parameters. This allows a systematic improvement of the quality is possible for example by guiding the output scatter due to well considered input changes to a location that is safe.

To set up simulations correctly and in a short time, guidelines and wizards often support the user in simulation tasks that are repetitive. For simulations that are not frequently used or that are very innovative automated processes often do not exist, which makes it necessary to have a careful and conscientious handling of the simulation software. This can also lead to a longer time that must be spent. So the objective must be a high-quality automation of simulation tools to make the early stage(s) as efficient as possible.

The sense of an investment in this early simulation stage is clarified even more by the “rule of ten” saying that the costs to eliminate the mistake that was identified increases in each stage of the development of a product by a factor of ten.

Due to the possibilities of innovation in the early stages, the minimization of the risk, the savings in time, the reduction of the costs and the increase of the quality today’s development process cannot be thought without simulation any more.

3 CATEGORIZATION OF SIMPLIFIED COMPUTATIONAL METHODS AT THE EARLY EMBODIMENT DESIGN STAGE

Through the use of computational methods at the early embodiment design stages costs as well as development times can be reduced. However, many conventional simulation methods are not suitable for the early embodiment design because they are either too laborious or to too inaccurate. Additionally, in many cases design engineers are no experts in simulation methods but especially at the early design stage simulations have to be performed by design engineers.

In the VDI 2211 a so called ABC method to classify simulations tools with respect to time consumption and result quality is shown (see Figure 1).

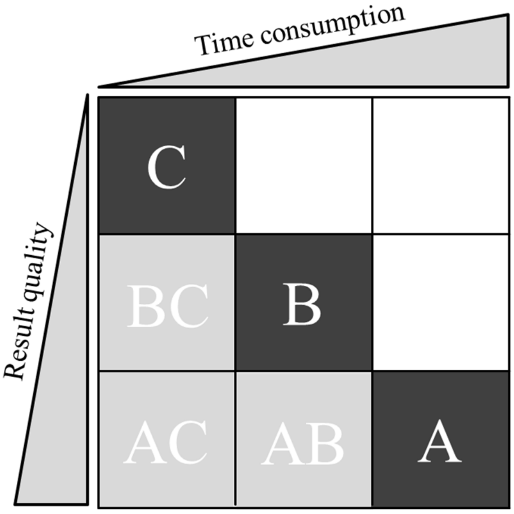

Figure 1. Classification of simulation methods according to VDI 2211 and Gruber (2014)

In this method three main categories are outlined. The first one is the so called A group in which methods with high time consumption and high result quality are considered. Due to their complexity, simulation methods in group A can only be applied by experts. Simulation methods in group B are classified by an average time consumption and result quality whereas simulation methods in group C are distinguished for low time consumption but also low result quality. Both the simulation methods in group B and group C can be applied by design engineers, and therefore, are the intended category for the simulation methods within this article. Nevertheless, with the help of product-related modifications methods from group A can be transferred into special methods in group AB and AC or methods from group B to BC (Loeffel, 1997) and, therefore, can be used by design engineers. Such product-related modifications can be, for instance, the use of simulation features like automated integration of beam spiders for screws or simplified model descriptions like a simplified material description for anisotropic materials (Gruber, 2012). Within this paper model techniques of the hybrid joint with a combination of both simulation features and simplified material descriptions will be presented in order to make the simulation methods accessible for design engineers.

4 DEVELOPMENT OF NOVEL METHODS FOR THE SIMULATION OF HYBRID JOINTS

4.1 Overview over the concept

The key task in this project is the development of a software module to realize an early computer – aided design of joints between aluminum/ CFRP hybrid structures by using constructive guidelines, operating rule curves and simplified simulation models. This should enable product developers in the early embodiment design stage to quickly answer questions about the system behavior of aluminum/ CFRP structures containing joints with a high prognosis quality and a low modeling and computational effort. This makes it possible to design light-weight constructions as energy efficient as possible and to exploit the full potential of such hybrid constructions (Figure 2).

The basis for the content of the software module is done by experiments of the different joints “adhesive bonding” and “riveting”. Here, quasi-static and highly dynamic experiments are performed while parameters like temperature, force angle and further parameters are varied. Special facilities and installations are used as shown in Figure 3. From the experiments two important basics for designing hybrid structures are extracted. On the one side this are constructive guidelines to avoid fundamental mistakes before the first simulation is performed and on the other side operating rule curves derived from the experiment allowing a statement whether a joint under certain conditions will fail or not.

As an additional point the experimental determination of the properties of the joints can be used for calibrating detailed simulation models, which will be explained later. After this the validated simulations will be the basis for all further considerations. By varying several parameters hundreds of different scenarios (design points) of the joints are simulated. To prove the validity of the simulation once more, well considered design points are once again validated by experiments and finally the simulation responses of the system are summarized and saved in metamodels.

These metamodels are tested with respect to their ability to make a prognosis and in a last step they are integrated in simplified simulation models. So the metamodels can give the correct physical answer within seconds when applying particular inputs (also see Chapter 4.5). This means, that a time-consuming simulation of the joints is replaced by simplified fast performing abstraction models. Their field of application is specified by the variation range of the inputs used in the detailed model.

For a user-friendly handling it is planned to provide these simplified models in a software module as features so that the user can apply them several times in a complex simulation model in a quick way. The computational time as well as the time for model creation are reduced to a minimum and so allow testing different situations and joints in the overall model. Also hybrid models with hundreds of joints will be possible at low modeling time.

To realize the use of the software module in the daily product development it will be tested and validated in the development of a door structure. Throughout the entire project the focus is on adhesive bonding as well as friction-locked and keyed riveting, as these are connection types that have been proven to work well in modern lightweight constructions. The simulations that are done for the software demonstrator are realized with an implicit solver of the finite element software ANSYS for the quasi-static load scenarios and with the explicit finite element software LS-DYNA for all highly dynamic load cases.

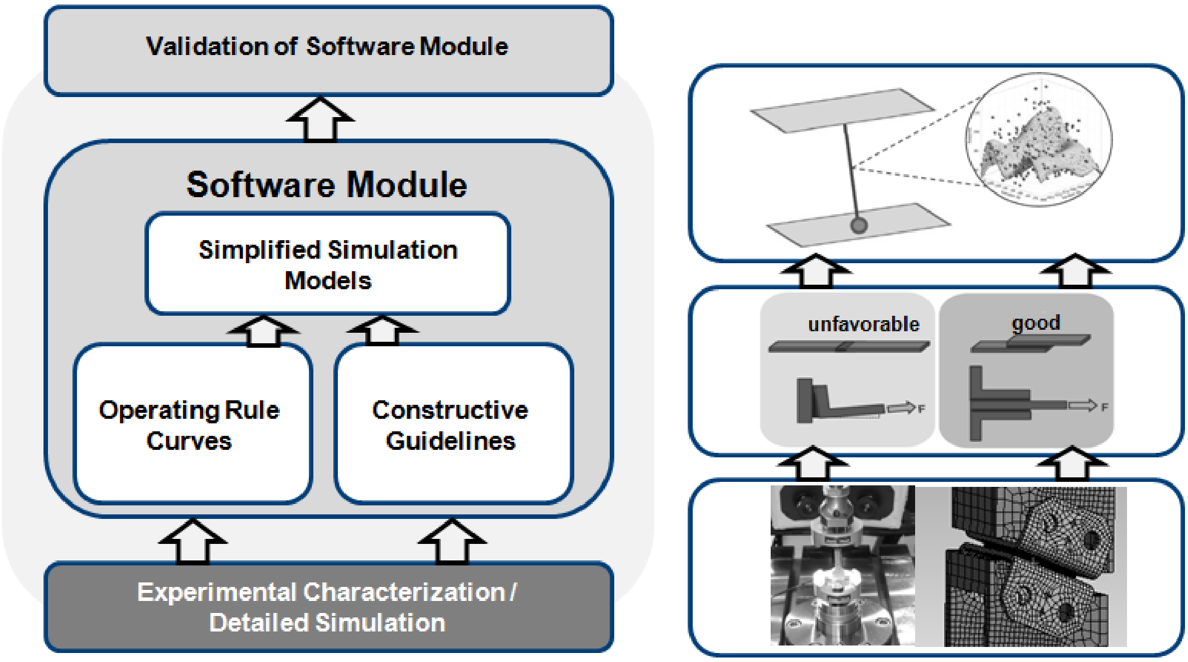

Figure 2. Process scheme of the project

4.2 Performing experiments

The experiments are carried out with a servohydraulic test rig. The measurement of the force is done with a load cell located at the clamping device. In order to keep the vibrations due to the dynamic loading in a small range, the mass between the test sample and the point of measurement was reduced. The test sample is surrounded by a temperature chamber with operating conditions ranging from -30 degrees Celsius to +80 degrees Celsius to explore the influence of the temperature.

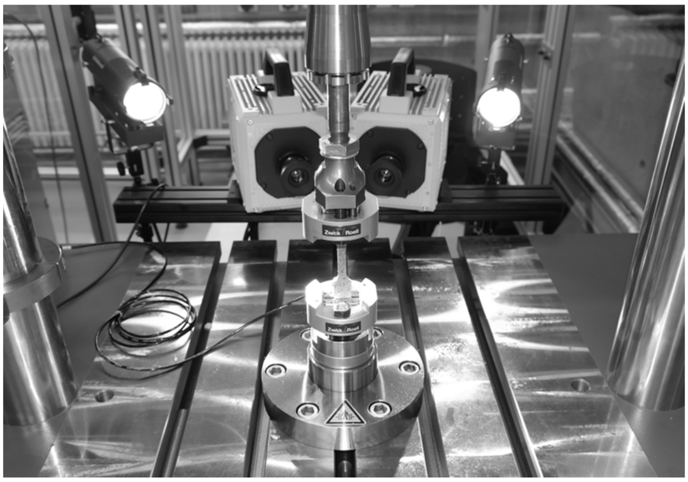

Figure 3. Servohydraulic test rig for CFRP

The following design constellations are physically tested:

- Thickness of the glue: 0.3mm / 0.6mm / 1.0mm
- Two different ply stackups
- Different angles of attack: 0° / 45° / 60° / 90°
- Velocity: 0.001 m/s / 0.1 m/s / 2m/s
- Temperature: -30° / 20°C / 80°C

Out of this a design of experiments is created consisting of 30 samples. Each design point is tested 3 till 5-times to quantify the inaccuracy due to measurement or manufacturing of the probes.

As an example Figure 4 is showing 3 experiments for a design point with a glue thickness of 0.3mm, an angle of attack of 60°, a velocity of 0.001m/s and a temperature of 20°C.

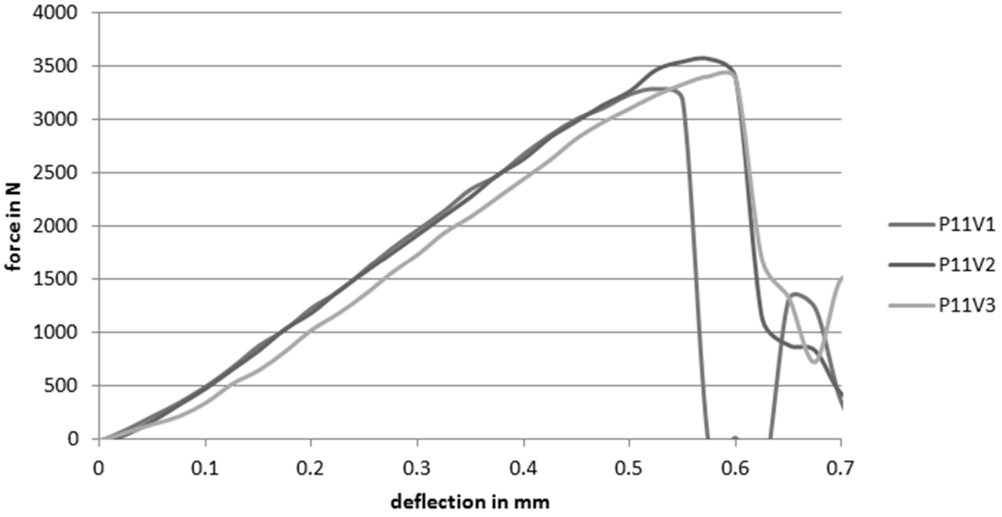

Figure 4. Forced-deflection curves resulting from servohydraulic test rig

4.3 Detailed simulation of experiments

In both detailed simulations - adhesive bonding and riveting - special attention was paid to a robust and conflict-free parameterization. Contrary to the physical tests the parameters can be varied in a continuous way. The variations are possible for

- ply stackup
- thickness of the adhesive joint
- angle of applied force by geometry variation (Figure 5)
- order of the aluminum / CFRP sheets
- velocity
- temperature

This is the prerequisite for the following virtual test planning to perform the sensitivity studies and the generation of the metamodels. By doing so it is also possible to do all simulations that have been done in the physical tests with just one well-considered simulation model. Further parameters are used for the calibration of the simulation by fitting the uncertain simulation parameters to the experiments. Here the scattering output values in the experiments are also taken into account.

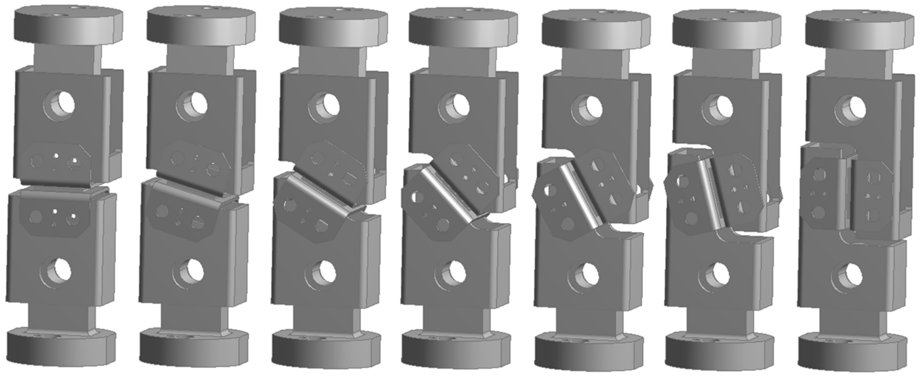

Figure 5. Variants of the adhesive joint samples to apply loads with different directions in the simulation that is used for the sensitivity study

4.3.1 Adhesive bonding

An adhesive joint can be described as a relatively soft material (polymer). A description that is resolved in detail results to a computational time that is very time-consuming but that can be afforded in the detailed simulation models. The gap distance that must be evaluated is very small in relation to the total deformation of the model so a very fine mesh must be taken to satisfy the element quality (Figure 6). To get a delamination behavior of the adhesive joint it is interesting to know, when debonding starts respectively how debonding continues. In this project the detailed simulation of the adhesive joint of an aluminum plate and a CFRP plate is done with an implicit solver. Special contact elements are used, which contain a cohesive zone model (CZM) (Alfano and Crisfield, 2001). There are three modes that are considered:

- Mode I: the separation that is perpendicular to the interface surfaces is dominant. The two important quantities are the normal tension stress as well as the gap in the contact area. Here the adhesive joint shows a linear behavior during loading as well as a linear behavior during debonding. During this process the „critical fracture energy“ can be measured. Important inputs are contact stress (tension), normal contact stiffness, contact gap, contact gap at the maximum normal contact stress as well as the contact gap at the completion of debonding.
- Mode II: the tangential separation is dominant. Important inputs that must be adapted are: tangential slip distance at the maximum tangential contact stress und tangential slip distance at the completion of debonding. From them the tangential critical fracture energy can be calculated.
- Mixed-mode debonding: Here normal and tangential separations are considered

The “energy needed to open the crack” per “crack area opened” can be described with two parts:

$$G_{c,n} = \frac{1}{2}\sigma_{max}u_n^c \tag{1}$$

with

$G_{c,n}$ = “energy needed to open crack” per “crack area opened”, part in normal direction

σ_{max} = maximum normal separation stress

u_n^c = contact gap at the completion of debonding

and

$$G_{c,t} = \frac{1}{2}\tau_{max}u_t^c \tag{2}$$

with

$G_{c,t}$ = “energy needed to open crack” per “crack area opened”, part in tangential direction

τ_{max} = maximum tangential separation stress

u_t^c = tangential slip distance at the completion of debonding

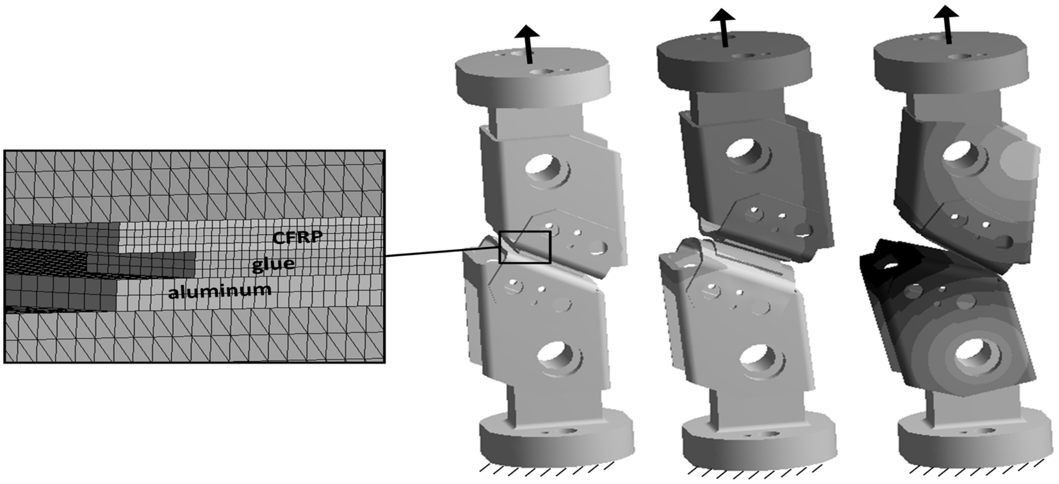

Figure 6. Discretization of the adhesive joint (left) and scaled image of the simulation of the debonding of the adhesive joint (right)

In the simulation also the influence of the temperature is considered, so the elements that are used are able to consider both physics domains – structural dynamics and thermal analysis. Furthermore, the influence of the stiffness change due to the different fiber orientations in the CFRP structure must be taken into account. Here the scatter is very important, as this can contribute very much to the overall stiffness.

Convergence in the model is just necessary till the debonding is completed. That is why the simulation uses a criterion (deflection value) to stop and evaluate the simulation. The resulting outputs are the force-deflection curves that have also been measured in the experiment as well as the failure mode. The parameters that have been mentioned in the three modes define the characteristics in the adhesive joint and can be adapted, so that the results of the simulation match with the results from the experiment.

For a quick evaluation the failure is saved in a representative screenshot and the force-displacement curve is written to a text file.

4.3.2 Riveting

In the second detailed simulation a solid rivet is connecting an aluminum plate with a CFRP structure (Figure 7). First of all the process of the riveting itself is calculated by using an explicit calculation, as the resulting stress distribution and the plastic deformation in the contact area of the shank nut have a big influence on the maximal force that can be transferred in the tension test.

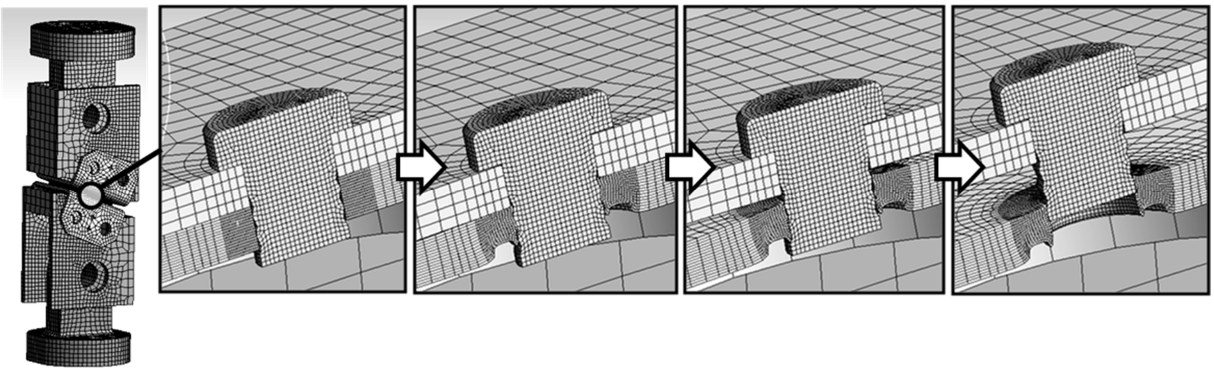

Figure 7. Rivet in tension loading

This kind of simulation requires a very good mesh quality, as the time step and so the total computational time depends on the smallest element edge that has been created in the discretization. This makes it necessary to prepare the geometry so that it is suitable for an adequate meshing in the simulation – also in consideration of a robust and conflict-free parameterization. In this quasi-static and highly dynamic simulation the force-deflection curve is calculated, too, and then written to a text file. For matching the simulation and the experiment uncertain parameters like contact pressure, friction coefficient or the material parameters of the aluminum is adapted.

As in the simulation of the adhesive joints the influences of different temperatures are explored. The CFRP structure is defined analogously to the first detailed simulation.

For a fast calculation time the explicit simulations are performed using several cores with high performance computing.

4.4 Parameter identification

So far the simulation is based on some assumptions, as the conditions in the test rig are not known exactly. For instance it is not sure if the parameters for alpha and beta damping (to define Rayleigh Damping) as well as the parameters for the CZM method have been chosen sufficiently well. For the start values damping parameter from similar projects were used, so alpha was chosen to a value of 2.5 and beta as a value of 4.5e-6 for example. But in the context of evaluation it must be proven that the developed detailed simulation models and these uncertain parameters show a satisfying result quality.

For that the reaction force as well as the failure modes must be analyzed. In the latter, one must distinguish between an adhesive failure in the glue, a cohesive failure in the interfaces (aluminum-glue / glue-CFRP) and a failure in the composite structure (delamination) or for the rivet a failure due to plastification of the aluminum. The force-deflection curve of the experiment is determined in the software environment of the optical metrology (Aramis). So for each design point several force-deflection curves will be written – one for each experiment. The exploration of different curves increases the confidence in the experiments.

The measurement of the force in the virtual models is done by extracting and summarizing the nodal forces at the supports and the deformation is determined according to the measure point definition in the real world experiment. For the quasi-static and highly dynamic analysis in ANSYS Workbench (implicit and explicit) there is the possibility to create output parameters with rule definitions at specified locations of the geometry (such as deformations, strains or forces) at all time steps. The goodness-of-fit information between experiment and simulation can be determined from the sum of square of errors (SSE) between the curves.

In this respect the scatter in the measurements must be taken into account. So the fit is not done for a single curve but for the mean value of several curves.

Furthermore the credibility of making a prognosis for the failure must be quantified to check the reliability of the experiments. At the time of failure a rapid increase of the displacement signal and a rapid decrease of the force signal can be recorded. So the failure can clearly be identified.

By using the angle of attack of the joining partner and the pulling force at the time of failure the maximum transmittable normal and shear forces can be calculated, which are the inputs for the operating rule curves mentioned in 4.1.

Next to the evaluation possibilities described above, it is necessary to take a look at the failure cause which is done by a visual opposing of images.

The criteria are summarized in an evaluation matrix. In the probes that are connected by glue an adhesive failure, a cohesive failure, a failure due to delamination in the composite structure as well as a mixture of all these failures can be observed. By the so-called reverse engineering – also known as calibration – the simulation parameters are adapted for all situations to get a good data match to these failures and the force-deflection curves. The simulation models show a satisfying match to the experimental data. For the highly dynamic tests the fitting is much more difficult due to the dynamic impact of the sample carrier. But still, a good comparison between experiment and simulation till to the point of failure can be done.

4.5 Novel abstraction methods that will be applied

In the next step novel abstraction methods will be used. This is currently being worked out. On the basis of the calibrated detailed simulation models the influences of the support conditions can be understood. A design of experiments (DOE) for the numerical simulations can be created that satisfies uniform distribution for the input data. This DOE equally covers the parameter space, that should be explored and additionally it contains “extreme” parameter configurations at the bounds of the space as well as the constellations that have been tested with the real experiments. With this DOE the output variables extracted from the detailed simulation models are calculated. This parameter list is used to create a sensitivity analysis at first, to identify important input parameters for the simplified analytical models. After that, the metamodel of optimal prognosis (MOP) in combination with variance-based sensitivity analysis is used (Most and Will, 2011). With this methodology it is possible to identify strongly non-linear and coupled correlations with a minimal amount of simulation runs, which can be expected especially in the highly dynamic simulation models. From experience other classical procedures, as for example correlation coefficients and step-wise regression are not sufficient. Additionally to the sensitivities of the input parameters the MOP can quantify the correlations between the inputs and outputs. So it should be possible to make a decision, if input parameters can (or even should) be neglected for the creation of the metamodel to get a prognosis with the quality that is needed. In a last step the MOPs are implemented in abstraction models for implicit and explicit calculations. This means, that the abstraction models deliver the correct answer (from the data that was calculated in the time-consuming simulation models) at any time for any input question by picking the corresponding value from the MOP. By implementing several of these abstraction models into a complex simulation it can also be expected that there are a lot of interactions between these abstracted joint models.

5 SUMMARY AND FUTURE WORK

With this work it will be possible to provide a tool that can predict the behavior of hybrid joints much faster and so makes it possible to consider them in the early design stage. This will enable the engineer to increase the use of fiber-reinforced composites.

For that the joint methods „adhesive bonding“ and „riveting“ have been measured for different conditions using design of experiments. To take the scatter into account, several tests for the same conditions have been done, which built the reference for the parameter identification in the detailed simulation models that have been set up. Subsequently the detailed simulation models have been evaluated in sensitivity studies and provided the information that will be necessary to create regression models with an optimal prognosis. These will be implemented in simplified abstraction models.

In a further step the process will be tested in representative simulation models. A demonstrator consisting of aluminum and CFRP will be simulated at the development site of Brose in Hallstadt, Germany and then be compared with the experimental data. Further simulations are conceivable, as for example the static calculation of load cases for window regulator systems as well as door lowering. For dynamic case studies, crash simulations can be done, as for example the side impact test of a car door. Furthermore it is planned to provide the method by a wizard-based module, to increase the efficiency in daily work.

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