Stacked Shell Modeling for Evaluation of Composite Delamination in Full Vehicle Simulations

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Abstract

Accurate prediction of delamination in composite materials is a challenge and often limits the application of lightweight materials in safety relevant components, as it may reduce the available strength significantly. Very detailed modeling (e.g. with solid elements) can be employed to correctly recreate this phenomenon, but this can normally not be simulated in a full vehicle simulation in an acceptable amount of time. Single shell modeling is widely used in full vehicle simulations because of its high runtime performance but cannot support the physical separation of layers.

In order to correctly evaluate delamination of composites while retaining a good runtime performance, a new modeling approach in LS-DYNA® was studied in this paper. A stacked shell modeling technique was developed. The new modeling approach was firstly investigated at coupon level with comparison with experimental results for assessing its accuracy and capability of delamination prediction. Furthermore, stacked shell modeling was adopted into components under more complex loading and its performance was evaluated in terms of accuracy and run time compared with conventional modeling. At the end, this modeling technique was studied in full-vehicle simulation.

Our stacked shell modeling approach has shown promising results at coupon and component level. At the full-vehicle simulation scale, the new modeling approach has presented robust delamination prediction capability while still retaining high run time performance. The approach presented in this paper can be adopted in full-vehicle crash and also aerospace simulations in order to evaluate composite delamination.

Introduction

Composite materials are used widely to reduce weight in vehicles, by replacing conventional materials, mainly using fiber reinforced polymers (FRP) [1]. Due to improved production processes, the cost of producing high quality FRP components has decreased significantly in recent years, making this solution more available and more viable for automotive applications [2].

In order to use this group of materials in a modern vehicle development environment, behavior has to be predictable in CAE and first of all be simulated in vehicle crash, where legal requirements are most strict and testing very expensive. Delamination of composite materials is one of the properties, which can hinder the introduction of these light-weight materials, as it may on the one hand reduce strength significantly while on the other hand it is not possible to have layers separate in standard single shell modeling, used primarily in crash simulation [3].

Some methods have been shown to be able to exhibit delamination, which can be divided into solid-modelling [4], stacked shell [5, 6] and in-situ-separation [7]. All of these are generally accompanied with an order of magnitude increase in simulation time, making it difficult to employ them in full-vehicle simulations, which may already total tens of millions of elements [8]. High performance in calculation is therefore necessary in order to transfer any of these methods to productive development.

The purpose of this study was to find a modeling technique to predict strength in carbon fiber reinforced polymer (CFRP) including the mechanism of delamination, while retaining calculation performance. A front bumper beam made from unidirectional tapes based on carbon fiber and polypropylene (TAFNEX™ CF-PP UD) was chosen to evaluate the simulation method on coupon, component and full-vehicle level.

Materials and Methods

TAFNEX™ CF-PP UD base material and components used in this study were provided by Mitsui Chemicals Group, the parent company of ARRK Engineering.
Coupons were cut out from base plates using water-jet, prepared and tested according to ASTM at the in-house testing facility at ARRK Engineering in Munich.
Table 1 shows the tests, which were performed on coupon level to establish the base properties. Tests were performed using a Zwick Z250 and GOM ARAMIS 3D for strain measurement using digital image correlation. Test series consisted of 5 valid samples and mean values were taken as results.

Table 1: Coupon level tests performed to characterize base properties.

Test	Property	Layup
ASTM D 3039	Tensile	0° and 90 °
ASTM D 6641	Compressive	0° and 90 °
ASTM D 3518	In-Plane Shear	±45°
ASTM D 2344	Interlaminar Shear Strength	0°
ASTM D 790M	Flexural	0°
ASTM D 7905	Mode 2 Fracture Toughness	0°
ASTM D 5528	Mode 1 Fracture Toughness	0°

Front bumper beams were made with the FiberForm technology from Krauss Maffei using a CF-PP sheet made of TAFNEX™ and back injection molded with a long glass fiber reinforced PP (EDX-4030). Quasi-static and dynamic tests were performed on component level to validate the simulation model. General setup can be seen in Figures 1a and 1b.

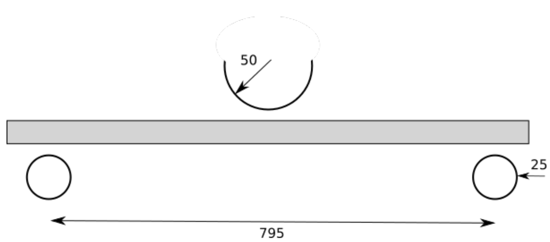

Figure 1a: Schematic setup of quasi-static and dynamic component test.

Figure 1b: Actual test setup for quasi-static testing of the front bumper beam.

Simulation models were set up as simple shell and reduced stacked shell with three layers. Three layers were found as a compromise between the need to have a delamination possibility on both sides of the middle surface and limiting the amount of elements and contact surfaces for performance.

Diverging from the general definition of stacked shell modeling, with each ply being represented by one shell layer, for this reduced approach plies were distributed on three layers in a symmetric fashion. Additionally, the connection between layers was realized using cohesive in one model and beam elements (see Fig. 2) as an alternative.

Figure 2: Reduced stacked shell modeling using beam elements.

All simulations were performed using LS-DYNA version 9.3.1 R140922 mpp. A SOFT=2 contact was used and Q2TRI=4 had to be defined to switch off a feature resulting in contact loss between elements which are connected with nodes.
Material models employed are shown in Table 2. For optimization of material parameters LS-OPT® was employed.

Table 2: Material models and application in this study.

Abbreviation	Application	Elform	Material Model
MAT_024	Out-of-plane Beams	1	*MAT_PIECEWISE_LINEAR_ PLASTICITY
MAT_058	In-plane Composite	10	*MAT_LAMINATED_COMPOSITE_ FABRIC
MAT_138	Out-of-plane Cohesive	20	*MAT_COHESIVE_MIXED_MODE

Results

Results are presented in the sequence of Material Characterization, Material Card Calibration, Component Validation and finally exemplary simulation in full vehicle.

A summary of all material properties characterized from coupon testing and the values used in simulation can be found in Table 3. Some of the parameters had to be adjusted, to better fit the stress-strain curve and failure mechanism, namely compressive and shear strength, due to plastic deformations of the PP-matrix.

Table 3: TAFNEX™ material properties from test and values used for simulation. Properties in transverse compression and shear had to be adjusted to match with the levels of plasticity seen in the matrix-dominated directions (noted as *plastic deformation).

Elastic Constants	**Units**	**Test (avg)**	**Simulation**	**Remarks**
$EA_{Tensile}$	GPa	118.00	118.00	
$EA_{Compression}$	GPa	61.41	42.00	Strain calculation deviation in test from ARAMIS
$EB_{Tensile}$	GPa	4.54	4.54	
$EB_{Compression}$	GPa	5.975	5.975	
PRBA = PRCA	-	0.015	0.015	
PRCB	-	0.38	0.38	
GAB	GPa	1.5	1.5	
GBC = GCA	GPa	-	1.3	Based on ILSS
Strength	**Units**	**Test (avg)**	**Simulation**	**Remarks**
XT	MPa	1570	1570	
XC	MPa	430	430	
YT	MPa	17.4	17.4	
YC	MPa	64.93	67	*plastic deformation
SC	MPa	28.80	29.5	*plastic deformation
TAU1	MPa		18	
Strain	**Units**	**Test (avg)**	**Simulation**	**Remarks**
E11T	-	0.0140	0.0140	
E11C	-	0.0086	0.0086	
E22T	-	0.0030	0.0030	
E22C	-	0.0437	0.056	*plastic deformation
GMS	-	0.160	0.180	*plastic deformation
GAMMA1	-		0.034	

Simulation results for ILSS setup showed different results when increasing the number of CPU. In order to reduce the influence of this unwanted effect, ILSS and component simulations were performed at same number of CPU.

For calibration of MAT_024 used for out-of-plane beams, the flow curve was extrapolated from the yield point of the Tension 90 stress-strain curve and a GISSMO Damage model was introduced for failure. As failure in DCB is in tension and failure in ENF is in shear, failure was introduced for these 2 modes using triaxility. Results of this calibration can be found in Figure 3.

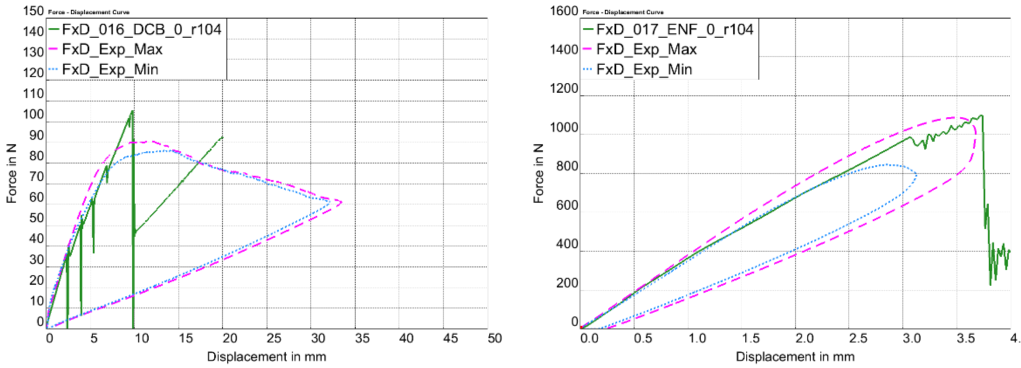

Figure 3: Results of MAT_024 simulation model (green) compared to the maximum (pink; dashed) and minimum (blue; dotted) test curves. Crack propagation in test after 10 mm displacement could also be introduced to material model, but was forgone.

Calibration of Mat_138 for out-of-plane cohesives was based directly on the test values and correlation of results on coupon level showed comparable results.

The calibrated material model was then used to simulate the bumper beam component with a layup of 90/0/(±45)$_8$/0/90. A clear difference could be seen in the load level with single shell reaching a maximum of about 8.5 kN, while stacked shell failed earlier and displayed delamination in the side walls. With a mesh-size of 4 mm and utilizing 20 CPU the time per increment was 9.4 ms for single shell, 12.8 ms for stacked shell using cohesives and 13.5 ms using beam elements. This is a 40% higher runtime using out-of-plane beams than single shell modelling. However, after performing the component test, the benefit of this modeling technique becomes clear, as both failure mechanism and load level were predicted by the stacked shell model, while single shell overpredicted the failure load. A comparison of force-displacement curve and failure mode can be found in Figures 4 and 5.

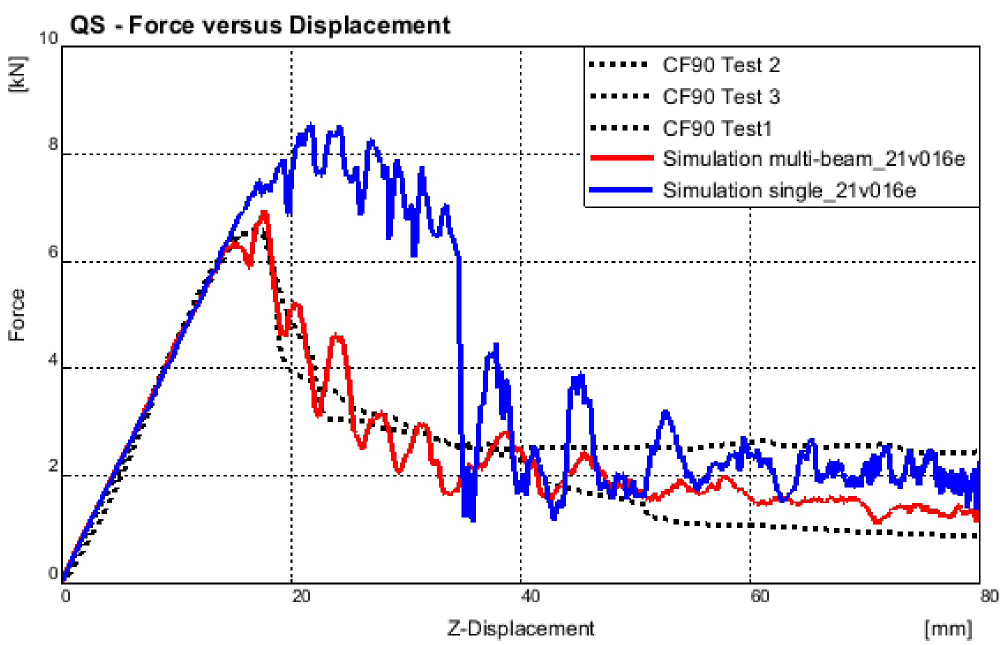

Figure 4: Force-Displacement Curve for quasi-static bending of CF90 bumper beam. Single shell modeling (blue) is overpredicting the failure load compared to stacked shell

(red).

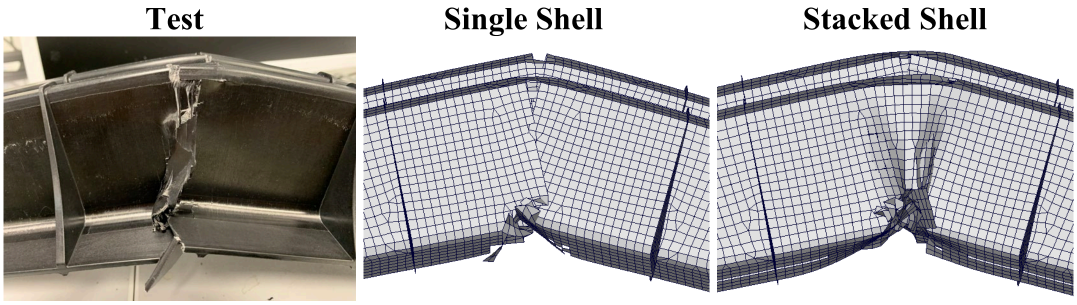

Figure 5: Failure of the side-walls is dominated by delamination in the test (left). While single shell models cannot physically separate out-of-plane (center), stacked shell with beams (right) shows a comparable level of delamination as in the test.

While modelling using beams and using cohesives showed similar load levels, cohesives were prone to be deleted in large areas after failure load was reached, as the available material models did not allow to freely define a plasticity plateau. Using this feature of Mat_024, element deletion occurred locally and only in the areas of highest deformation.
Additional to quasi-static testing, results from drop-tower testing were compared to the simulation. As the material cards were not bacohessed on any dynamic testing on coupon level, a lower level of correlation for dynamic component testing, as can be seen in Figure 6, was to be expected.

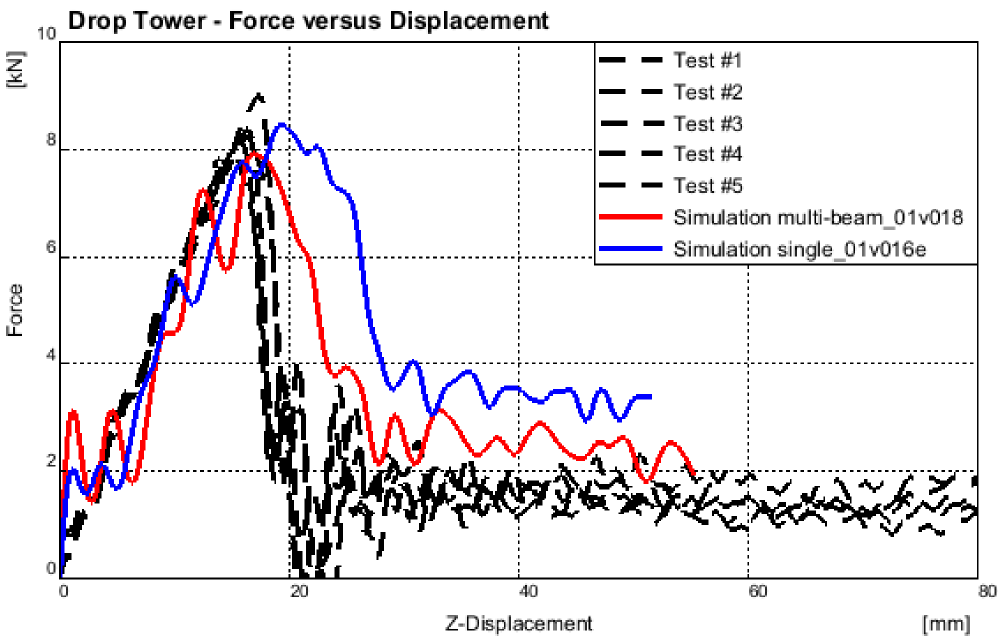

Figure 6: Force-Displacement Curve for drop-tower testing of CF90 bumper beam. Single shell modeling (blue) and stacked shell (red) are not predicting abrupt failure as seen in the test.

The stacked shell bumper beam was then mounted on the 2012 Toyota Camry mid-size passenger sedan, developed through a reverse engineering process by Center for Collision Safety and Analysis researchers [9].

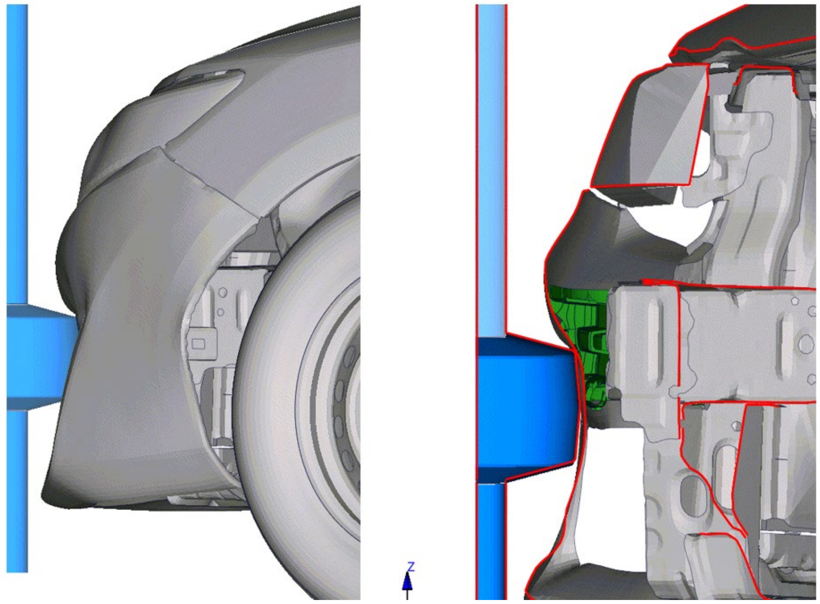

Figure 7: Evaluation of TAFNEX™ bumper beam with stacked shell modelling according to US Part 581 Front – Pendulum No. 3 in a full vehicle model (Camry [9]).

Low speed crash according to US Part 581 was evaluated with this model and showed that while outboard positions were sufficiently supported (see Figure 7), energy absorption for the central position was lacking. If commercial use of this component is planned, further improvement of energy absorption, e.g. by layup optimization, is recommended. Runtime increased by 2% compared to the original model with steel bumper beam.

Discussion

It was shown that reduced stacked shell modeling can be used to predict delamination in a CFRP based component. By implementing this failure mechanism, load levels decreased in simulation and correlated to those measured in physical testing.

While other studies by [5] and [6] also showed application of stacked shells to evaluate delamination in composites, our approach was focused on maintaining computational performance in order to be able to integrate this modeling in full vehicle simulation. This was achieved by calibrating the material to a mesh size of 4 mm and Elform 10, while reducing the stack to 3 layers with multiple plies each.

As next steps, we will optimize the bumper beam layup in order to increase toughness and reevaluate the component. Also, the implementation of the effects of crack propagation and adequate representation of strain rate dependency will be investigated.

TAFNEX™ CF-PP UD material from Mitsui Chemicals is commercially available and we are open to discuss new projects together.

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