Simulation and testing of adaptive FRP-substructures for automotive safety

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Paper Number 15-0068

ABSTRACT

This paper describes the development of a basic finite element simulation model of a concept for an adaptive structure made with carbon fiber reinforced plastic materials. Thereby in particular the prediction of the mechanical properties of necessary deformation zones in the structure, that are realized with an elastomer matrix system, is challenging due to the different properties of this material compared to conventional composites. Available material models in the FE-Code LS-DYNA are analyzed for their usability in this task. For the parameterization of the material models a number of coupon tests are conducted and the deviations between the material with the elastomer matrix and the material with the conventional duromer matrix system is analyzed. The results of these tests is used to validate the material models for both, the material used in the expansion zone and the conventional composite material in the rest of the structure. It is shown, that the prediction of the shear properties of the elastomer based material creates difficulties with the used material model (MAT_54) but in total the correlation between test and simulation is good and comparable for both materials.
The first task that has to be approved for an adaptive structure made of FRP-materials is the expansion-process from the initial to the pressurized final geometry. For this purpose a quasistatic inflation test is performed. The results of the test and a corresponding simulation correlate well for the pressure at which the expansion of the structure begins. Regarding the maximum burst pressure and the location of the material failure deviations between test and simulation occur. Possible reasons for this deviations are analyzed and discussed.
Finally the additional necessary steps in the creation of a predictive simulation model for an adaptive FRP structure under crash-load and possible approaches for the latter are discussed.

INTRODUCTION

Currently the automotive industry is highly demanding simulation models that are able to predict and optimise the crash behaviour of mass produced Fibre Reinforced Polymer (FRP) composite structures, which will be increasingly used in vehicles in the future. The ability to investigate crashworthiness of FRP vehicle structures by numerical simulation is very important for these lightweight materials to see widespread use in future cars.
In this paper, the current status of the development of simulation models for shape-adaptive FRP-Structures, as shown in (1), is described. It is analysed if state-of-the-art modelling-approaches and existing material models can be used, or if novel developments are necessary to predict the mechanical properties and behaviour of such components. The process of the parameterization of a material model, including the conduction of material tests as well as the validation of the models, is described.

MOTIVATION

Shape-adaptive FRP-Structures address the demand for lightweight vehicles structures as well as the need for reduced injury-risk of car occupants. The potential benefits of those two topics are summarized in the following:

Use of FRP-Materials in automotive application

The increasing demand on reduced emissions, lower fuel consumption and higher safety in the automotive industry requires not only a development of alternatively powered vehicles, but also consistent lightweight design. The use of lightweight materials such as glass or carbon FRP is a possible approach to achieve these goals. In contrast to metal materials FRP have very high values for specific stiffness and strength. The usage of FRP structures within new vehicle concepts beneficially leads to a further enhancement of structural safety while lowering the vehicle's mass.
Compared to metal materials the use of FRP for the Body-in-White (BIW) shows a weight saving potential of up to 60% to 70% (2), (3). This potential has been exploited for many years in motorsport and comes more and more into focus for conventional cars. In particular for future alternatively powered vehicles, weight saving is directly linked to increased range which brings FRP-materials into such cars in greater extent (e.g. BMW i3 (4)).
In addition to the weight saving potential FRP also show a very high ratio of energy absorption per weight, compared to metal structures (CFK~ 100kJ/kg vs. Al ~50kJ/kg (5)). This makes it a very interesting material for the crash-structures in a car. Actual applications can be found predominantly in sports cars (e.g. Mercedes SLR (6)) but as soon as some shortcomings of those materials (e.g. cost, recycling, …) are solved, it is very likely that they are applied also in more vehicle types in the future.

Adaptive structures in automotive application

Recently expandable structures, which provide different mechanical properties due to a geometrical adaptivity, have come into focus of vehicle safety development. These structures are principally folded in their undeployed state to minimize the cross section. Thus these adaptive structures are very compact, which brings benefits regarding packaging in the vehicle. Due to the fact of cross sectional adaptivity, the structure shows very high potential concerning weight reduction. Wall thickness can be reduced due to increased stiffness, as a result of the increased moment of inertia by the expansion of the structure and additionally also due to the pressure within the structure (7).
Adaptive crash structures show potential for further increase of safety and lightweight performance. Different approaches with varying design goals and realisations have been discussed in recent publications. The main goals for the use of adaptive structures can be summarized as described in (8):

- Increase of deformation length
- Increase/decrease of crash load levels
- Increase of energy absorption
- Weight reduction
- Packaging benefits

One alternative approach describes the goal of improving the driver's vision by use of adaptive A-pillars (9).
Adaptive structures made of steel have already been developed by Daimler AG and used in prototype vehicles such as the Experimental Safety Vehicle (ESF 2009). For example, by expanding structural components to the ouside of the car, additional space for deceleration of impacting objects is created, which leads to a significant reduction of intrusion velocities of the door in case of a side impact (10).

When one tries to combine the above described benefits of FRP material and crash adaptive structures, an elementary question arises: Is it possible to realize a structure that allows for geometrical adaptivity with FRP-materials that are typically very stiff and allow only very low enlongations at failure?
One possible concept for a successful realisation of such a solution is described in (1). For a better understanding of the development of a corresponding numerical model, the chosen approach for this structure is summarized briefly.

For the realization of a shape adaptive CFRP (carbon fiber reinforced plastic) structure a novel hybrid-matrix approach is used to integrate multiple matrix materials into one CFRP structure. This hybrid-matrix approach allows the local integration of elastomer matrix material. Since the matrix material significantly influences the bending stiffness and strength in FRP, an elastomer matrix material leads to a strong flexibilization (11). Herewith, a large geometry change in FRP structures can be realized.
Based on the hybrid-matrix approach a suitable design concept for a reinforcing door structure is developed which is capable of a significant change in shape in case of an inner pressurization.
In the unpressurized state the hollow structure has a u-shape cross section at the expansion area (see Figure 1). In case of pressurization the cross section areas with the elastomer matrix material can change into a semicircle shape, which almost leads to a doubling of the structure's moment of inertia. The bottom area of the cross section geometry as well as the end area of the structure do not change their geometry due to the

rigidity of the thermoset matrix material. At the rigid end areas both, the fixation to the door frame and the integration of the pressurization device can be realized.

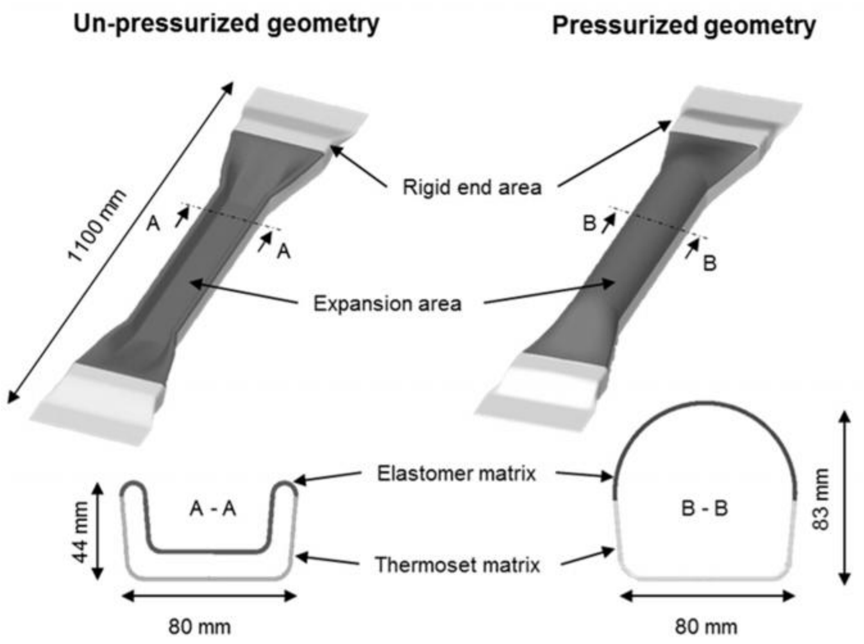


Figure 1: Shape adaptive FRP-Structure

This design concept represents the background for the manufacturing of prototypes which are tested regarding the inflation behaviour and their mechanical properties in pressurized and un-pressurized state.
The materials in the expansion area of this structure vary considerably to conventional FRP-materials with rigid thermoset resins as matrix materials. In particular the large strains that have to be sustained in the expansion-area require tailored material properties.
In addition to the proof of concept with prototypes as described above, numerical models of the used materials are developed and validated with coupon- and component-tests. In this paper the process of the development and validation of the material models, that are able to predict the mechanical behavior the adaptive FRP-Structure described in (1) is shown. Prior to that the state-of-the-art modelling techniques as well as the available standard material models are analyzed.

METHODS

In general the FE-simulation models are set up based on a three level development process that is shown in Figure 2. This process consists of a basic material, a principle component and finally of a full vehicle implementation testing and validation level.

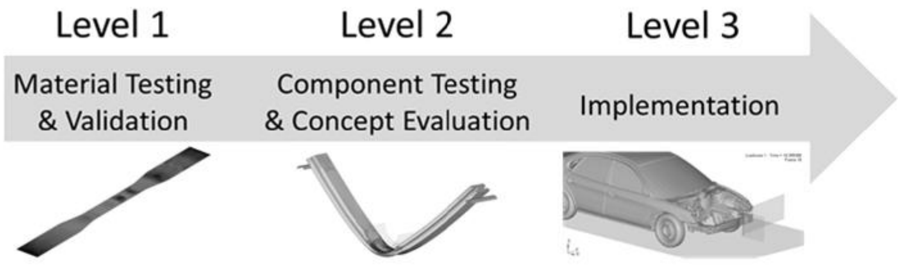


Figure 2: Development process of FE-Model of adaptive FRP Structure

At the material level, tests on coupon level are performed to derive the necessary data for the parameterization of the selected material models. In addition to the tests literature data is used (if available) for the verification of the test results.
At the principle component level the derived FRP simulation approaches are used to develop and evaluate the functionality and effectivity of design concepts of adaptive FRP structures. The FE models are used to investigate

and evaluate the adaptive behaviour of the FRP structure. Therefore all essential influencing parameters to the adaptive structure like, for instance, the use of different materials, wall thickness, FRP lay-up, position of the elastic areas, needed internal pressure for the unfolding process as well as the maximum burst pressure of such structures will be investigated in detail. Moreover, the FE simulation will be used to configure the setup for the component tests.
Once the second validation step is finished, the designed adaptive structure can be integrated into a full-vehicle simulation model and its potential regarding weight saving and increase of occupant safety can be assessed.

Beginning with a review of possible modelling techniques and available material models, a first simulation approach which is capable of predicting the behaviour of the laminate is defined. In order to derive the parameters necessary for the material models, a series of coupon tests are conducted and for each test a corresponding simulation model with the adjusted boundary conditions is created. Beginning with literature values and information of data-sheets, the material parameters are optimized iteratively to fit the test results as closely as possible. For this process also optimization tools (LS Opt) are applied.
In the following, the used data and the selected numerical tools are described in detail and the results of the first two validation steps are presented.

MATERIAL TESTING AND VALIDATION

Simulation approach for the laminate

In general, modelling techniques for FE simulation have to be classified into simulation of FRP UD (unidirectional) and woven laminates. First, UD laminates are simulated by the use of solid and layered shell element formulations in combination with special FRP material models. With the aid of these material models the elastic behavior as well as the failure and damage behavior can be simulated based on several available failure and damage criteria (e.g. (12)). Second, woven laminates are basically simulated by the use of two different modelling approaches (13), the cross ply and the smeared ply approach (see Figure 3).
These special approaches are motivated by the fact of interweaved, undulating fibers in warp (0°) and weft (90°) direction within one single layer. Within the cross ply approach interweaved fibers are split into two single unidirectional layers with half the thickness of the real woven single layer. One represents the warp and the other one the weft fibers. In contrast, within the smeared approach the warp and weft properties are smeared to one single layer.
In general the smeared approach is easier to apply concerning parameterization of the material models but gives less quality results regarding failure behavior. This is caused by the fact that existing failure criteria are designed for UD laminates but not for woven ones. In contrast, the cross ply approach is more elaborate regarding the parameterization of the material model caused by the split modelling of the woven fabric. Within this approach the failure and damage behavior can be simulated by using the existing failure criteria.
For this study the cross ply approach is used for simulation of woven laminates within the adaptive CFRP structure. The simulation of possible failure and damage mechanism during pressurization and external loading is of main interest to evaluate the structural effectivity of the adaptive structure.

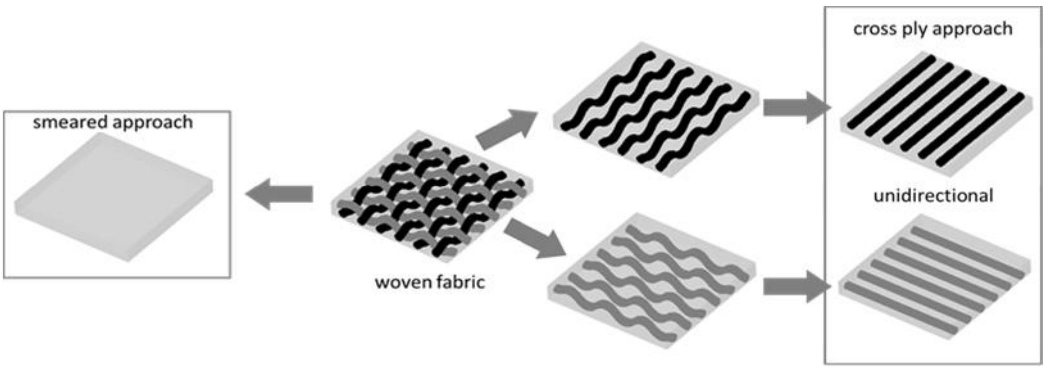


Figure 3: Modelling approaches for woven fabrics

Selection of material model

Once the modelling approach is set, a suitable material model has to be selected. As the properties of the used materials (i.p. expansion zone) vary significantly from conventional thermoset FRPs, it has to be evaluated firstly which material model can describe the mechanical behavior in the best way. The used FE-Code LS-DYNA offers

a large variety of available material models dedicated for the simulation of FRP-materials (14) with different advantages and disadvantages (15).
With the chosen modelling approach of the laminate comes the need for the definition of material parameters that describe the integral mechanical properties of the FRP-material. A possible first step is to calculate the laminate properties (e.g. stiffness, strength in principal axis) based on the material properties of fiber, matrix system and the layup (16). This generally provides a good initial value for the subsequent validation with experimental data. With these determined first material parameters the different available material models of LS-DYNA were filled in, to provide an initial estimation of the usability of the different material models. With the comparably simple models: MAT_22, MAT_54 and MAT_58A, already a good correlation can be achieved. For those material models the previous calculation of the mechanical properties provide most of the required input parameters. For non-existing input parameters the material card must be completed with literature data and assumptions.
The application of more recent material models such as MAT_261 and MAT_262 is currently not considered, because they require very extensive material testing for the determination of the individual input parameters. For these material models many assumptions would have been necessary, which would have led to a worse predictability of the models.

Performed coupon tests

The data required for the parameterization of the models can be divided into “basic” data (e.g. Youngs modulus, poisson ration, etc. in longitudinal and transverse direction) and parameters that describe the material behavior after failure. In particular for the latter, the more complex material models (e.g. MAT_261, …) need more parameters for the definition and validation of the failure- and damage models and therefore require additional test configurations.
The values of the “basic” material parameters can be determined with tensile and compression tests in different layup configurations. For the shear properties a tensile test with a [±45°]$_s$ laminate has to be carried out.
In order to be able to parameterize the material models used in the adaptive structure, the material used in the flexible areas as well as the stiffer material with the duromer resin system have to be examined.
An overview about the conducted tests is given in the following figure:

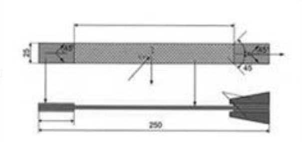
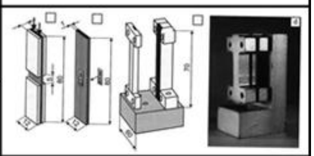
Test	Norm	No. Of Tests	
Tensile Test [0/90]$_s$	DIN EN ISO 527	5	
Tensile Test [+45/-45]$_s$	DIN EN ISO 527	5	
Compression Test [0/90]$_s$	Boeing Compression Test	5	
Compression Test [+45/-45]$_s$	Boeing Compression Test	5	
ENF [0/90]$_s$	AECMA prEN 6034	5	Sketches taken from: „Kunststoffprüfung“, Wolfgang Grellmann , Sabine Seidler, 2nd Edition, Hanser Verlag, 2005
DCB [0/90]$_s$	ASTM D5528-01	5	
MMB [0/90]$_s$	ASTM D6671	6	

Figure 4: Overview of performed coupon tests in the MATISSE Project

For the creation of the first simulation models, only the tension and compression tests are used. They are going to be analyzed further in the next chapters. The additional three tests (ENF, DCB and MMB) are used for the validation of a novel delamination model which is not part of this publication. This model has already been presented in (17) and (18).

Results – Validation of material models

In the following the results of test and simulation with the final material model are compared and discussed:

Elastomer matrix system – Expansion area of adaptive structure

For the expansion area of the shape-adaptive structure, which has to sustain large deformations during the unfolding process, the material model *MAT_54 was selected. The latter is a simple progressive failure model for FRP materials. It requires only a few input parameters, thus it reduces the difficulty and extensive material testing for input parameters. *MAT_54 describes a progressive failure within the limits of strength and strain (19).

For the determination of the input-parameters a number of material tests in longitudinal and transverse direction are performed. In 0° tension loading, the material shows an almost linear behavior up to failure (see Figure 5). This characteristic can be realized very well by the use of *MAT_54.
The shear component is adjusted by a 45° tension test. Typical duromer based FRPs show a non-linearity under shear loading (20). The elastomer based FRP does not show such a behavior, its force deflection curve is also nearly linear, as can be seen in Figure 5.

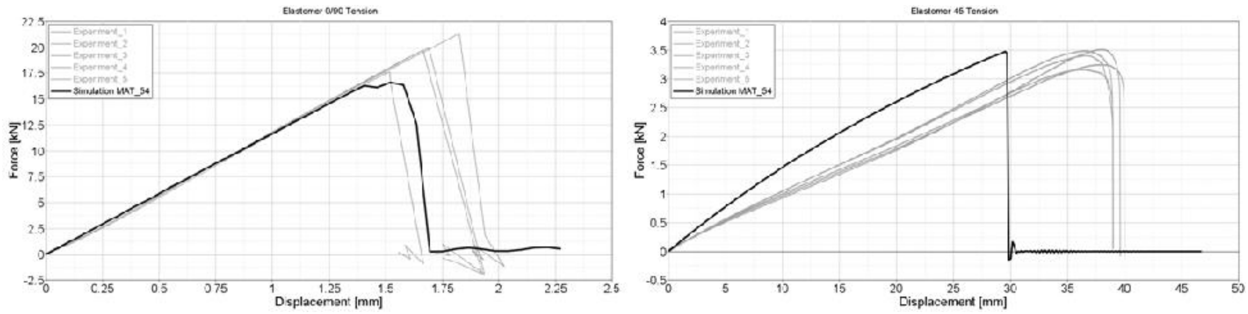


Figure 5: Tension tests: Elastomer matrix system

The simulation results of the $[0/90]_s$ laminate under tension loading show a high correlation to the test. In contrast the results of the tension test with a $[\pm 45°]_s$ laminate show a significant difference to the simulation. The increase of the reaction force under predominant shear loading of the material is overestimated, the elongation at break is too small whereas the maximum force correlates well with the test results. In the selected material model the ascent of the reaction force cannot be reduced without degrading the correlation in the $[0/90]_s$ configuration. Therefore for this first simulation approach the fair correlation in the shear properties is accepted.
Under compression load (see Figure 6) a higher variation in the test results can be seen. In the $[0/90]_s$ configuration the curves show a distinct peak value before first material failure occurs. In contrast at the $[\pm 45°]_s$ tests the force level is almost constant when the material begins to fail. After a certain value of deformation the reaction forces rise again in both test settings. This characteristic is mainly driven by the test setup.

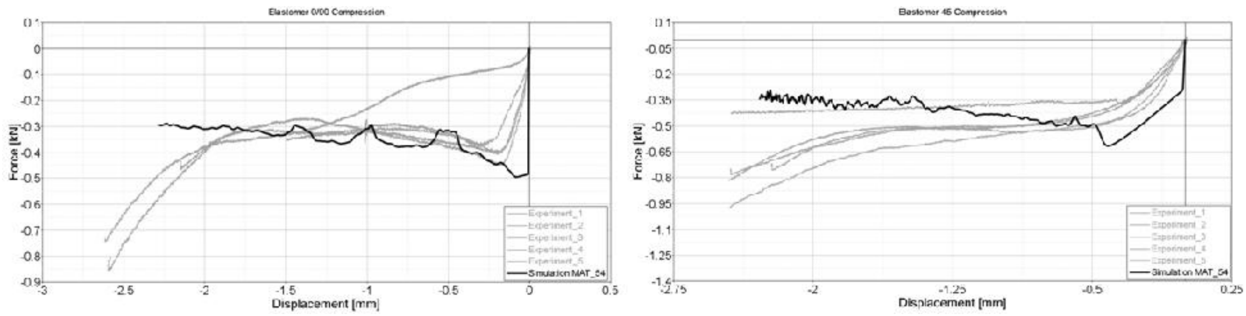


Figure 6: Compression test: Elastomer matrix system

When comparing the test results with the corresponding simulations it can be seen, that in particular at the $[0/90]_s$ configuration the ascent of the reaction force in the simulation is significantly higher. In this test-setup it has to be taken into account, that already smallest errors in the alignment of the upper and lower clamp of the specimen or deviations in the angle can artificially reduce the stiffness of the material. This effect is even higher, when testing soft materials such as the elastomer-matrix system used in this case. As the ascent of the reaction force in the area of elastic deformation correlates perfectly for the tension test with the $[0/90]_s$, layup it is assumed that the above mentioned effects influence the results to a certain extent.
For both cases the peak force before material failure is correlating well with the test results. After this initial peak the damage model in the simulation is obviously not capable of representing the real material characteristic. After failure the broken material is still supporting itself to some extent. In addition, the small test length leads to a buckling and an increase of thickness, which is not happening in the simulation model. An increase of the stiffness of the material after failure, which would be necessary to predict such a behavior, is not possible in any of the analyzed material models.

Duromer matrix system – "Stiff" parts of adaptive structure

To simulate the parts of the structure that are built with conventional carbon fiber/duromer material system, the material model *MAT_58 is used. *MAT_58 is a continuum damage model for representing unidirectional tape and woven fabric composite materials (21). The material behavior of a conventional carbon fiber/duromer material system under a tension loading in $[\pm45°]_s$ fiber direction shows a nonlinear load deflection curve, while a loading in fiber direction results in a linear response. Results for the different layups are shown in Figure 7.

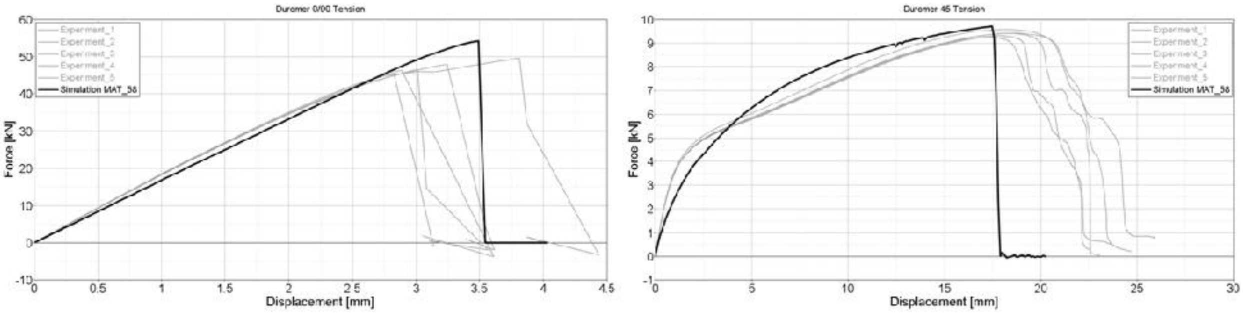


Figure 7: Tension tests: Duromer matrix system

It can be seen that in both configurations the results of simulation and test correlate regarding the peak force and also the elongation at break. For the $[\pm45°]_s$ tests, the behavior after the peak force as well as the non-linear characteristic of the f-s-curve in particular in the initial ascent show a difference to the simulation results.
In case of the compression test with the duromer matrix system and a $[0/90]_s$ layup the material fails completely at very low strain levels. No residual force can be observed. In contrast the tests with $[\pm45°]_s$ shows a certain residual force but the increase of the reaction forces at larger deformation, as seen with the elastomer matrix system under compression load, cannot be seen.

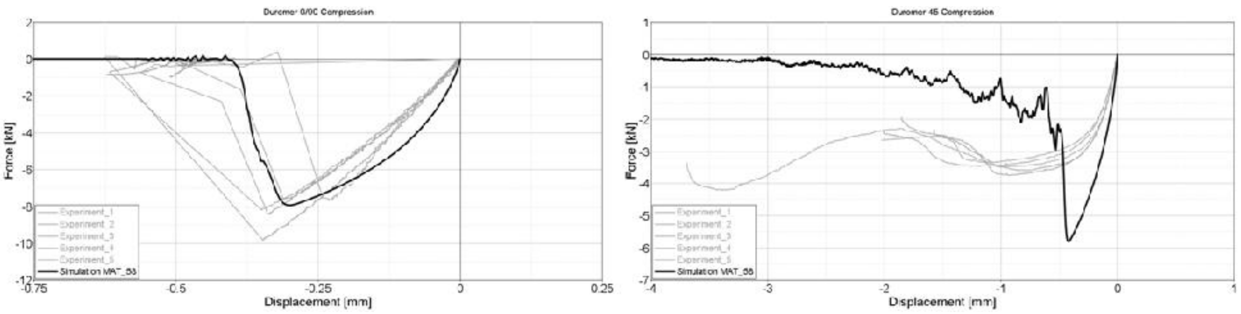


Figure 8: Compression tests: Duromer matrix system

Comparing the results of test and simulation the values for the initial ascent of the reaction forces correlate well. The peak force fits to the test results in case of the $[0/90]_s$ configuration, but is significantly too high for the $[\pm45°]_s$ layup. The above mentioned issue with the damage model allowing no increase of stiffness after material failure leads to good results for the $[0/90]_s$ and comparable deviations as seen at the elastomer matrix system.

The shown correlation is the result of an iterative optimization of material parameters, whereby their respective physical boundaries are respected. A compromise setup is chosen in order to minimize deviations between test and simulation in all analyzed loading configurations.

It can be summarized that the available simple standard material models can be used in order to simulate the mechanical behavior of materials that allow for a shape adaptivity of a FRP structure. The correlation of the simulation with the conducted coupon tests is comparable for the conventional FRP based on a duromer matrix system and the material dedicated for the expansion-zones based on an elastomer matrix system.

COMPONENT TESTING AND VALIDATION

Also for the testing, a stepwise approach for the proof of concept was chosen with the final goal to conduct a dynamic impactor test on an adaptive beam, which is expanded within few milliseconds by a pyrotechnical inflator. Before that a number of intermediate steps have to be carried out, beginning with the verification, that the actual expansion process of the beam can be realized without failure of the structure. For this purpose the structure is pressurized with water, slowly increasing the inner pressure.

Inflation-Test of expandable beam with quasistatic pressure

This test also gives some essential information for the validation of a corresponding numerical model:

- Pressure at which the structure begins to unfold
- Unfolded beam-geometry
- Burst pressure of entire beam

For that purpose the inflator is replaced by a water-pump that slowly increases the pressure within the structure. As the mountings for the inflator can be used for that purpose, there is no modification of the structure necessary. The following pictures show the attachment of the pressurization device and the beam in the process of unfolding.

Figure 9: Mounting of pressure transducer

Figure 10: Unfolded shape of beam

This test shows, that the static expansion process of the beam from the folded to the final shape begins at a very low pressure of around 100 to 200 kPa. After the expansion the elastic areas of the beam are creating a more or less semi-circular cross-section, whereas the areas with the duromer-resin maintain their initial shape.
The pressure is further increased to see at which level and at which location the first material failure occurs. At an inner pressure of around 4.400 kPa, a first small leakage can be observed in the transition area of the u-shape to the attachment points as displayed in Figure 11.

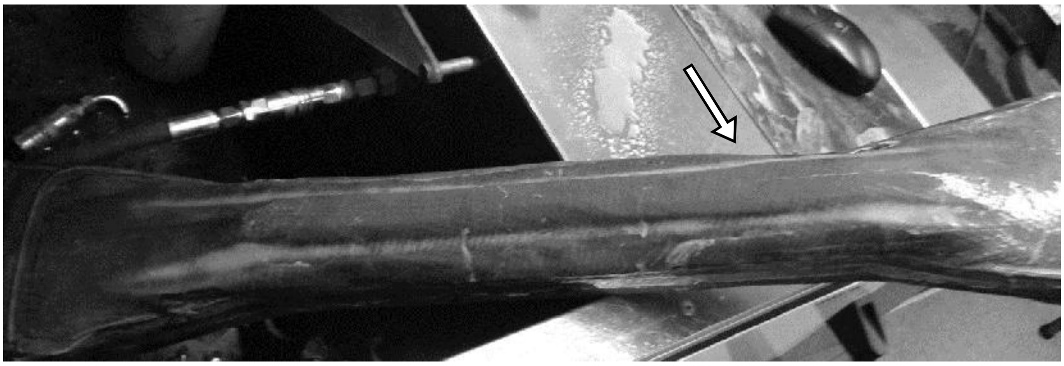


Figure 11: Expanded structure with initial leakage at 4.400 kPa

This leakage is not necessarily caused by a material failure as water could also have leaked through an area with higher porosity. Nevertheless, this pressure value gives a first idea of the possible pressure level that can be sustained.
In order to validate the simulation model of the component with this test, the same boundary conditions as in the test are applied to the model and the material data, which has already been validated with the coupon tests, is used.

Simulation approach for the inner pressure

Besides the availability of valid FRP material models a detailed approach to simulate the inflation process is mandatory for the cost and time efficient development of crash adaptive structures. Therefore, LS-DYNA offers three fundamentally different methods to mathematically model the inflation process of the expandable pressurized structures.

Depending on the optimization task and the level of detail, one of the following approaches can be used:

- Uniform Pressure Method (UP)
- Arbitrary-Lagrangian-Eulerian Method (ALE)
- Corpuscular Particle Method (CPM)

Typically, in the early development stage of crash adaptive structures no inflator specifications like heat capacity, mass flow rate and temperature profile of the inflowing gas mixture are known (22). Instead of calculating the inner pressure based on the inflator data the UP-approach offers the possibility to specify an idealized pressure versus time profile.
Due to the not existing discretization of the inflowing gas mixture the pressure distribution within the structural component is uniform. Accordingly, this yields to the following drawbacks:

- exact representation of the internal pressure requires technical measurement during inflation tests of the original component (hardware needed)
- no local interaction between gas and structure due to global pressure value
- evaluation of local temperature or pressure peaks (eg. close to the inflator) not possible

It is obvious that, as soon as the pressurization is realized with an inflator, the CPM or ALE-Method has to be applied in order to achieve a realistic loading of the structure in the simulation model. For the test with the quasistatic water-pressurization there is no benefit by applying this more complex approach, therefor the UP-Method is used.

Results – Validation of component test

In the selected simulation model of the structural member, both ends are constrained allowing only translational movement in the longitudinal direction of the beam. The structure can expand its shape without interacting with any other component. The pressure is steadily increased to reach 5.000 kPa after 500ms. These values are chosen to simulate the "slow" increase of pressure compared to an inflation with a pyrotechnical device. Even though the material properties are not modelled with strain rate dependency as described above, still the dynamic of the structure is influenced by the rate at which the inner pressure is rising in the simulation. The chosen configuration thereby is a compromise in order to limit the necessary calculation time. The inflation process as well as the curves for pressure and inner volume of the structure are displayed in Figure 12.

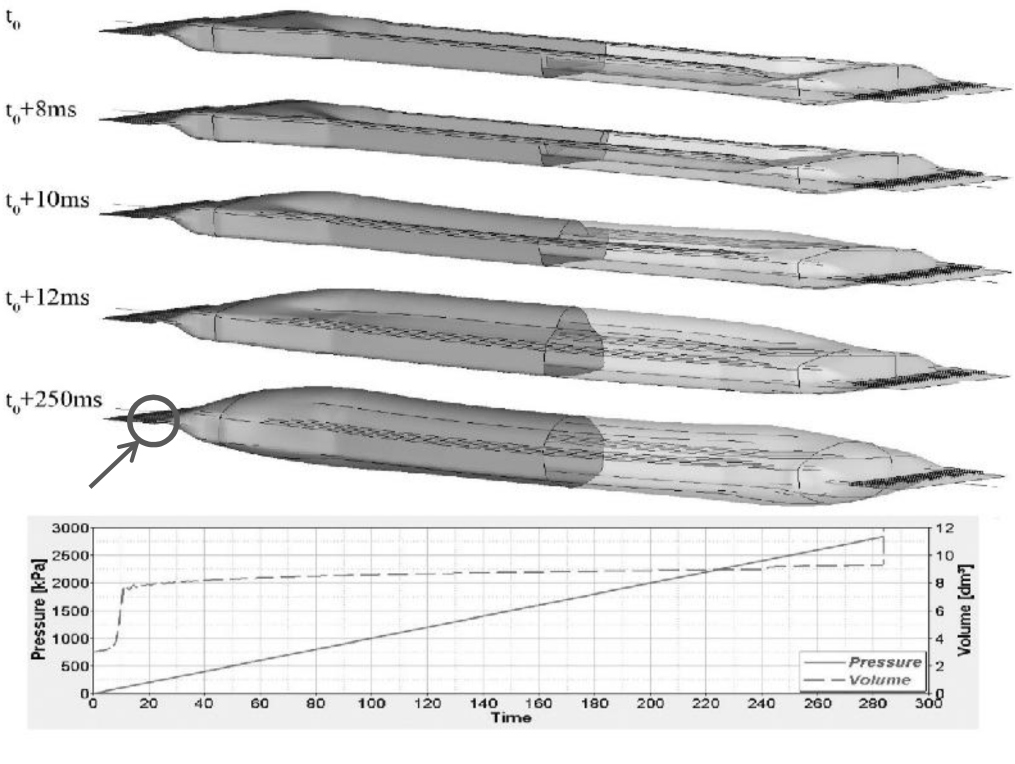


Figure 12: Simulation of quasistatic pressurization

It can be seen that the volume of the structure in the initial status is about 3 liters. The unfolding and thus the gain of volume begins at a pressure level of 100 kPa. At a pressure of around 150 kPa the expansion zone of the structure has completely unfolded and from that time on the increase of volume is caused by a transition to a more or less circular cross-section of the structure. Even though the pressure during the expansion process is low, the unfolding itself takes place with high dynamics. This effect correlates well with the conducted test in which the expansion process also begins already at very low pressure levels.
With increasing pressure also the volume slightly increases until the first material failure in the model at a pressure level of 2.800 kPa. This failure occurs in the transition area between the attachment and the expansion zone (see Figure 12, 250ms) which is not correlating with the location of the leakage in the test. By evaluating the stress-distribution within the layup areas with high loading can be identified. This analysis shows, that the area of the leakage in the test is the zone of the structure loaded with the highest shear-stresses. The part of the structure in which the failure occurs in the simulation is the zone with the highest principal normal stress.
This leads to the assumption, that the parameterization of the failure models for the two materials found in the coupon tests does not fit perfectly for the loading situation found in the structure.
Another issue is, that the geometry in the area of material failure shows some very small radii that lead to discretization errors caused by the mesh. That could be addressed with a refined mesh in that specific part of the model, which has the drawback of increased calculation time.

SUMMARY/CONCLUSION

The goal of this study was to find suitable material models that are required to allow for an accurate simulation of the geometrical adaptivity of FRP structures. By comparing the results of conducted coupon tests with corresponding simulations it was demonstrated, that this goal can be achieved already with standard material models. The achieved correlation for the elastomer-based material in the expansion-zone is comparable to the standard-material used in the remaining parts of the structure. For the shear-stiffness of the elastomer-based CFRP only a fair correlation between test and simulation could be achieved with the used material model.

Whereas the results in the coupon tests match well, a significant deviation in the simulation of the component tests is noticed. With the performed coupon tests only in-plane compression and tension loading was analyzed. Based on these results the damage- and failure models in the chosen material models (MAT_54 and MAT_58) were parameterized. In the current structure obviously more complex loading conditions occur (inner pressure, bending load, …). That might be one reason, why the results for maximum pressure of the simulation is not matching the results of the component test. This issue suggests additional coupon tests (e.g.: 3 pt. bending, etc.) in order to have a wider basis for the parameterization of the damage models. With additional material data available also the application of more complex material models can be taken into account.

The first step in the development process for numerical models of shape adaptive beams is the capability of the simulation of the unfolding process. Based on this work it can be demonstrated that the used hybrid-matrix approach, which is one suitable concept for the realization of the necessary flexibility of the structure, can also be represented in a numerical model. Limitations of the chosen material models and the conducted coupon test lead to deviations in the correlation between simulation and tests. In order to improve the predictability of the simulations some possible approaches were discussed.

For the prediction of the mechanical properties of shape adaptive FRP-structures under crash-loads, the complexity of the modelling increases significantly:

Firstly it is assumed, that the unfolding process itself already causes local damage of the material which can lead to a weakening of the structure in the actual crash-load. First of all, this effect has to be analyzed by tests in order to understand the influencing parameters. Then basically two approaches are possible for the integration of this effect in the model of the structure: Either the used material model provides a “damage-history” that allows for the use of different parameters for the first loading (expansion – no damage) and the second loading (crash – pre-damage). Alternatively it is also feasible to run the expansion process in a pre-simulation and the actual crash-simulation with an exchanged material model.

Secondly it is known, that FRPs and hereby in particular the matrix materials show a high dependency of the mechanical properties to the loading velocity (23). This effect was not considered for the above presented numerical model but for the final purpose of this study it cannot be neglected. For the expansion process as well as the crash loading itself such effects can lead to a different stiffness and strength of the structure but also to different failure modes. Strain rate dependencies can be considered also with the material models used in this study but the parameterization of these models requires an enormous amount of material testing.

Finally, it has to be considered that for the pressurization of the structure an inflator is used. Depending on the used inflator-technology the exhaust gas can reach several hundred degrees Celsius. The combination of hot gas and its high velocity in the area of the inflator, abrasive damage of the structure material can occur. This needs to be considered in the design of the structure. This effect cannot be simulated, so extensive testing is necessary.

The global heating of the structure during and after the inflation leads to varying material properties, which can be significant for plastic materials (24). Due to the very short time of interaction of the hot gas with the structure, this effect is possibly neglectable but it has to be confirmed for concept evaluation. A heat-dependency of material properties is not yet realized in available material models of LS-DYNA. So alternatively, after a pre-simulation for the expansion process the material model can be adjusted to simulate the material with the actual temperature during the crash-load.

It can be concluded that still a lot of research topics have to be solved in order to create a predictive numerical model of a shape-adaptive FRP structure but with this work a first step was achieved.

ACKNOWLEDGEMENT

The research leading to these results receives funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 314182 (the MATISSE project). This publication solely reflects the author’s views. The European Community is not liable for any use that may be made of the information contained herein.

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