Design and material characterization of reinforced plastics for secondary structural load paths in an early development phase

David Moncayo[1], Matthäus Cyperling[2], George Dumitru[3],Tobias Graf[3]
Daniel Coutellier[4], Hakim Naceur[4]

[1] DAIMLER AG, Sindelfingen, Germany
[2] Mercedes-Benz Werk Hamburg, Germany
[3] Dynamore GmbH, Germany
[4] Université Polytechnique Hauts-de-France, France

Abstract

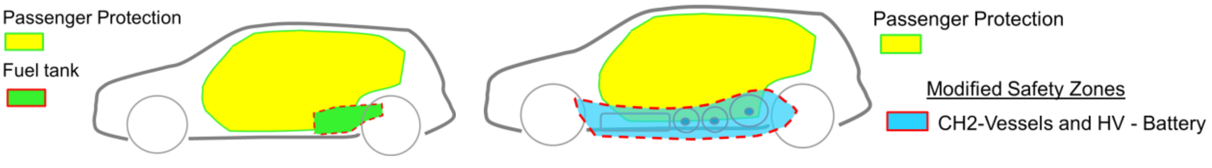
This paper presents different modeling approaches and technical challenges for the discretization of anisotropic elastic-viscoplastic materials in secondary structural parts for the automotive sector.

In terms of accuracy, complex geometries based on reinforced plastics in secondary load paths need to factor in the manufacturing process and the resultant local anisotropies within correspondent CAE models. However, during the early phase of product development, integrating reinforced plastics, a robust numerical basis throughout the concept evaluation is required. The basic idea is to maintain the correspondent level of complexity through the subcomponent design within certain limits, in order to improve, speed up and adequately handle complexity in CAE concepts for the automotive sector.

Finally, a benchmark analysis of possible options and modeling techniques is introduced, as a contribution to evaluate the balance between the dimensioning of structural load paths and the required material characterization within an acceptable effort.

1 Introduction

New powertrain configurations using compressed hydrogen or natural gas and high voltage battery systems require flexible dimensioning of the structural framework in new vehicle architectures. The complex interaction between the structural modules represents a technical challenge, when the safety zones and deformation zones for energy absorption differ strongly within the same structural development (Figure 1).

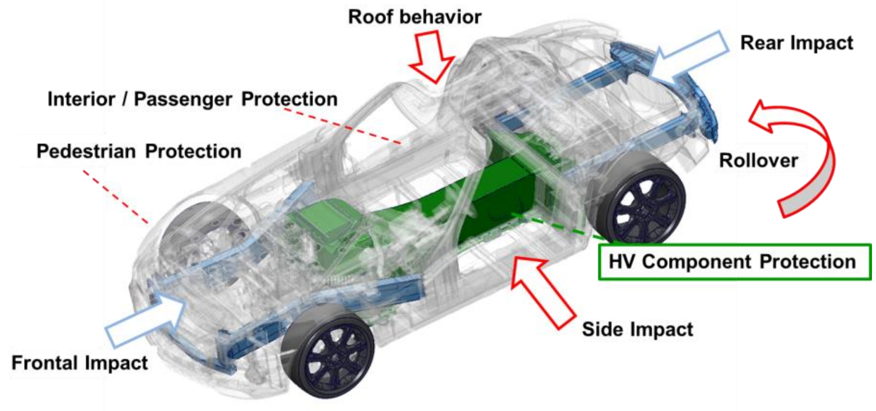


a: Conventional Powertrain *b: Alternative Powertrain*

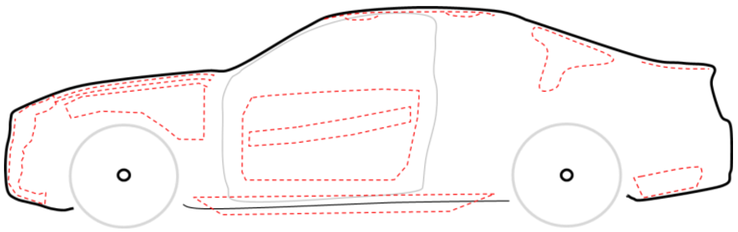
Figure 1: Deformation zones in vehicle architectures

Reinforced plastics are part of the structural load paths during the development process. The interaction with the surrounding parts and components leads to a final ratification of the structural concept (Figure.2a), while their isolated analysis helps the engineer to achieve a flexible and improved local behavior.

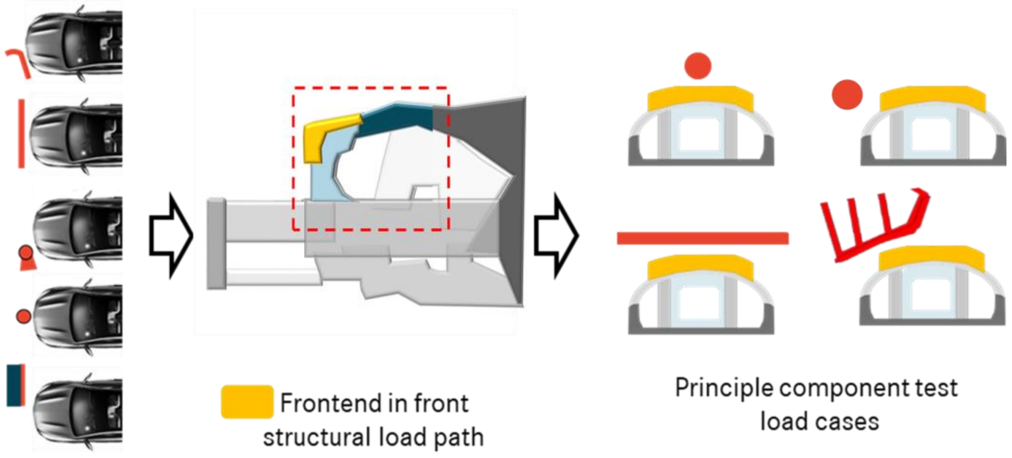
Figure 2b represents some of the possible regions, where implementing reinforced plastics influences the damage tolerance of the local structural behavior.



a) Structural concepts under crash loads [1]



b) Identified zones with possible reinforced plastics as a secondary load path



c) Isolated analysis on a segment level, numerical and experimental dimensioning

Figure 2: Structural levels in the numerical concept evaluation

However, experiments on a full-scale crash might still depict some discrepancies in the structural targets. These aspects require attention in an organized workflow, especially at the early phase of the structural development. Nowadays, principal load-paths develop and bifurcate mainly through metal parts in vehicle architectures for a high volume market. Never the less, advanced plastics and reinforced plastics have gain interest and are used as secondary support or force-deflection within certain zones of the vehicle. Having a secondary influence in the development of a load path, these plastic parts do not carry the principal load for the structural integrity of the whole system but they certainly have the potential to enhance the functionality and the design approach.

Figure 3 depicts the workflow for modular part groups in the vehicle and their structural target based on a valid structural-segment in order to set up an efficient analysis-framework on the component level to enhance the maturity at early development stages. On a component level, the following criteria are considered to concatenate the evaluation effort progressively until it's structural integration in a full vehicle is properly achieved:

- Internal energy
- Force and displacement characteristic
- Modeling method
- Joining method and attachment to surrounding areas
- Morphological deformation, damage and material failure
- CPU cost and modification agility (pre – and post processing)

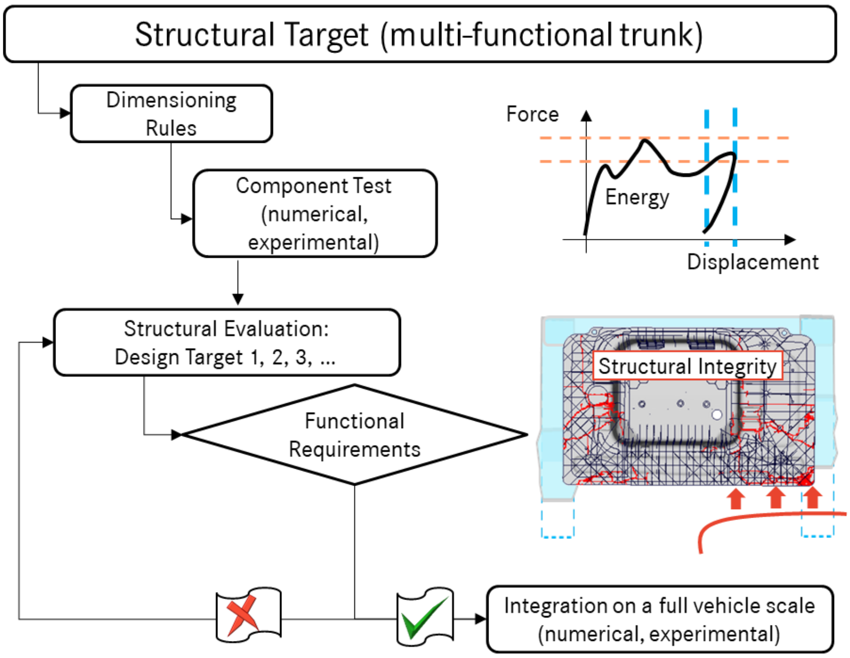


Figure 3. Modular Workflow for a target dimensioning

2 Reinforced plastics

Combining a thermoplastic matrix with glass or carbon fibers is a possibility to dimension shell-like structures with a certain amount of energy absorption or force distribution in structural reinforcement areas. Table 1 lists for example, the possible combinations of polyamide-reinforced plastics, which are relevant to high-volume parts.

PA-GF-xx	Influence factors on the physical properties
Polyamide Matrix + short glass fibers	- part geometry, production-configuration - fiber content, distribution, - strain rate - temperature - humidity
Polyamide Matrix + woven fabric of glass fibers	
Polyamide Matrix + unidirectional glass fibers	

Table 1: Thermoplastic combinations for secondary structural load paths, with a polyamid matrix

Usually the structural response of polyamide-reinforced plastics reflect humidity, strain rate and temperature levels as influence factors throughout the numerical dimensioning process. These issues and the fiber distribution in complex geometries increase the numerical effort, which is necessary to reach a reliable and stable CAE-part design within a structural load path.

Considering the factors listed in Table 1, underlines the importance of using reduced segment models as depicted in Figure 2. In this manner the analyst ensures that the designed target fulfills the structural requirements for a wide range of influence factors, all within a reasonable computational effort.

3 Energy absorption with high fragmentation

The material crushes progressively, while dimensioning reinforced parts for energy absorption. Through local geometry and thickness variations, a systematical crushing behavior and a force-displacement target can be achieved. However, a stable, functional force-displacement-characteristic also requires a design-space as well as an adequate mounting support and fixation, in order to transfer forces and deformation further within the structural load path.

3.1 Energy absorber as a principle component

Figure 4 presents the crush behavior of a principle geometrical test for a rib-based geometry as basis for the design analysis.

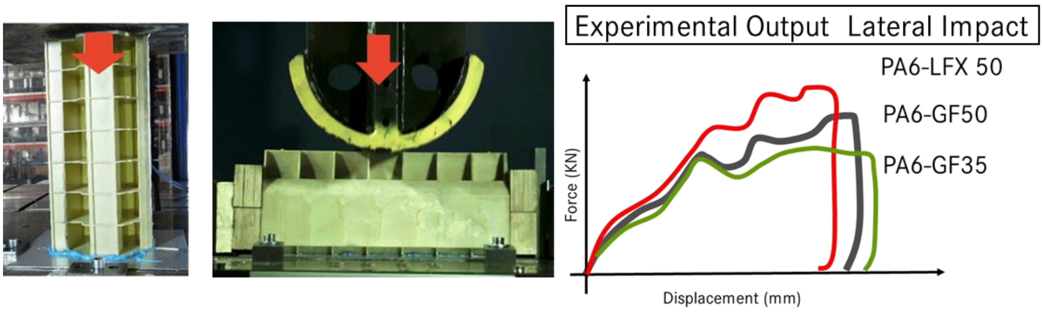


Figure 4. Principle component test for energy absorption

While short fiber configurations depict strongly broken portions where the material is not used properly, long-fiber configurations show a stronger resistance to broken transitions zones and the adjacent fracture propagation (Figure 5). Consequently, this configuration describes an increase of the developed force in the time-history-plot.

Although the part geometry significantly controls the observed morphological fracture patterns, the results also show the achieved flexibility for a certain functional-target without changing the design space. Changing the force orientation vectors has a much bigger influence, increasing the effective distance to the safety zones behind the acting point. This fact dominates geometrical dimensioning and weight distribution in the part, depending on the area which is to be reinforced.

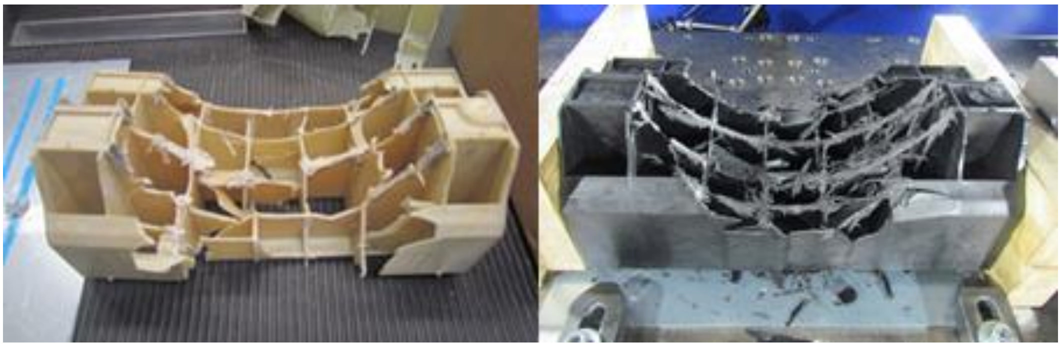


Figure 5: Damage topology of the structure after the same parallel impact test: a) short fiber configuration; b) long fiber configuration

4 Energy absorption and force distribution with reduced fragmentation

In addition to the structural response of short-fiber and long-fiber reinforced plastics presented in the previous section, organo-sheet surfaces integrated in the design provide a higher amount of ductility and damage tolerance. An engineered dimensioning of injected reinforced ribs provides additional stiffness and buckling resistance to the structure, in order to maintain weight and costs within reasonable margins. A common polyamide matrix between reinforcement ribs and flat patterns of organo-sheet material seals the interfaces and locks the ribs preventing them from detaching easily from the flat patterns.

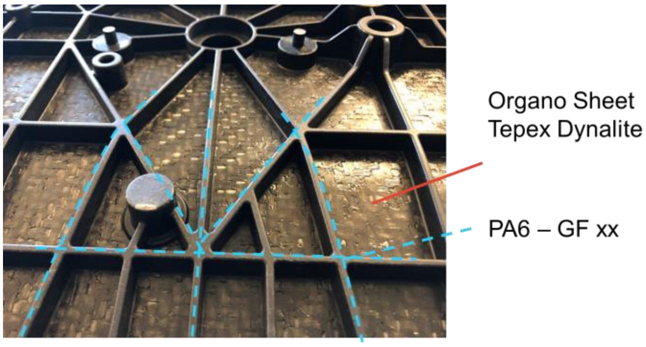


Figure 6: Reinforced plastic ribs and flat patterns of organo sheet material

4.1 Multi-functional trunk as a principle component

Under rear crash loads, some components in a trunk should not be lose from the vehicle. In this study, in order to meet functional, weight and cost requirements, the combination of two material configurations presents a principle component development through a common dimensioning work as described in Figure 3.

The two material configurations:

- a thermoplastic matrix with short or long glass fibers
- a thermoplastic organo sheet with woven fabric glass, twill weave pattern

Couple the damage tolerance of the organo sheet zones with the additional structural stiffness of short fiber zones through the part dimensioning task.

While a dynamic component test in a drop tower configuration ratifies the functional target (Figure 3), the correspondent simulation reveals the technical challenges for the numerical prediction of the structural behavior as well as important issues regarding the efficient integration in a full vehicle structure.

An accurate qualitative and quantitative numerical representation of the part requires the discussion of the following criteria in the discretization of the component:

- accurate material modeling and fragmentation prognosis
- accurate prediction of failure in the joining method
- accurate quantitative prediction of the force load path evolution

Table 2: Discretization criteria (reinforced plastics)

Moncayo [1] provides an overview of the numerical effort abstracting these materials and the numerical homogenization effort at different structural levels of a conventional building block approach.

At an early phase of product development, some reasonable assumptions lead to a significant reduction of the validation effort, without losing the possibility to enhance the numerical calibration with more experiments, once the engineer identifies an adequate design target.

Figure 10 describes the building block approach as presented in [1]. Figure 11 depicts a scheme overview of the correspondent experimental effort and a reduced workflow as the possible compromise between accuracy and efficiency during the material characterization.

Within a reduced workflow (Figure 11), the numerical analysis enhances the stability of the structural response in a design target due to the geometrical development and its influence as presented in Table 1. On the other hand, a set of experiment-based assumptions and an additional numerical evaluation leads to a more well-engineered and progressive prognosis capability, as pointed in Table 2.

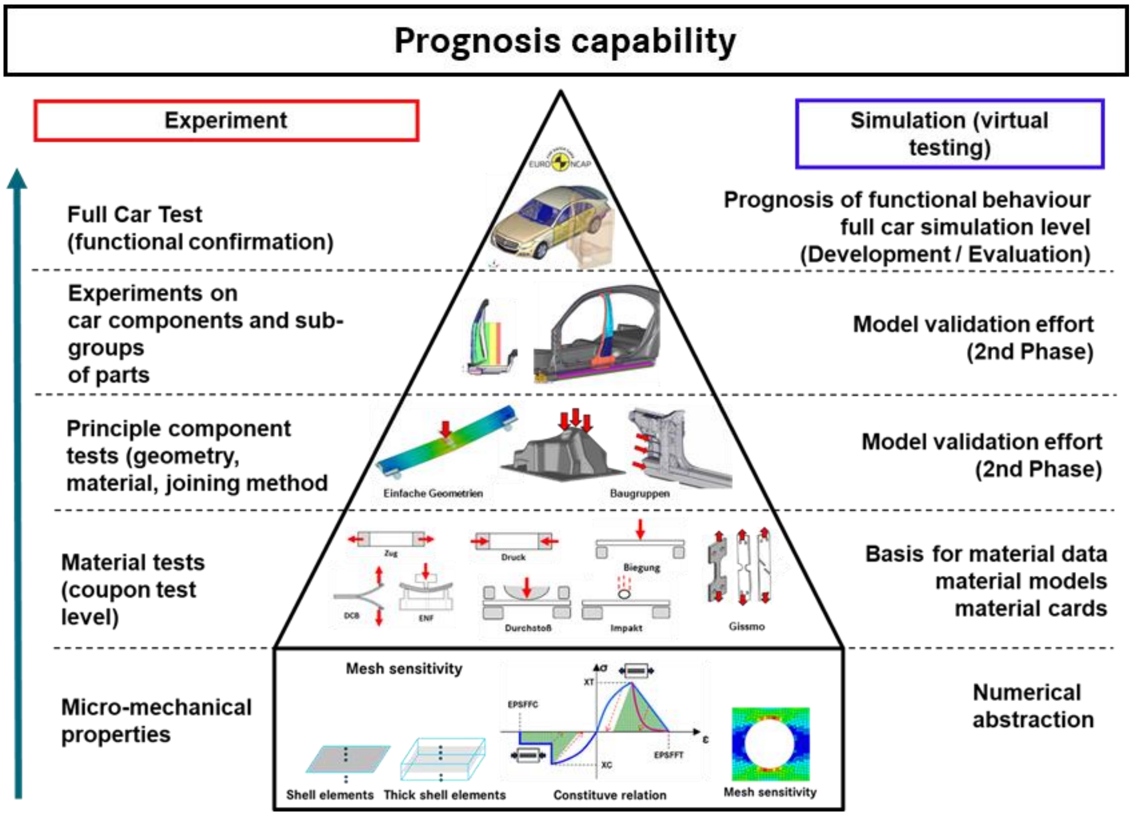


Figure 10: Building block approach [1]

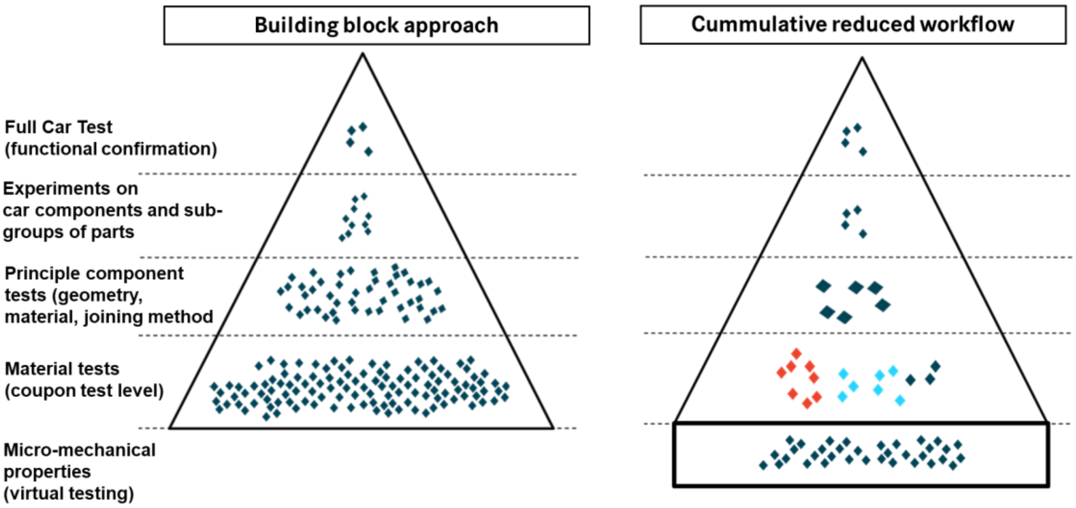


Figure 11: Experimental effort scheme

5 Material Characterization

There are different schemes describing a possible approach to effective material characterization and to a reliable prognosis capability for reinforced plastics under crash loads. As described in figure 11, a building block approach demands a high amount of coupon tests to capture the homogenized physical properties of the matrix-fiber compound.

Further, the identified values for the physical parameters generally require some recalibration in order to capture the damage and the morphological material failure.

However, common material test-standards based on coupon-tests are not enough to reach the necessary prognosis capability. A validation effort based on a principle component level completes the analysis framework but does not necessarily satisfy the requirements to achieve a good numerical prognosis. Therefore the discretization correspondent to the geometrical parameters also needs to be considered at different levels of the material validation effort.

Figure 12 describes a reduced amount of experimental coupon specimens, used as the basis in a reduced cumulative workflow, in addition to the common data-sheet available from each technical material supplier. These coupon tests help the engineer validate the principal elastic material parameters. They can also be used for the progressively validation the necessary numerical parameters in the material routine, in order to capture both, the allowed strength and catastrophic failure as well.

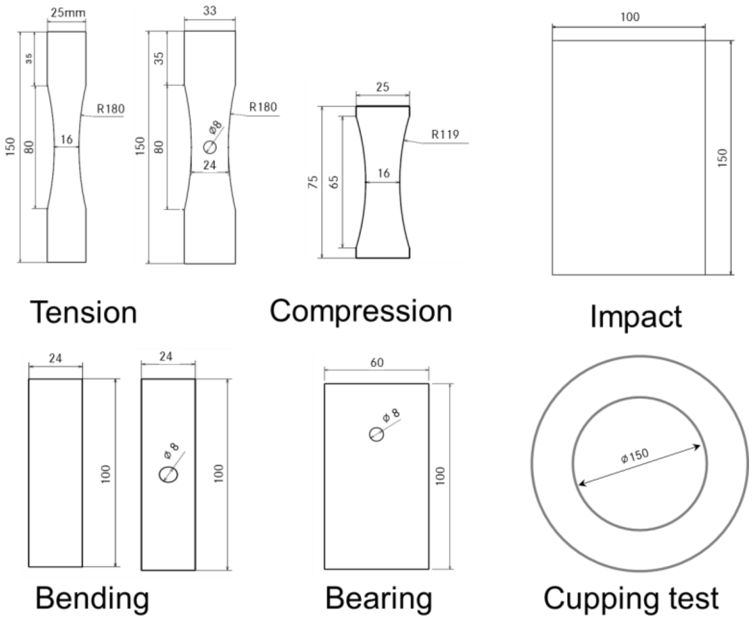


Figure 12: Coupon tests configurations for a reduced cumulative workflow

5.1 Discretization

A common discretization approach for these kind of reinforced plastics is depicted below:

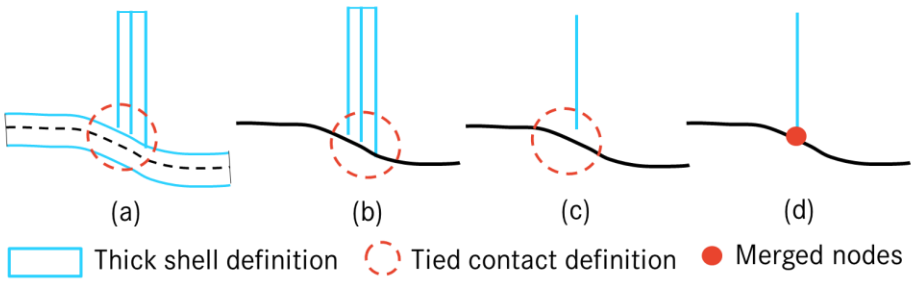


Figure 13: Discretization approach

a. A thick shell modeling approach with tied nodes for ribs and transition zones
b. (Hybrid modeling) a single shell modeling approach for shell like patterns and a thick shell modeling approach with tied nodes for ribs and transition zones
c. Single shell modeling with merged nodes for ribs and transition zones
d. Single shell modeling approach with tied nodes for ribs and transition zones

Figure 13 depicts the numerical attachment of ribs (Figure 6) with the flat patterns of the geometry.

An efficient handling of the numerical modules and their integration in large full vehicle models leads usually to a preference for single shell modeling techniques.

6 Numerical Calibration

The following aspects correlated with the calibration of additional numerical parameters need to be continuously monitored during the model validation effort for reinforced plastics.

- Mesh sensitivity: characteristic mesh size, element topology
- Damage localization and failure
- Geometrical transition zones
- Fixation and joining method
- Thickness and mesh size relationship

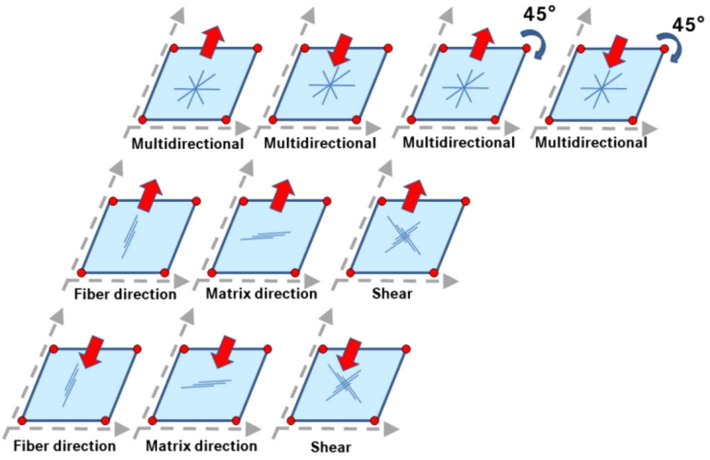


Figure 14: One element test

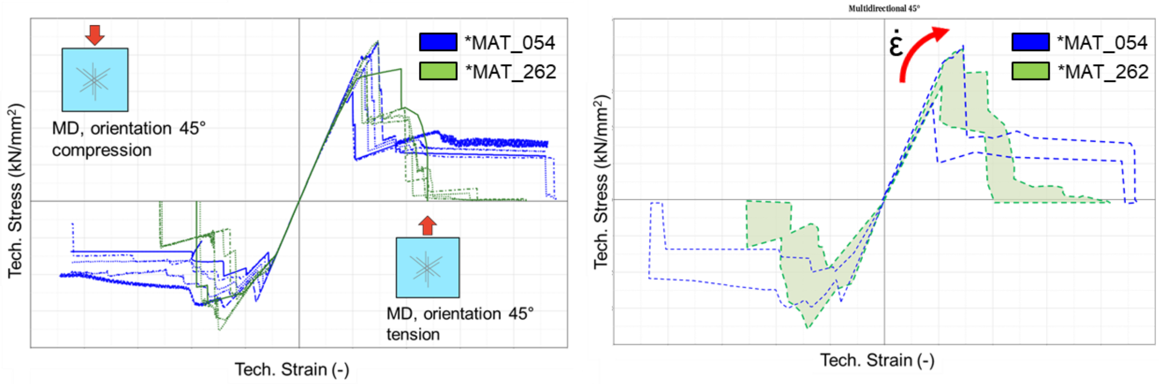
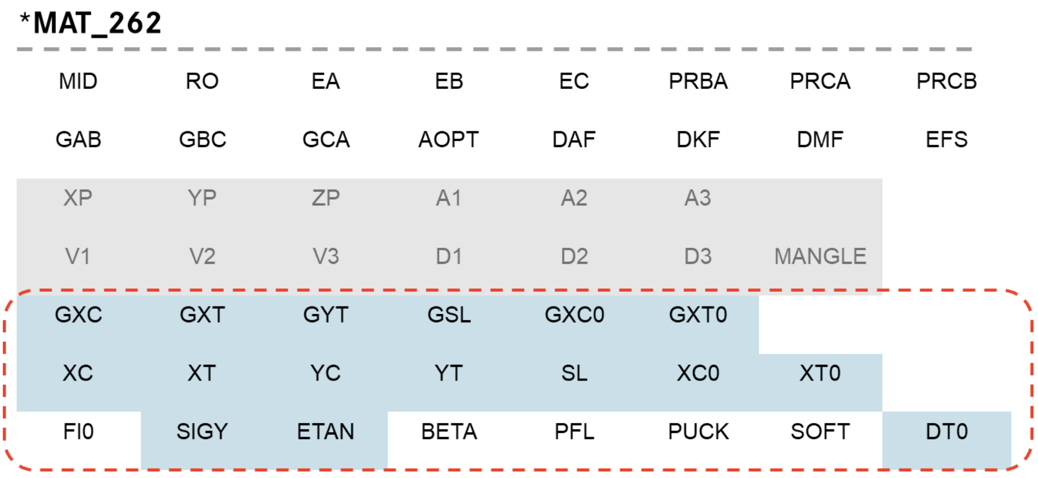


Figure 15: Stress-strain relationship, multidirectional lay-up

The presented one-element-test evaluation for a multidirectional lay-up (Figure 14 and Figure 15) describes the stability and representation of material parameters in the stress strain relationship. A comparison between `*MAT_054` and `*MAT_262` with a multidirectional lay-up describes the progressive failure and degradation of the material properties through the thickness of the laminate, especially for the off-axis loads in a 3mm mesh size. After a strong degradation of the material properties the erosion of the element in `*MAT_262` is determined through an effective strain limit.

In addition, the discretization of the presented open-hole coupon tests describes easily the stability during the localization and failure of the specimen within a mesh size target, between 2 mm and 8 mm. A quantitative and a qualitative calibration of mesh size and strain rate dependency is achieved through the correspondent parameters in `*MAT_262` highlighted in Table 3.



*MAT_262

MID	RO	EA	EB	EC	PRBA	PRCA	PRCB
GAB	GBC	GCA	AOPT	DAF	DKF	DMF	EFS
XP	YP	ZP	A1	A2	A3		
V1	V2	V3	D1	D2	D3	MANGLE	
GXC	GXT	GYT	GSL	GXC0	GXT0		
XC	XT	YC	YT	SL	XC0	XT0	
FI0	SIGY	ETAN	BETA	PFL	PUCK	SOFT	DT0

Table 3: MATERIAL LAMINATED FRACTURE DAIMLER CAMANHO, [2]

Figure 16 and Figure 17 show the achieved regularization between 2,5 mm and 5 mm mesh sizes for the open-hole specimen. Consistent damage evolution and quantitative strength levels increase the numerical stability in more complex part geometries.

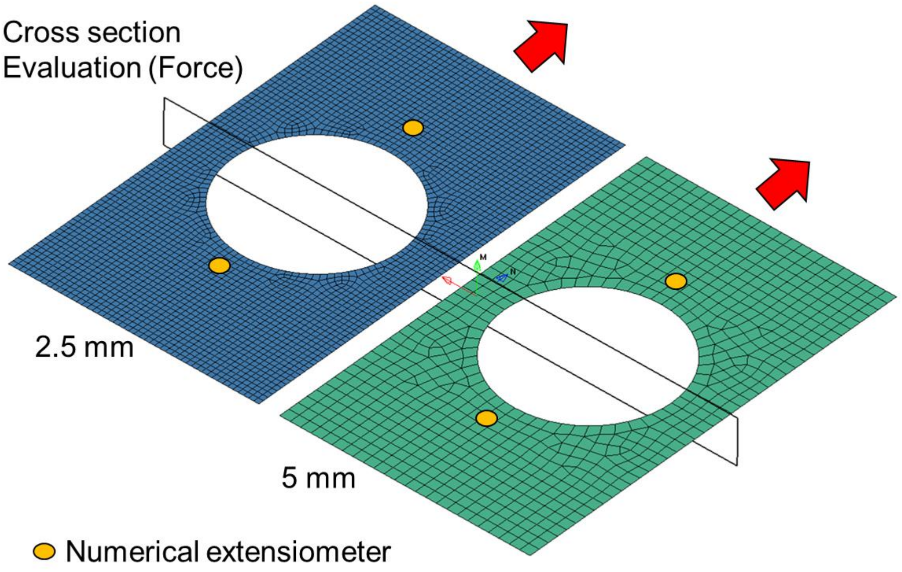


Figure 16. Open-hole tensile specimen, CAE Model

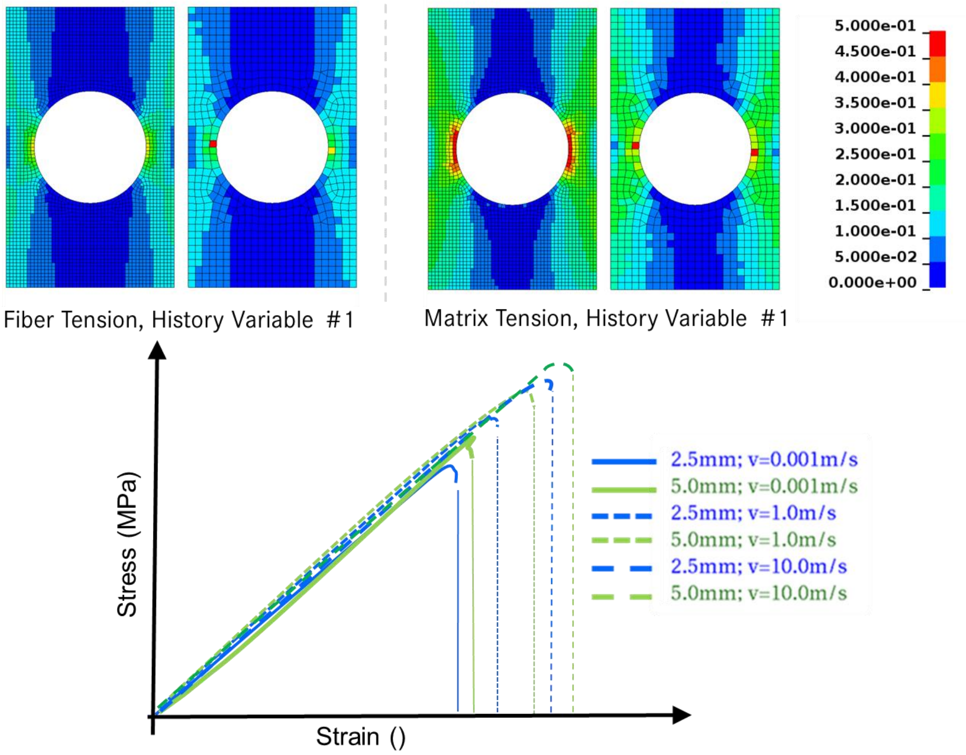


Figure 17: Localization and quantitative evaluation of strength

The impact-coupon-test configuration and a modified cupping-test-configuration are useful when calibrating the out-of-plane structural behavior and damage, suitable for industrial parts in structural loads. The ply thickness and part thickness has an influence on the damage evolution and on the chosen mesh strategy in industrial parts [3]. Here the model validation uses the homogenized ply as the reference for the material parameters but the representation of the laminate in shingle shell models has its limits in the accuracy when dealing with partial damage and delaminated zones.

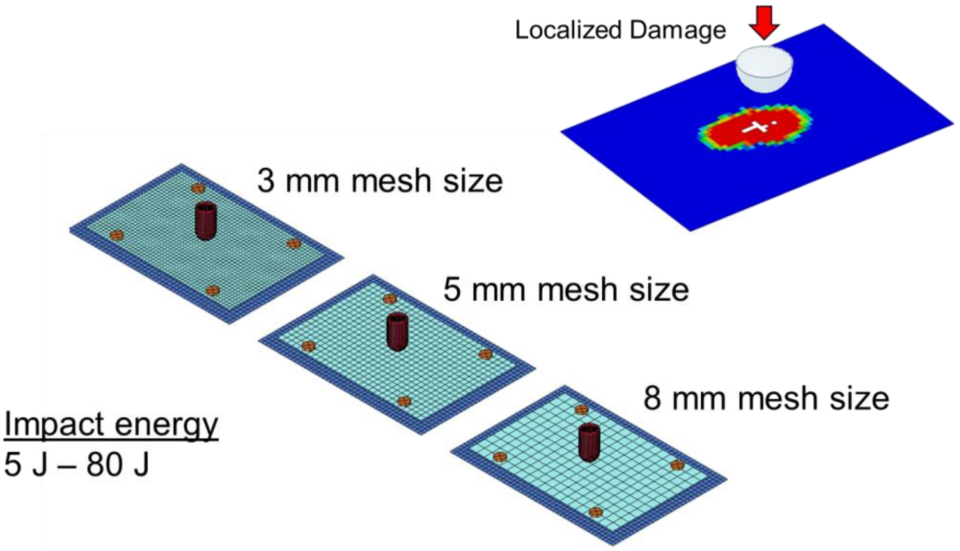


Figure 18: Impact test specimen

The impact test specimen is based on the proposal DIN EN 6038 [4]. Similar to the open hole test specimen, the impact test comprises a flexible thickness range. A representative evaluation for partial damage propagation such as delamination or local material plastification is possible in selected mesh sizes. With this approach the calibration of material parameters can be supported in a more strain-based driven manner (Figure 18).

Figure 19 depicts the achieved prognosis capability under out-of-plane impact or bending loads. In order to maintain a reasonable relationship between thickness and characteristic element length the discretization needs to be monitored carefully.

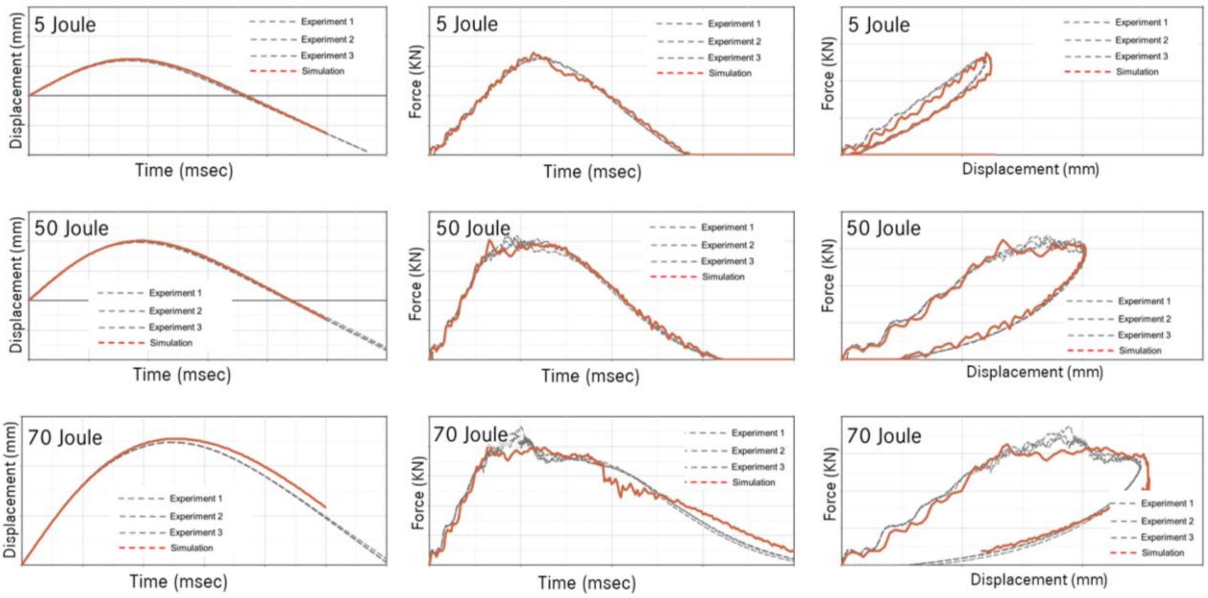


Figure 19: Quantitative analysis, impact coupon test

7 Model validation

While the geometry of an energy absorber, is useful for the dimensioning and the calibration of short and long fiber reinforced plastics, the complex multifunctional trunk geometry and the corresponding experimental set with the consideration of the surrounding areas, exhibits a reasonable correlation between the experiment and simulation results (Figure 20)

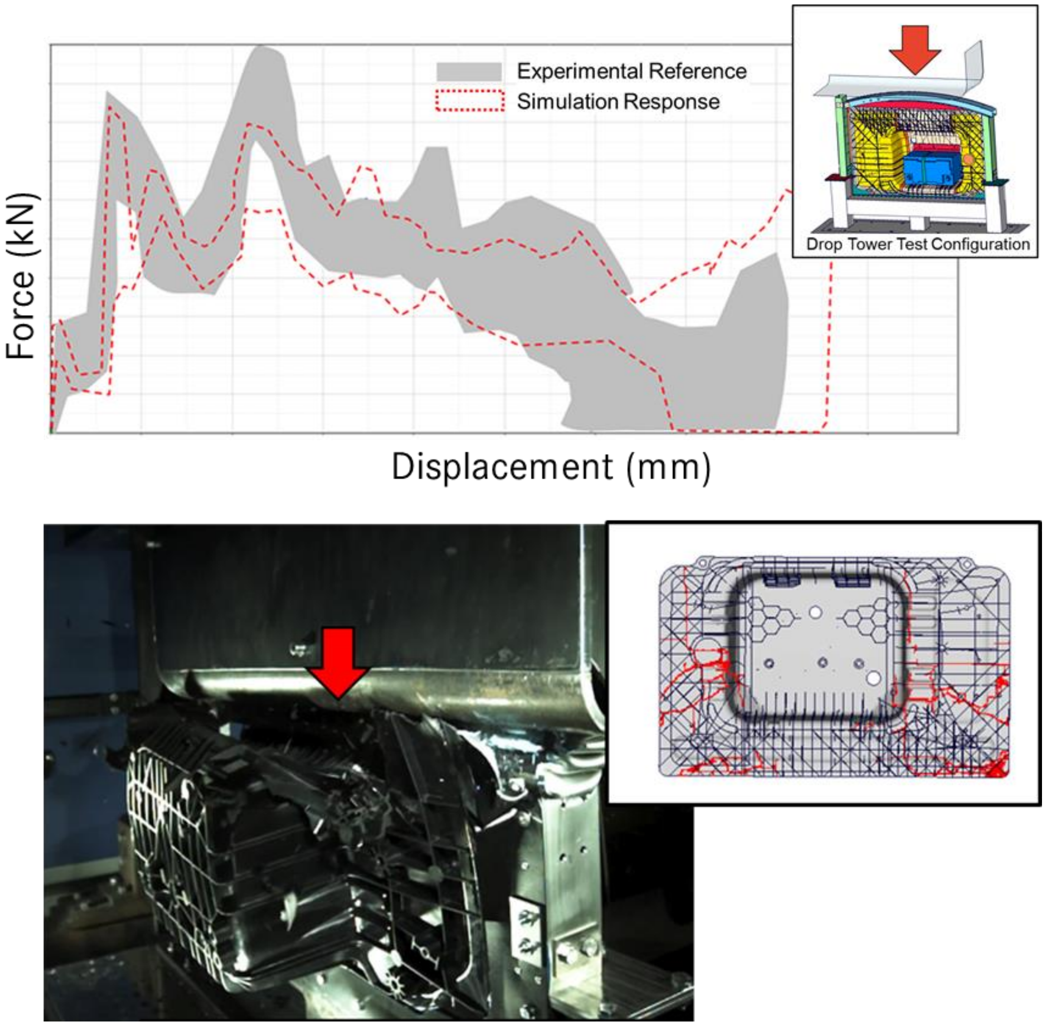


Figure 20: Multifunctional trunk , principle dynamical test, rear crash

8 Summary

Nowadays the automotive sector is in need of alternatives for vehicle architectures and powertrains. As presented in [5] a virtual test environment requires also an optimal use of computational resources. The presented approach enhances the load path definition and the calibration within a certain development without jeopardizing the architecture or the geometrical design space. The flexibility achieved by introducing reinforced plastics in secondary load paths requires a reliable prediction under real crash loads. With the available computational resources, the model validation effort is enhanced through extensive experimental work in a virtual test environment. The conducted assumptions and a systematic approach at different structural levels lead to higher flexibility and numerical efficiency. Which is very important at an early stage of the product development, where dimensioning of load path patterns considers a diversity of options in terms of material, geometry and design-flexibility.

9 Literature

[1] Moncayo, D., Modeling Laminate Failure in Composite Materials for Automotive Applications: Technical challenges and design experience, Chalmers University, Götheburg – Sweden, Sept. 2018

[2] LS-DYNA, KEYWORD MANUAL Volume II, Material Models, LS DYNA R11, Livermore Software Technology Corporation

[3] Köster F., Henning F., Moncayo D., Approaches for an advanced modeling technique for component design and prediction of the laminate failure in thick multilayered composites, 14th International LS-DYNA Users Conference, Detroit 2016

[4] DIN EN 6038; Aerospace series - Fibre reinforced plastics - Test method - Determination of the compression strength after impact, 2014

[5] Moncayo, D., Glöggler C., Technical challenges in the integration of hybrid components in new automotive applications, 11th LS-DYNA Users Conference, Salzburg, 2017