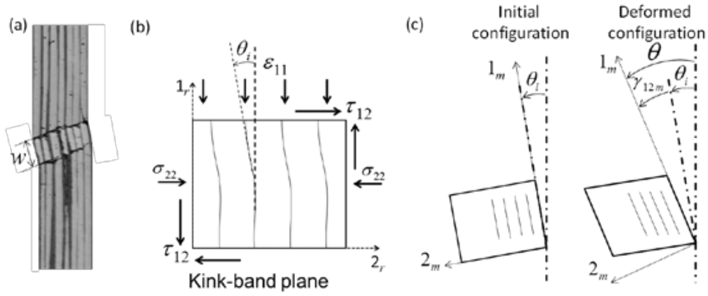
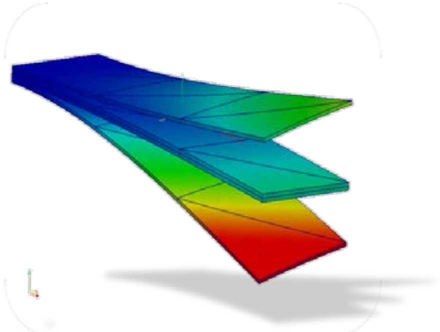
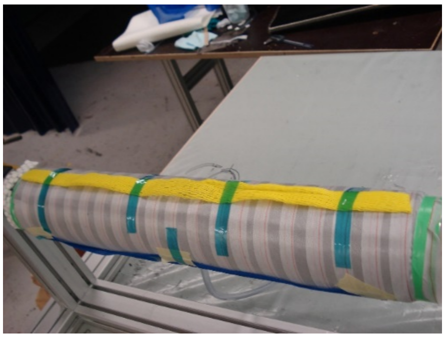
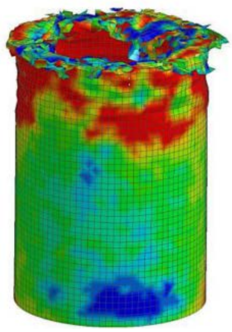
Final report on

Modelling crash behaviour in future lightweight composite vehicles - step 1









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Trafiksäkerhet och automatiserade fordon

FFI Fordonsstrategisk Forskning och Innovation
VINNOVA Energimyndigheten TRAFIKVERKET FKG VOLVO SCANIA VOLVO

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1 Summary

The project has addressed key issues in a Computer Aided Engineering (CAE) methodology aimed for representative modelling of energy absorbing mechanisms in carbon fibre reinforced polymer composites at crash events. In fact, the proper CAE based crash simulation methodology for composites is one of the prominent enablers for a sustainable development of safe lightweight composite vehicles. Our ultimate goal in a ten years perspective is to establish confidence in crash predictions of composite vehicles to a level comparable with the state of the art for conventional metallic structures. The main operational goals of the project relates to 1) material model development, 2) modelling the composite at the component level, 3) implementation of developed models in commercial software platforms, and 4) the outline of an operational CAE-method for crash analysis.

To tackle the problem the project work has been carried out in four main work packages WPA, WPB, WPC and WPD comprising research issues of efficient damage modelling at the ply-level in WPA, the modelling of the composite laminate behaviour in WPB, experimental assessment, model verification and validation as well as valorisation in WPC and dissemination in WPD. As to WPA, a damage model for a fibre reinforced ply has been developed at SICOMP. The model successfully describes the degrading mechanisms at compression at the ply level. In WPB carried out at Chalmers, the proper structural modelling of a composite laminate, considered as a stacked sequence of plies, has been addressed. In this development much effort has been placed on the crucial accurate stress evaluation and representation of the delamination mechanism for shell structures in order to establish an efficient methodology to model large components or structures. The developed adaptive shell technology has shown good potential in significantly reducing the simulation time compared to state-of-the-art techniques currently available in commercial finite element software. This indicates that, in the future, this technique can be used to simulate full crash analyses of composite cars which would not be possible with the technology currently available. In WPC we have explored the state-of-the-art possibilities to analyse the failure of laminated composite components under crash like conditions with commercial codes, LS-DYNA and RADIOSS. We also developed an experimental test campaign of composite components for the model validation with respect to axial crushing and bending dominated crash modes. In this development, test components were designed and tested and thereafter the tests were modelled using the model developed in WPA to assess the accuracy and robustness. The conclusion is that we are on the right track but that much more work is required to capture the complex interplay between failure mechanisms and to make the model robust in more extensive simulations. Much of the work within WPC has been carried out by keen dedication by the industrial partners.

As to the project result and dissemination in WPD, we have spread the project results in several journal and conference publications. We also developed fours master theses (three were initially planned) and one licentiate of engineering thesis (the second one will be presented in November). We conclude that much of the goal settings have been fulfilled within the project, although, in retrospect, it was perhaps a bit optimistic to think that the models could be fully validated already after three years even though our long term perspective was set out to be ten years.

The project was carried out under 2014, 2015 and 2016 with a total end budget of SEK 10 083 000, and the project was led by Professor Ragnar Larsson and Associate professor Martin Fagerström, Department of Applied Mechanics, Chalmers University of technology. In total ten partners were involved the project, where Chalmers – Applied Mechanics and Swerea SICOMP represent the academic and institute sides, whereas Volvo Car Corporation and AB Volvo represent car and truck manufacturers, and Autoliv, Altair Engineering, DYNAmore Nordic, Epsilon AB, Semcon AB and Escenda Engineering AB represents FKG. The relevance of the project is reflected by the significant industrial dedication and participation to increase our competitiveness in lightweight design in the Swedish automotive industry. The project results and knowledge development give us the confidence to further push the project idea towards the efficient and robust CAE methodology for representative modelling of energy absorbing mechanisms in automotive composite structures.

2 Exekutiv sammanfattning (på svenska)

Projektet behandlar strategiska forskningsfrågor för utveckling av datorstödda konstruktionsmetoder (CAE metodik) som på ett adekvat sätt beskriver energiupptagning vid krockförlopp i fordonsstrukturer gjorda av kolfiberförstärkta polymera kompositmaterial. Faktum är att CAE-assist vid krocksimulering för kompositer är en nödvändig förutsättning för att på ett smart sätt kunna utveckla framtidens fordonsstrukturer som kombinerar hög krocksäkerhet med energieffektiv design. Vårt långsiktiga mål (i tioårsperspektivet) är att skapa en minst lika god kvalité i CAE-simulering av krockförlopp av fordonsstrukturer (helt eller delvis) gjorda av kompositmaterial som för den simuleringsmetodik vi har idag för konventionella metalliska fordonsstrukturer.

Projektet har genomförts inom fyra arbetspaket, WPA-D, med skademodellering på fiber/matrisnivå (WPA) och modellering kompositlaminatets beteende på strukturnivå (WPB), provning och verifiering med SOTA metoder (WPC), samt kunskapsspridning och förädling av uppnådda resultat (WPD). I WPA, har en skademodell för en tryckbelastat fiberförstärkt skikt utvecklats vid SICOMP. Materialmodelleringen i WPA är kopplad till strukturmodellering i WPB (som utförs på Chalmers) för representation av ett kompositlaminat med skalteori. I denna utveckling har stort fokus lagts på effektiv spänningsanalys och representation av delamineringsmekanismen för ett kompositskal. I WPC har vi undersökt SOTA när det gäller krockanalys av kompositkomponenter med kommersiella FE-koder, LS-DYNA och RADIOSS. Vi utvecklade också olika experiment, avseende axial och böjbelastade komponenter, för validering av material- och strukturmodellerna. En stor del av arbetet inom WPC har utförts med ett stort engagemang av våra industriella partners i projektet.

Projektresultaten har spridits genom flera konferensbidrag och uppsatser i internationella tidskrifter. Vi har också utvecklat 3 examensarbeten och 2 teknologie licentiater inom projektet. De flesta av projektets operationella målsättningar har på olika nivåer förverkligats. Vi har inte nått riktigt hela vägen till TRL 4 när det gäller fullskalig modellvalidering i laboratorieexperiment. Projektet genomfördes under 2014-2016 med en slutlig budget på kostnadssidan på drygt 10 083 000 kr. Projektet har letts av professor Ragnar Larsson och docent Martin Fagerström vid institutionen för tillämpad mekanik, Chalmers. Totalt 10 parter har deltagit där Chalmers – tillämpad mekanik and Swerea SICOMP representerar akademi- och institutsparter. Volvo Car Corporation and AB Volvo representerar personvagns- och lastbilstillverkare, och Autoliv, Altair Engineering, DYNAmore Nordic, Epsilon AB, Semcon AB and Escenda Engineering AB representerar FKG.
Projektrelevansen reflekteras av det stora industriella intresset för projektet för att öka vår konkurrenskraft inom lättviktsdesign inom fordonsindustrin. Våra resultat och kunskapsutveckling som projektet gett ger oss råg i ryggen att driva projektidén vidare mot effektiv och robust CAE metodik för korrekt simulering av energiupptagning vid krockförlopp i fordonsstrukturer gjorda av kolfiberförstärkta polymera kompositmaterial..

3 Background

Designing and optimising new vehicle structures is a complex, iterative task already today requiring expensive and time consuming physical test programs. Furthermore, environmental requirements (CO2 emissions, global anti-pollution policies, resource management) and economic developments call for vehicles with reduced size and weight, which are still both affordable and safe. As stated in the ERTRAC (The European Road Transport Research Advisory Council) Safety roadmap, an important route to realise substantial weight reductions is the application of lightweight materials, particularly carbon reinforced composites in the vehicle structure. Similar conclusions, emphasizing lightweight design and in particular the introduction of composites for structural and energy absorbing components, have also been reached at the national level, e.g. in the FFI steering board who approved this project. Without the enhanced composite design methodology (including design with respect to crashworthiness) this development would substantially add to the load of physical testing required.

In this context, virtual component testing using numerical simulation makes is possible to reduce the amount of physical testing, thereby saving both time and money in the development process. Virtual testing also introduces a large flexibility in what can be assessed; such as the component performance using novel types of composite systems (e.g. stacking sequence and/or reinforcement type of the composite) without the need to manufacture expensive prototypes as well as the risks associated with a wider range of traffic accidents and spread in vehicle sizes.

However, as also stated in the ERTRAC Safety roadmap, numerical crash simulation tools with truly predictive capability still constitute a major barrier for the introduction of composites in structural components in the virtual development processes of the automotive industry. Consequently, further research is crucial to bridge this gap. To conclude, the safety issues of lightweight vehicles, with composite components involved in the primary car body structure, constitute major challenges that have to be resolved before polymeric composite materials can be fully exploited. Thereby, safety issues of high performance composites in cars and trucks are indirectly considered as a prominent enabler towards lighter vehicle solutions.

In this context, we also note that the development of the design methodologies based on the proper CAE methods are of utmost importance in order to fully exploit the intrinsic properties of the material. It is emphasized that the use of composites in automotive structures requires an in-depth knowledge of their unique performance characteristics in the crash and safety perspective.
Therefore, in this project the development of constitutive- and structural modelling methodology for composite materials aimed for crash simulation in automotive composite components have been addressed. Indeed, these issues pose challenges to the developer of the computational models. Much detail must be included to model the relevant mechanisms separately, but, on the other hand, too much detail inevitably leads to overly demanding computations. Therefore, there is a need for smart numerical procedures that include the relevant mechanisms efficiently. We want to model what can be relied upon as to give reasonable results, but which does not have to be waited upon for weeks before those results are computed.

Presently, to facilitate the transition towards lightweight composites vehicles, there are still a number of additional challenges to be resolved. These are for instance the issue of high volume manufacturing including automatisation and scalable process technologies. Such challenges are currently addressed with numerous national platforms, such as SAFER, LIGHTer, COMPRASER, and international platforms, e.g. EUCAR, CLEPA, and EARPA.

4 Purpose, research questions and methods

The general purpose of the project has been to address key issues in Computer Aided Engineering (CAE) methods aimed for representative modelling of energy absorbing mechanisms in automotive structures made of advanced, in particular, carbon reinforced, polymer composites in the event of a crash. This in the perspective that within ten years we should reach the same level of confidence in crash predictions of composite vehicles as was the state of the art for conventional metallic structures at the beginning of the project. For industrial acceptance of these CAE methods, an important prerequisite is that the final simulation methodology is well balanced with respect to, on the one hand, computational robustness and cost efficiency, and, on the other hand, relevant composite failure analysis.

The failure mechanisms present in a laminated composite require that the computational procedure simultaneously resolves both the macro-scale (the component) and the meso-scale (the many layers in the laminate) simultaneously. In the project, we have therefore addressed the damage evolution on the meso-scale (in each separate ply or layer of the composite) and on the macro-scale separately in work packages A and B with the ambition to connect them in a final validate model in work package C. Subsequently, the purpose of the remaining work package D was then to disseminate the results to the partners as well as to the research and industry community via journal publications, conference contributions, licentiate of engineering these etc. More details of work package specific purposes, research questions and methods used are given in the subsections below

4.1 Work package A: Development of damage evolution models for crash analysis

The purpose of the work in WPA was to develop a material model for predicting the crash behavior of composite materials in cars. The material model should allow implementation in efficient finite element (FE) models for crash simulations. Composites for structural applications in cars are typically based on polymers with carbon fiber textile reinforcements. Textiles dominated by fibers in a single direction, so called "uniweaves", provide the best ability to tailor the structure to given loads and to obtain a high structural performance.

Most models for composites focus on failure initiation, while the behavior during the subsequent damage growth actually is more important for energy absorption and crash behavior. State-of-the-art models for the damage growth are based on an assumed linear softening, and require complex and difficult measurements of the fracture toughness. Furthermore, the fracture toughness for composites differs between loading along or transversely to the fibers and between compression and tension.

4.1.1 Methods used

A physically based model has been developed for damage initiation and growth in a composite ply under general triaxial loading. The prediction of failure initiation is based on existing failure initiation criteria for unidirectional fiber composites. The new model for damage growth assumes that it can be related to growth and coalescence of microcracks, and that the energy absorption is related to the frictional forces on these crack surfaces. The resulting material model has been implemented in a commercial FE software.

4.2 Work package B: Multi-scale laminate modelling

The purpose of work package B was to develop a numerical method in which the local composite damage evolution in each ply can be considered and included in the analysis in an efficient manner such that a shell modelling approach can be adopted on the macroscopic (component) scale for components of interest. Thus, the governing research question of this work package can then be formulated as:

How can we develop a good methodology for modelling and simulating failure of laminated composite parts such that it both includes the relevant failure mechanisms and is computationally efficient enough to be used in large scale crash simulations?

4.2.1 Methods used

Initially, the approach was to device a so-called a multi-scale model in which detailed meso-scale finite element models (so-called RVE-models) of the local laminate response (including damage evolution in each ply represented by models coming from work package A) were to be coupled with a shell modelling approach on the macroscale, cf. Figure 1 for a generic sketch. The intention was to follow the method presented by Larsson and Landervik [1] showing very promising results. However, after having applied their method to the current application of a laminated composite it was clear that their method was not accurate enough to be used as planned. The main issue is that stress components transverse to the laminate (shear and normal stresses) are not accurately predicted, cf. also section 6 below, which means that the initiation and propagation of delamination of plies cannot be modelled properly.

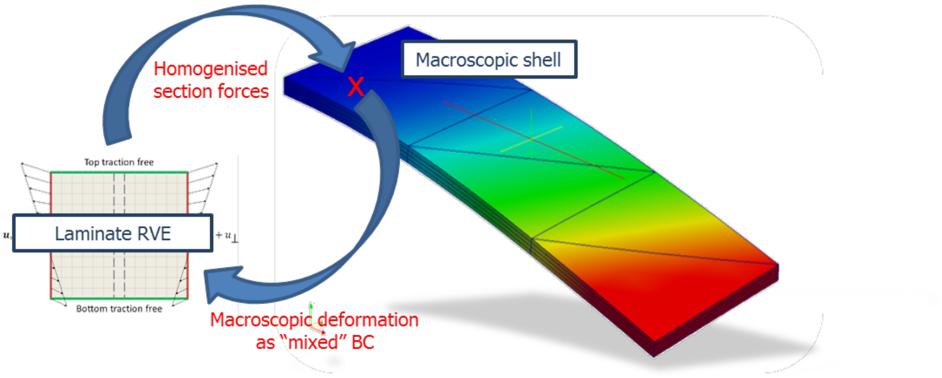


Figure 1. Generic sketch of a multi-scale approach where the material behaviour is analysed on the meso-scale level via a detailed RVE analysis to predict damage evolution in individual plies given the macroscopic deformation as boundary conditions. The resulting homogenised section forces of the shell are then transferred back from the RVE to the macroscale level and used as input to solve for the component deformations.

Therefore, a shift of focus had to be made after approximately one year of the project such that still the overall purpose of the work package could be fulfilled and the research question answered. Instead of focusing on a multi-scale modeling strategy, the adaptive shell method based on the eXtended Finite Element Method (XFEM) and proposed by Brouzoulis and Fagerström was adopted. This method allows for an efficient modelling of laminated composites on the macroscale in terms of a single layer of shell elements, which then can be enhanced during the simulation such that any number of delamination cracks can be considered, cf. the illustration from Brouzoulis and Fagerström in Figure 2 illustrating the possibility to represent six delamination cracks of different length in a simple specimen using only one shell element through the thickness. The representation of such cracks is possible since the XFEM allows for an adaptive modification of the displacement approximation of the shell such that new cracks can be introduced in an automated manner. What was lacking at this point was *i)* a proper method to predict the transverse stresses in a single layer of laminated shell elements to detect where delaminations may initiate and *ii)* a proper methodology for how and when to enhance the shell elements to model propagating delaminations. Thus the remaining part of work package B was devoted to develop methods to resolve *i)* and *ii)*.

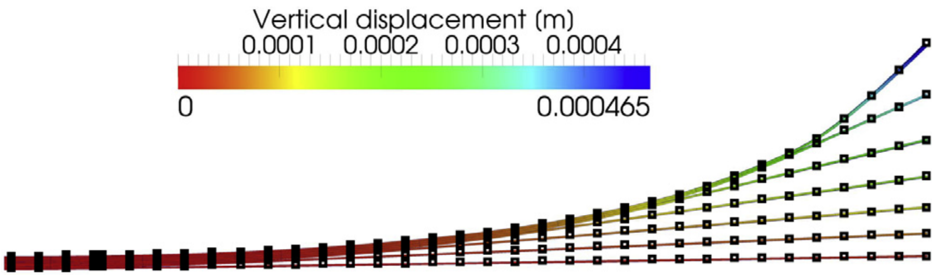


Figure 2. Illustration of the ability of the adopted XFEM shell concept to represent multiple (six) delamination cracks of different length suing only one shell element through the thickness. The FE result is in the figure compared with the analytical solution to the problem (black squares).

To obtain accurate predictions of the transverse stresses, a so-call stress recovery method was adopted, cf. e.g. [2]. This however had to be adapted to the needs of shell elements and the fact that stresses are not continuous across element boundaries in any traditional FE application. Thus, a particular patch recovery technique was develop and is described in Främby et al. [3] which shows a good ability to predict the transverse stress distribution under general conditions, see also Section 6 below.

As the last step, an adaptive methodology for how and when to allow for an enhancement of the shells in order to represent delamination was devised based on the fact that a good prediction of transverse stresses now can be achieved. As is common in the literature, a stress based criteria for delamination initiation was adopted. This was later combined with a strategy to enlarge the delamination zone around any point where developing interface damage is discovered, for details refer to [3].

4.3 Work package C: Assessment, evaluation and validation of models

The main purpose of this WP was to bring together the results from WPA and WPB and to valorise the results in a commercial FE software and to use this platform to validate the constitutive models against experiments with respect to axial crushing and bending dominated crash modes. In addition, the purpose was also to: gain knowledge on existing state-of-the-art possibilities with commercial codes to analyse the failure of laminated composite components under crash like conditions; design suitable test cases for the model validation; and design, manufacture and test two types of composite components (one type per test case) to obtain reference data against which the models developed could be assessed.

In retrospect, it was a bit optimistic to think that the models could be fully validates already after three years even though the long term perspective was set out to be ten years. Still, models were implemented in available finite element codes (such as LS-DYNA and the open source code OOFEM (www.oofem.org)) although not to the extent that they could accurately represent the behaviour observed from the tested components, cf. also the results in Section 6.

4.3.1 Methods used

To obtain a good understanding of state-of-the-art possibilities in simulating composite components in crash, a Master thesis project was carried out at ÅF early in the project. The scope of the Master's thesis project [4] was to evaluate material models and methods currently available in commercially available finite element software. As an initial part of the project, a literature study of relevant research and development concerning crash modelling of composite structures was conducted in order to obtain an overview of the existing possibilities in commercially available finite element software. Furthermore, simulations have been performed using the software LS-DYNA and RADIOSS. The theory and behaviour of three different material models were investigated. The investigated material models are: MAT54 and MAT262 in LS-DYNA and LAW25 in RADIOSS. Simulations that were performed were compared with results from a physical test.

To design and analyse suitable validation cases that could be experimentally tested and used for model validation, a second Master thesis project was carried out at Escenda [5]. Two different components subjected to axial and bending loads respectively were considered. For axial load, a crash box was selected and designed to yield suitable testing conditions. Similarly for bending, a door beam was selected and designed. Simulations of the tests were later also compared with the actual test results.

A number of specimens of each type of components were then manufactured at Volvo Cars. For the cylindrical crash boxes, a two-piece tool in aluminium was manufactured and utilised, see Figure 3. The dry layers of fibre fabric (04510-1000F9773, Porcher, 205 g/m^2 UD) were put (rolled) onto the tool whereafter everything was bagged and vacuum infused with the polymer resin blend including Huntsman Araldite LY556, Huntsman Aradur HY917 and Huntsman Accelerator DY070. The crash boxes were thereafter cured in an elevated temperature cycle up to 120 °C.

For the beams, a second aluminium tool was manufactured in which two beams could be manufactured at the same time. The same material and a very similar manufacturing procedure was used as for the crash boxes. Detailed can be found in [6]**.**

Figure 3. The aluminium tools for the crash box (left) and for the beam (right).

Quasi-static testing of four door beams was done at Volvo Trucks using the rig shown in Figure 4. A hydraulic cylinder connected to a cylindrical impactor moved at an average velocity of 3.6 mm/s. The testing is described in detail in Volvo report “er_662382_crashbox_beam” as well as in [6].

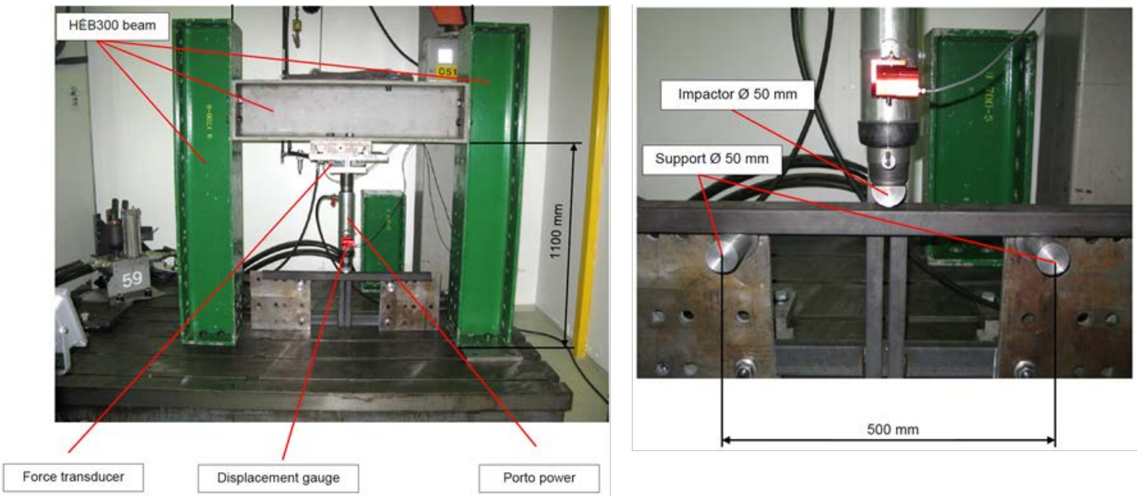


Figure 4. Rig used for quasi-static testing

The dynamic testing of the door beams were carried out as three-point bending with the same boundary condition as in the quasi-static tests. The drop tower at Volvo Cars Safety Centre, see Figure 6, has a maximum capacity of 150 kg impactor mass at a maximum impact speed of 16 m/s.

In these test a cylindrical impactor with 50 mm diameter and 24 kg mass was used at velocities between 5 and 10 m/s. The beam was placed at two cylindrical supports with diameter 50 mm at a distance of 500 mm from each other. Four force transducers, two accelerometers and three high speed cameras (2000 frames/s) were used. Further information on the test setup is available in the test report (testing_Report_VCC_Rapport_156191.doc) and in [6].

As for the mechanical testing of the crash box component, four crash boxes each were crushed dynamically mounted to a sled at Autoliv and quasi-statically by a hydraulic cylinder at Volvo, see Figure 6 for images on of the test set-up. Force and displacement were registered. Pictures and videos were captured. All data has been stored at the project server and is available to all partners for further research.

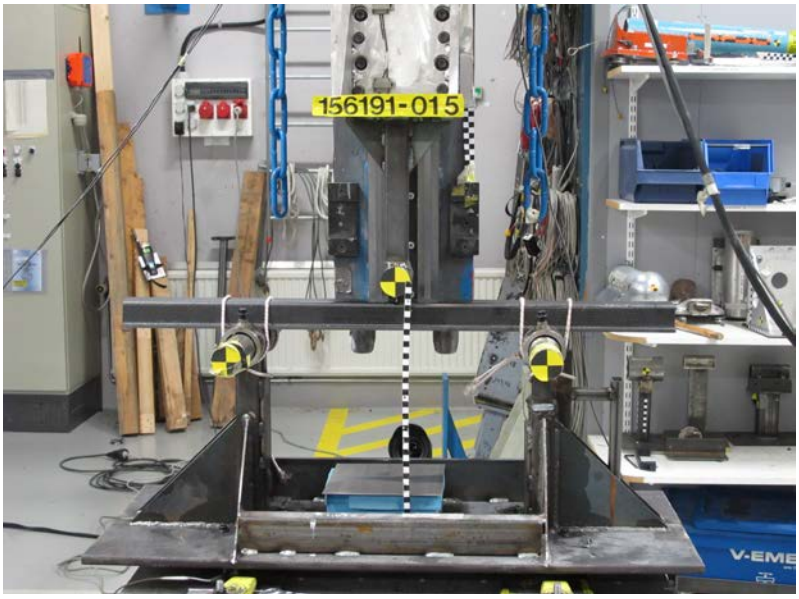


Figure 5. Drop tower rig used for dynamic beam testing

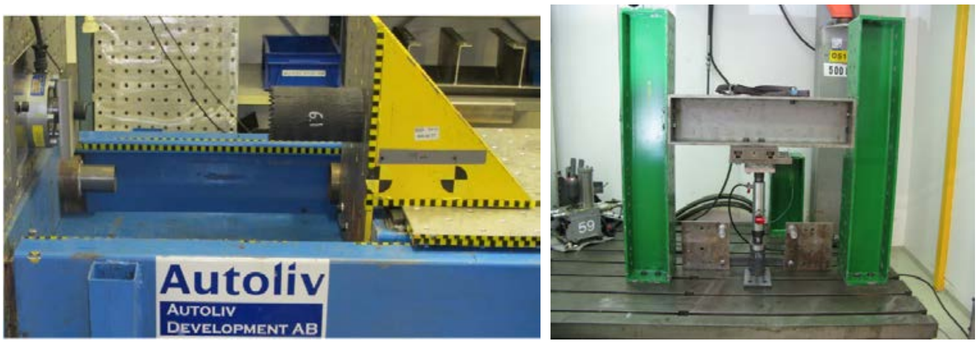


Figure 6. Dynamic test at Autoliv to left and Quasi-static test at Volvo to the right

To investigate the dominant failure mechanisms of the tested components, i.e. the nature and sequence of failure, in the tested components, a fractography investigation was performed on four of the beams and four of the crash boxes. This investigation also gave information on the manufacturing quality and the extent of damage throughout the components, the latter which is important in order to assess the accuracy in the predictions obtained in the numerical simulations of the same test cases.

For the beam specimens, the extent of ply splitting was evaluated with non-destructive testing (ultrasonic A-scan) and verified by dissection of the specimens. For the crash boxes, the non-destructive inspection with the A-scan was not possible because of the too high curvature of the surfaces. Region of interest were selected in the crush region, samples extracted and prepared for optical microscopy.

To assess and benchmark the models developed in work packages A and B against the experimental results, a third and final master thesis project was carried out at Semcon [7] with support from Chalmers and SICOMP in spring 2016. It should however be noted that only the first version of the material model delivered form work package A was benchmarked in this work, since the second version was not yet delivered at the start of the master thesis project and since the prototype implementation of the shell element in LS-DYNA had already been shown to behave as expected in earlier simple test cases.

This third master thesis project was divided into two main parts. In the first part, the transfer of the material model from an ABAQUS environment to an LS-DYNA environment was successfully verified and benchmark tested against the physically based material model MAT261 (built in LS-DYNA material model) in a small application. In the second part, the major benchmarking study was performed by a crash investigation of a three-point bending test of a beam, see Figure 7. An additional benchmarking study was carried out by investigating crushing of a corrugated specimen. The results were compared to already performed experimental tests.

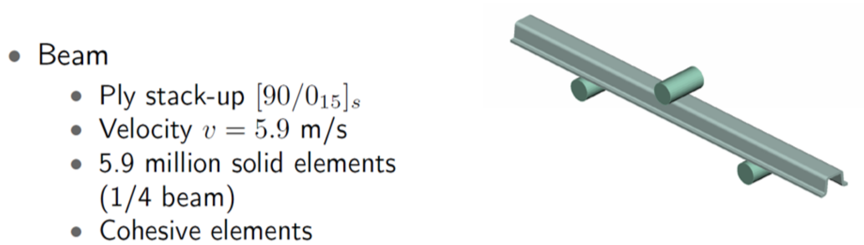


Figure 7. The model of the three-point bend test used in the master thesis carried out at Semcon

4.4 Work package D: Dissemination

As stated above, the purpose of work package D was to disseminate the results to the partners as well as to the research and industry community via journal publications, conference contributions, licentiate of engineering theses etc. This has also been done throughout the project with the clear ambition to spread the results in different journals and at different conferences. A list of all dissemination activities are included a separate subsection of Section 6.

5 Goals

The perspective of the present research program, in which the current project is the first step, was set to 10 years staring from 2012, thus the goal settings concerning the steps towards a fully-fledged computational design methodology are to be viewed in that perspective. As for the present project, the goals initially formulated for the project were:

1. To develop a material model for each individual ply in a laminated composite with textile (uniweave) plies which accurately incorporates the basic failure modes of such a composite laminate
2. To develop a homogenization strategy enabling efficient modelling at the component level.
3. To implement the developed models and methods in commercial software platforms
4. To outline the operational CAE-method for crash analysis invoking the ideas and methods produced in the project.

5.1 Modification of project goals during the project

The main goal of the work in work package A was to predict failure initiation and the subsequent behaviour for all the different failure modes of fiber composites, i.e. shear, transverse tension or compression and axial tension or compression. The main goal was an improved description of damage initiation and growth under compressive loads, which are particularly important in crash situations. A further goal was to allow modelling of textile reinforced fiber composites of the type relevant for the automotive industry. The material model should allow implementation in the more computationally efficient FE elements developed within WPB.

The work was initially focused on damage initiation and growth in unidirectional fibre composites. The development of a model for composites with more general textile reinforcements was found to be very complex and was not pursued, as the unidirectional fibre model was found to be a sufficient approximation for the material studied in the project, i.e. composites reinforced by uniweaves.

As already mentioned and also better explained below in Subsection 6.2, the multi-scale approach had to be abandoned in work package B when it became obvious that it in its current form was not accurate enough to be applicable for laminate composites. The choice was then to either further develop the multi-scale method itself, which was not according to the ambitions of the project and would most probably consume most of the remaining Chalmers efforts, or to focus on establishing a feasible CAE-method for crash analysis which is both accurate and computationally efficient, in line with the fourth goal above. It was then within the project consortium agreed that it would be better to focus on establishing an efficient approach based on an equivalent single layer of adaptive shells building on developments within a parallel European project on crash modelling of composite components (MATISSE).. Thus, the second goals for reformulated removing the multi-scale part such that it could be formulated as:

2.b To develop a principal computational concept which (long-term) enables large-scale crash analyses of composite vehicles.

6 Results and goal fulfilment

The current project has spanned several areas even though the core area is crash safety, and the focus on developing light, optimised energy absorbing zones and an accurate, efficient and robust CAE methodology for crashworthiness design and assessment.

By together working towards developing such a methodology, we have started to facilitate the virtual development of future vehicles which will be both safer and lighter. Safety benefits in terms of better occupant protection will be achieved since the methodology will enable the introduction of CFRP in automotive protective structures yielding both improved structural performance and reduced weight. Increased material stiffness and strength will have a direct impact on improved intrusion protection, and the superior energy absorption capabilities of CFRP will lower peak accelerations experienced by the vehicle occupants. Reduced vehicle weight will lower the total impact crash energy of a crash (beneficial for the occupants) and improve the performance of both basic and active safety systems (breaking, steering etc.), the latter since less vehicle mass allows for shorter response times of these systems. Thus, by this project we actively contribute to the goal outlined in the *FFI Traffic Safety and Automation* roadmap on developing new technology to lower the amount of traffic casualties (and severely injured).

Furthermore, by increasing the competence level at the Swedish industry partners, we will enable a more efficient virtual development process of new lightweight vehicles. By having a more efficient design process for composite structures compared to their international competitors, we foresee that the Swedish automotive industry will remain very competitive and in particular world-leading in automotive safety, also for future vehicles with composite solutions. Also this is perfectly aligned with the goals outlined in the *Traffic Safety and Automation* roadmap.

More specific for the project, results and goal fulfillment are reported below for all work packages.

6.1 Work package A: Development of damage evolution models for crash analysis

A physically based model has been developed for failure in compression along and transverse to the fibers. The model fairly correctly predicts the nonlinear softening behavior observed in experiments, and explains the ability to carry loads and absorb energy under large compressive strains. An important result is that the model eliminates the need for cumbersome measurement of the fracture toughness in compression.

The model has been implemented and tested in small three-dimensional FE models, and has been experimentally validated for a few test cases. Approaches have also been developed to make the predictions independent of the chosen FE mesh size, and the resulting mesh objectivity has been demonstrated in a number of test cases.

As a consequence of the limitation to unidirectional composite material the model is unable to predict differences between the in-plane and out-of-plane behaviour transverse to the fibres.

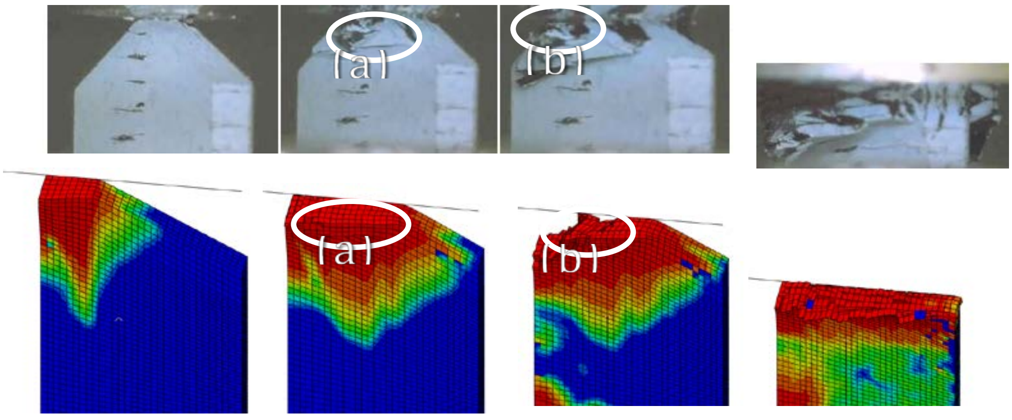


Figure 8. Experiments and model prediction during crushing transverse to fibres.

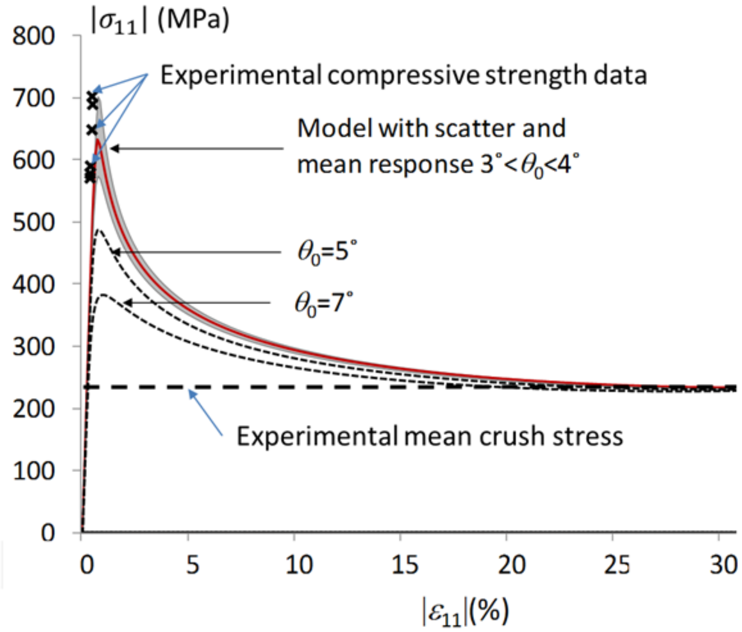


Figure 9. Prediction of compressive behavior and comparison with experiments for different fiber misalignment angles θ

6.2 Work package B

To be able to perform large scale simulations of progressive failure in laminated composites while maintaining a good level of predictability (e.g. ability to capture delamination), new types of FE models, which combine computational efficiency and accuracy, need to be adopted.

To achieve this, the idea is to maintain the numerically efficient Equivalent Single Layer (ESL) shell formulation and describe the internal failure process by local extension of the element formulation, when the damage state no longer can be represented by the simplified ESL model. However, a known drawback of traditional ESL shell element formulations is the low accuracy of the predicted transverse stress components [2], which are the main drivers of delamination failure in laminated structures. In addition, the simplified kinematics in ESL shells cannot describe the kinematics associated with delaminating plies. Therefore the ESL model must be combined with a technique that:

1. Can improve the prediction of the transverse stress components;
2. Locally can describe delamination failure using extension of the FE element formulation.

In an initial approach we have investigated the potential of using a multiscale approach where the macroscopic ESL shell model is coupled to a mesoscopic RVE, capable of modelling the laminate in detail. As a starting point, we assessed whether a multiscale approach could improve the prediction of the transverse stress distribution.

6.2.1 Improved prediction of transverse stress distributions in equivalent single-layer shell models

In a first journal paper [8], we have investigated the potential of using a multiscale approach as a possible remedy to the problem of low accuracy in the prediction of the through-the-thickness distribution of the transverse stresses in ESL models. A long term idea of adopting such an approach is to enable a model-adaptivity procedure, cf. e.g. Oden and Vemaganti [9], where initially the model is build up as an ESL model. Based on some measure, either a model error estimator or a failure initiation criterion, a transition to a coupled multiscale approach could be made locally in critical areas. In particular, we have adopted the multiscale concept introduced by Larsson and Landervik [1] for simulating deformations of thin-walled porous structures by coupling the macroscopic shell model to a mesoscopic 3D element representation (RVE) of the heterogeneous material structure. Due to their promising results, our intention in [8] has been to address whether a similar procedure can be adopted for simulating progressive failure in a laminated FRP plate. The main conclusion drawn from the investigations is however that, the concept proposed in [1] is not a suitable approach to increase the level of accuracy of the predicted transverse stress distributions.

The reason is because, in order to ensure deformation equivalence across the scales, the boundary conditions on the RVE cannot be chosen as in [1]. Instead a larger amount of the boundary of the RVE must be tied to the kinematics of the macroscopic shell element. Unfortunately, the resulting through-the-thickness distribution of the transverse stresses will then correspond to what is obtained in a pure shell analysis. Thus no improvements, with respect to accuracy of stress prediction, can be observed.

These findings lead to a slight shift of focus in work package B; we replaced the multiscale approach by an approach where the ESL model kinematics are extended only on the macroscopic level, without resolving the mesoscopic scale. This work is a continuation of the contribution by Brouzoulis and Fagerström [10] where they use the eXtended Finite Element Method (XFEM) [11][12] to enable mesh independent representation of arbitrary delaminations by introducing kinematic enrichments locally in the vicinity of propagating delaminations.

Even with this new approach, the problem of low accuracy in the prediction of transverse stresses must still be addressed. As an alternative method, in [8], we also identified a suitable, and seemingly robust, post-processing procedure which allows accurate predictions of the transverse stress distribution to be made. This stress recovery technique, which was further developed in journal paper [3], involves a polynomial fit to the stress values in the integration points, such that the in-plane derivatives of the in-plane stress can be approximated. This approximation can then be integrated using the 3D equilibrium equations to yield the transverse stress distributions, cf. Figure 10 and Figure 11.

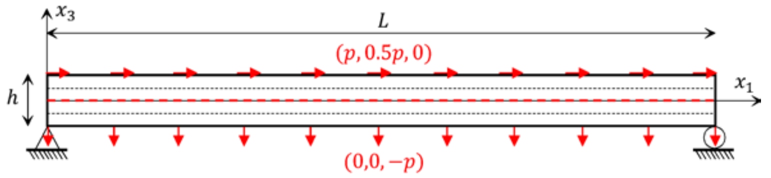


Figure 10. Simply supported [90/-45/45/0] beam used to illustrate the stress recovery technique. A negative vertical traction $\mathbf{p}$ is applied to the bottom surface and on the top surface shear tractions $\mathbf{p}$ and $\mathbf{0.5p}$ are applied in the x_1 and x_2 directions respectively. The red dashed line indicates a cohesive interface. From [3].

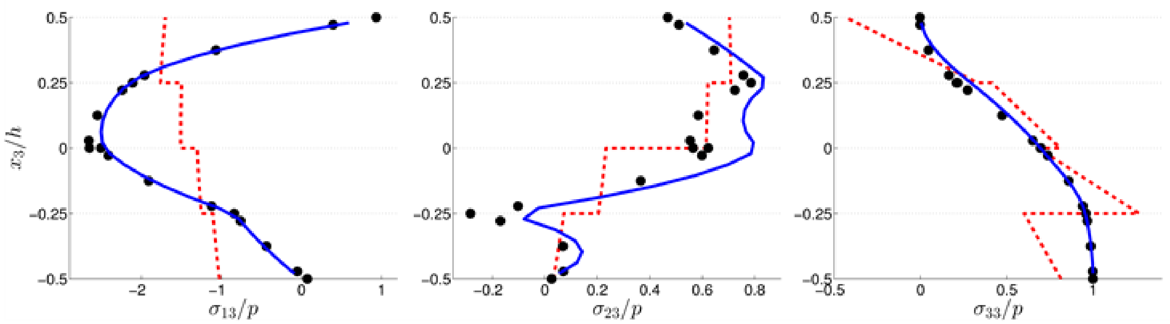


Figure 11. Transverse stress components in reference 3D (blue solid) and shell (red dashed) models together with recovered stresses (•) at $x_3 = L/3$ in simply supported beam. From [3].

6.2.2 Adaptive modelling of delamination in an equivalent single-layer shell formulation

In journal paper [3] the stress recovery technique is used in an adaptive methodology in order to locate critical areas where the ESL shell formulation should be locally refined, by local XFEM enrichment of the formulation, such that the kinematics of delamination can be captured. The methodology involves the following steps:

1. The laminated structure is initially built up by a single layer of ESL shell elements through the thickness;
2. The interlaminar transverse stresses, calculated using a stress recovery technique, are used in an interlaminar failure criterion f_I in order to predict interface areas where delaminations are starting to form;
3. When the criterion reaches a threshold value r_I^2 (less than one) in any interface in an element, this is locally refined by introducing delamination enrichments and associated cohesive zone models, cf. Figure 12. This way the former ESL model is refined into a layer-wise model, where the interface is described by a cohesive law, such that the kinematics of a delamination can be described;
4. If the cohesive law in an enriched interface starts to evolve damage, i.e. if the interface starts to soften, the enrichments patch is expanded in-plane such that the fracture process can be accurately resolved, cf. Figure 13.

In summary, the main idea is that by representing the laminated structure by a single layer of shell elements a computationally efficient model can be constructed. During loading, the model is then enriched locally in critical areas where delamination is predicted. In this way the additional computational expense, associated with the complicated fracture process in laminated composites, can be limited while at the same time maintaining a high level of accuracy. For more details regarding the methodology please refer to [3].

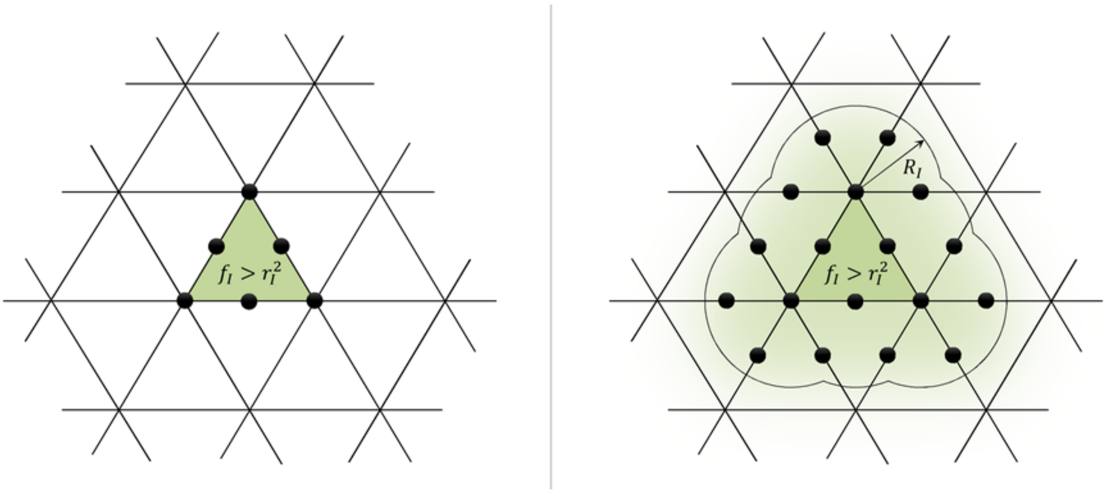


Figure 9. When the initiation criterion f_I exceeds the threshold value r_I in an element the associated element nodes are enriched (left) along with the nodes within a radius R_I (right). From [e].

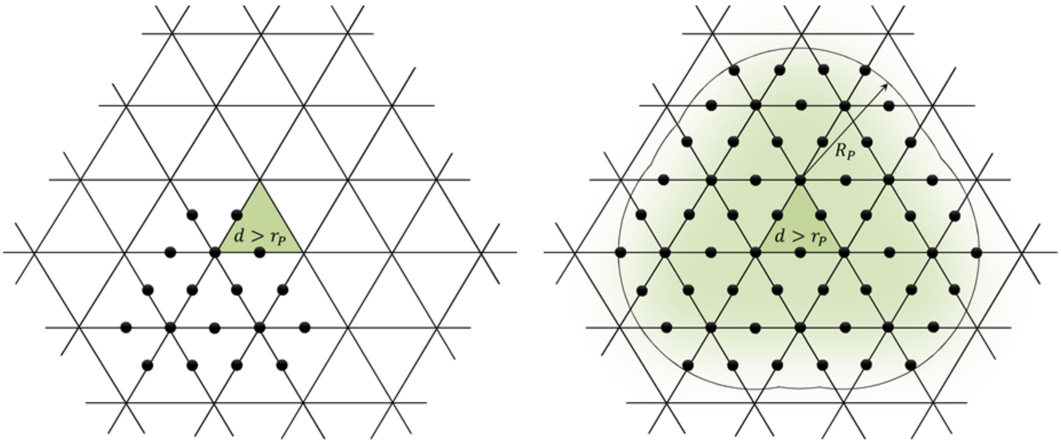


Figure 10. When damage is initiated in a cohesive law (left), the delamination enrichment patch (marked by •) is expanded to include all nodes within a radius $\boldsymbol{R_P}$. From [3].

The proposed methodology is very computationally efficient because the number of active enrichments during the simulation is limited, both with respect to time and location. Even for small example problems, cf. Figure 14, Figure 15 and Figure 16, where all interfaces finally become enriched, more than 50 % computational time is saved compared to the case where all interfaces are enriched during the entire simulation. In full vehicle crash simulations the computational save of this methodology is therefore expected to be even more substantial since only limited amount of the vehicle structure will deform.

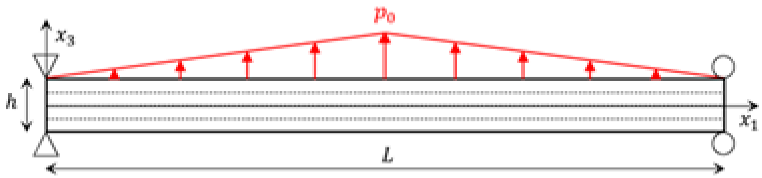


Figure 11. Simply supported $[0]_4$ beam used to exemplify the adaptive delamination modelling methodology. A vertical traction load is applied on the top surface. The beam has a low thickness to length ratio which will lead to delaminations being initiated in the mid interface at the supports of the beam. From [3].

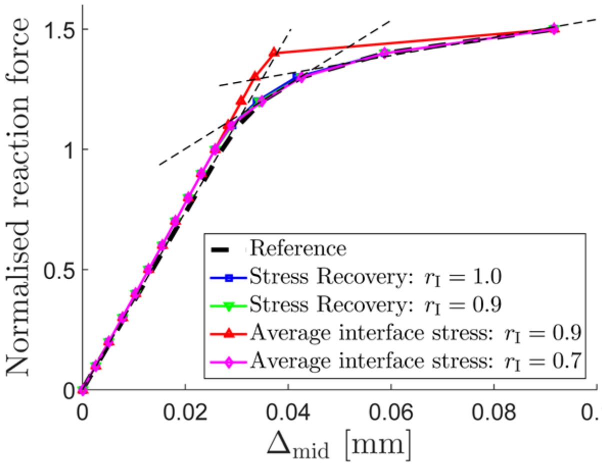


Figure 15. Reaction force (normalised w.r.t. delamination initiation level) versus mid-point deflection of simply supported $[0]_4$ beam with traction load. The reference case with predefined cohesive interface enrichments is compared to cases where the initiation criterion $\boldsymbol{f_I}$, evaluated using either recovered or (from the shell) average transverse interface stresses, is used to initiate the enrichments during the simulation. Analytical Timoshenko beam stiffness for a virgin beam, a beam with a delamination in the mid interface and a beam with three delaminations are also indicated with dashed lines. Using stress recovery, the reference force response is matched even for a threshold value $\boldsymbol{r_I}$ of 1.0, In contrast, using the average interface stress, a lower threshold value is needed in ordet to match the reference solution. Even so, the stress recovery delamination sequence is correct – starting in the mid interface followed by the top and bottom interface – while the average stress, incorrectly initiate the delaminations in the top interface first. From [3].

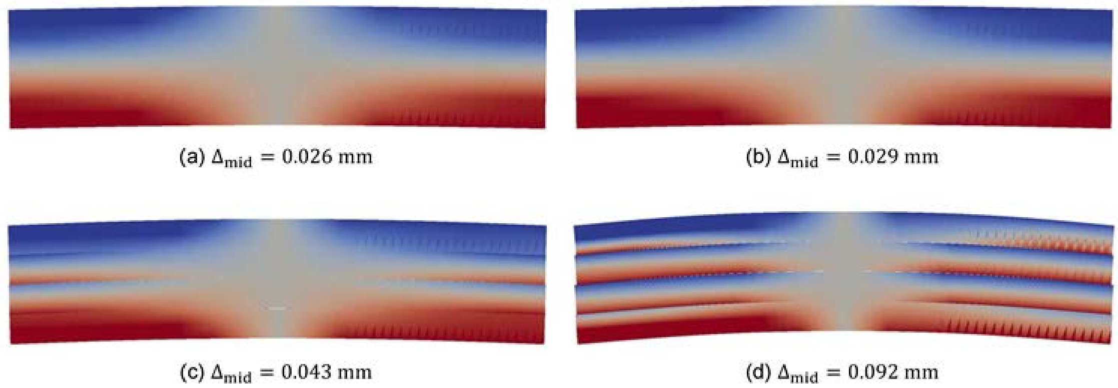


Figure 16. Deformation plots of the adaptively enriched simply supported beam: (a) after delamination enrichment initiation but prior to expansion, (b) after delamination propagation in mid interface, (c) after all delamination enrichments have been initiated, expanded and all delaminations has started to propagate and (d) final deformation before top interface detaches. Five times deformation scale. From [3].

6.3 State-of-the-art assessment of composite modelling for crash applications.

All three material models considered in the state-of-the-art analysis use different material parameters, failure models and degradation schemes. MAT54 is a simple model, for which many input parameters lack direct physical meaning. Failure is based on the Chang-Chang failure criterion. MAT262 is an advanced material model based on fracture toughness and includes a continuum damage behaviour. LAW25 in RADIOSS is also an advanced material model and involves a plasticity formulation which gives the user the possibility to define a complex stress-strain curve. All tested material models could be tuned to match the test data, but with different accuracy. The predictability could not be commented for the material model MAT262 and LAW25, since vital material data could not be obtained. All material data was known for MAT54 and the material model exhibits a poor predictability. All results are summarised in the Master thesis report [4].

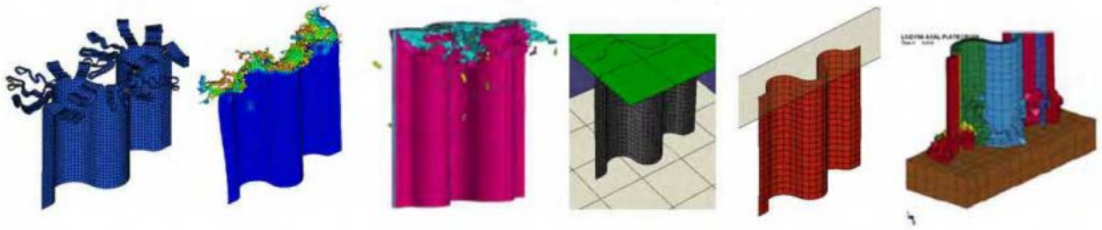


Figure 12 Simulations of a corrugated specimen in different software, from literature study.

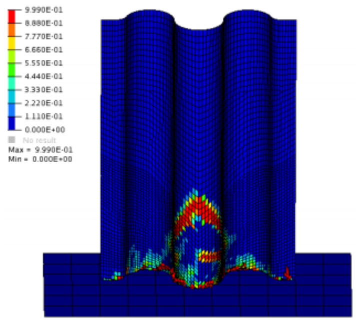


Figure 13. Simulations of a corrugated specimen, from analyses in Master's thesis.

6.4 Implementation of prototype adaptive shell element in LS-DYNA

DYNAmore Nordic has within the project implemented a proof-of-concept XFEM-element in LS-DYNA. The element is provided as a user defined element routine, open for the user to adapt according to needs. It contains the combination of layered solid-cohesive-solid elements as well as 'thick shell'-cohesive-'thick shell' formulations within a single element.

The XFEM-element is based on the ghost node approach where element cracks are represented by internal element nodes, not visible to the user. With few changes the current element can support multiple cohesive interfaces or stacking of several XFEM-elements to simulate multiple delaminations.

A drawback is that the ghost nodes can currently not be switched on or off during a simulation, making the procedure relatively computational expensive. However, from a CAE point of view, one of the challenges is the complexity in creation of laminate models which can be facilitated by a user friendly and stable element that is easily accessible for the CAE-engineer. The LS-DYNA code containing the newly developed features are available to all partners on the project server.

6.5 Design of test cases

For both components considered a simple geometry was chosen due to manufacturing of prototypes. For the crash box, a cylindrical shape with one teeth-shaped side for crushing initiation was identified as most suitable. For the beam, the corresponding analysis came to the final design of a beam with a hat profile. For images of the prototype design please refer to Figure 19.

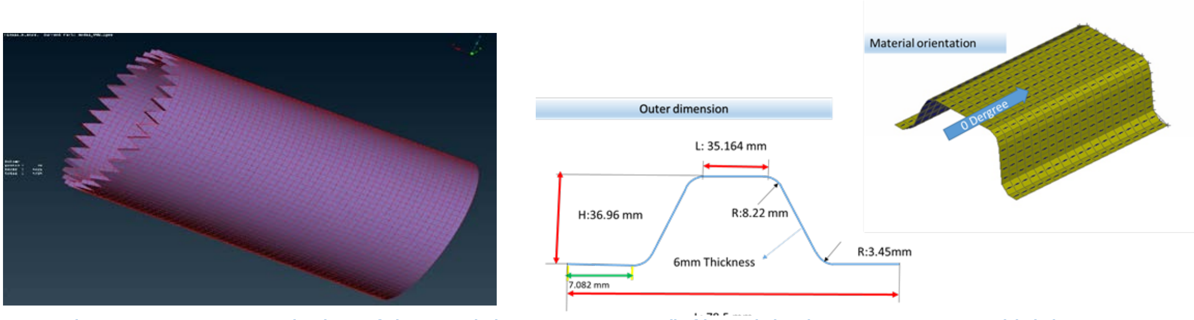


Figure 14. Prototype design of the crash box component (left) and the beam component (right).

The lay-up was then designed in order to have the same structural performance as corresponding steel components (compared by simulation). Different modelling techniques and material models was tested and verified with coupon tests in order to have an understanding of how the structural performance are affected. Simulation graphs from the analysis are shown in Figure 20 below. All results are summarised in the Master thesis report [5].

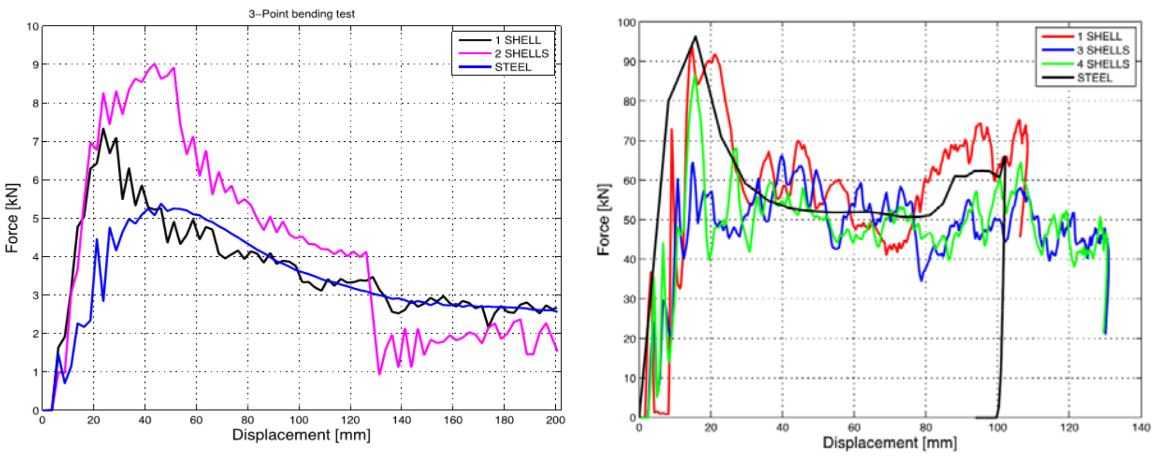


Figure 20. Analysis results of door beam bending load case (left) and crash box crushing (right) for both a steel and a composite design

6.6 Mechanical testing

6.6.1 Crash boxes

The crushing behaviour was similar between dynamic and quasi-static testing, Figure 21 and Figure 22.

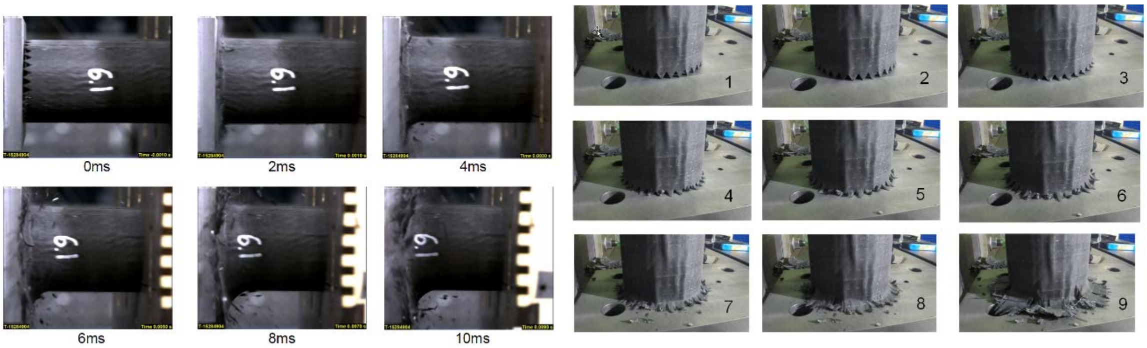


Figure 21 Dynamic crushing left and quasi-static crushing right

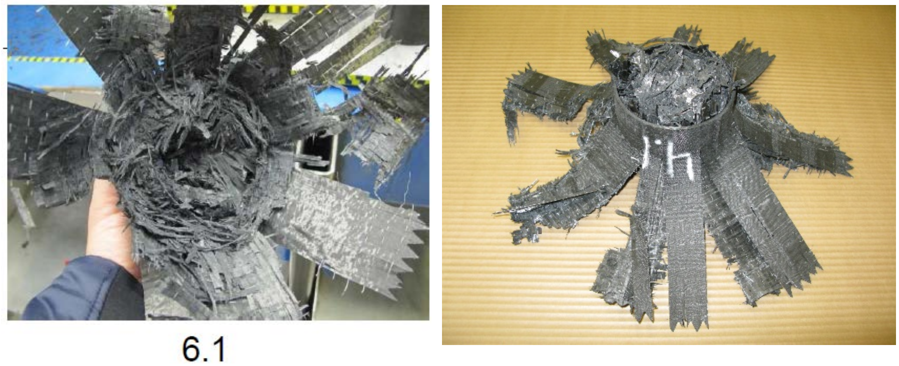


Figure 15 Crash box after dynamic test to left and quasi-static to the right

An increase in force was observed in the slow quasi-static testing, Figure 23. The energy absorption calculated from force-displacement in the quasi-static tests were around 30% more, ~ 6.5 kJ/100 mm compared to ~ 5kJ/100 mm.

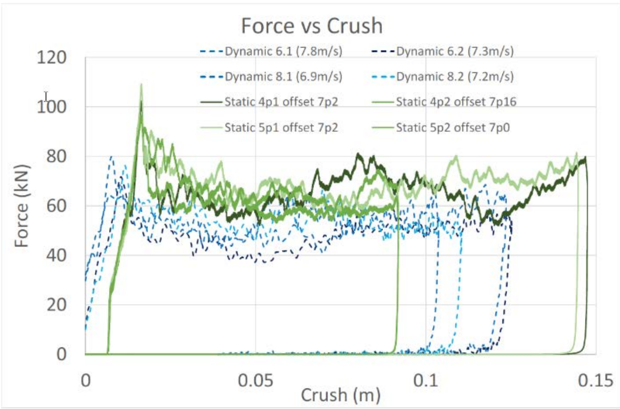


Figure 163 Crushing force crash boxes

The tests were performed to verify virtual calculations and material models. The LS-DYNA simulations in the master thesis performed at Escenda matched the dynamic tests well Figure 24.

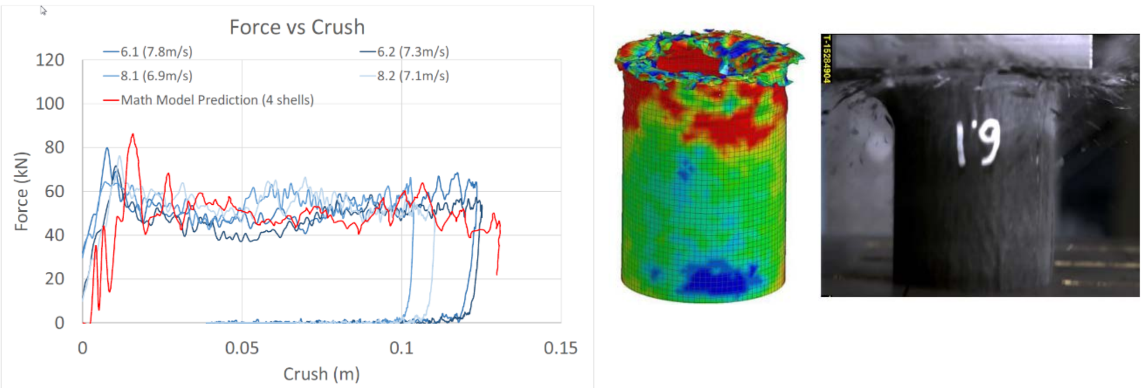


Figure 24. Dynamic tests compared to simulation

A summary of the results of the crash boxes as well as the beams can be found in [6].

6.6.2 Beams

The four beams quasi-statically tested at Volvo Trucks are shown in Figure 25 below.

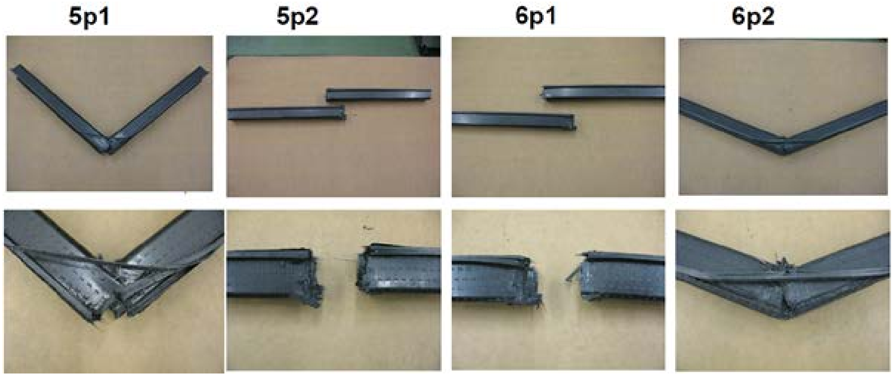
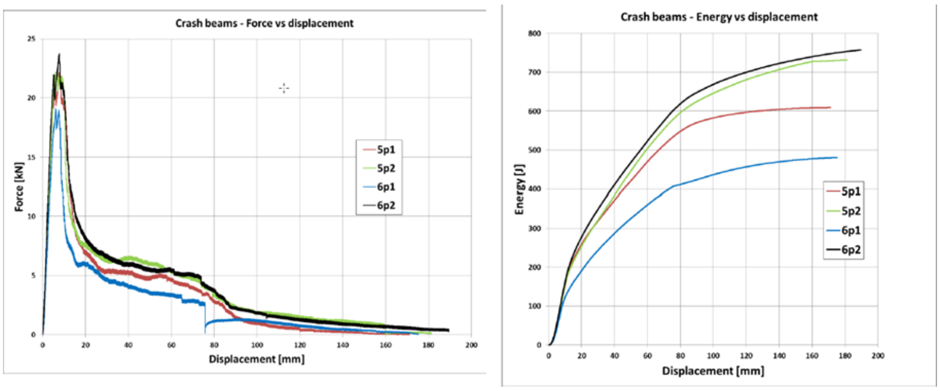


Figure 17. Beams after quasi-static testing

Results in terms of force-displacement curves, absorbed energy versus displacement and a short tests summary are shown below in Figure 26.



Crash beam	Max force [kN]	@ [mm]	Energy [J]	Thickness [mm]
5p1	22.2	8.0	609	5.8
5p2	22.6	7.0	732	5.7
6p1*	19.1	6.2	480	5.0
6p2**	23.7	7.8	758	6.5

*Beam has two less layers in 0 dir.
**Beam has two extra layers in 0 dir.

Figure 18. Force-displacement curves and absorbed energy for quasi-static tested beams

Five beams were available for the dynamic testing. Based on preliminary simulations, the first test was carried out aiming at a velocity of 10 m/s, and an actual measured velocity of 9.85 m/s. Since the beam broke in halves, the velocity was reduced in each of the following test until no breakage occurred at 5.01 m/s. All tested beams are shown in Figure 27.

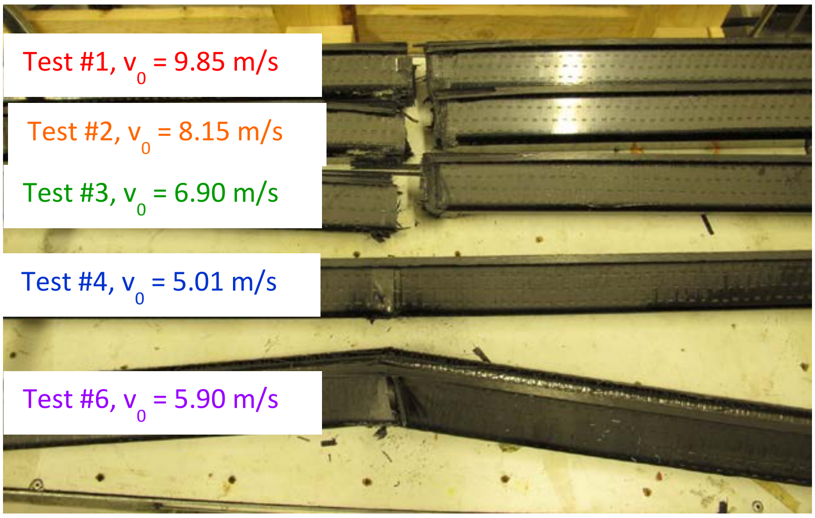


Figure 19. Dynamically tested beams

Since no direct measurement of displacement is possible in the drop tower, film analysis was performed to verify the double integrated acceleration signals. The force vs displacement response of the dynamic beam bending testing is shown in Figure 28. As a reference, an average value of the quasi-static tests is included as a black curve. The curve colours corresponds to the labels in Figure 28.

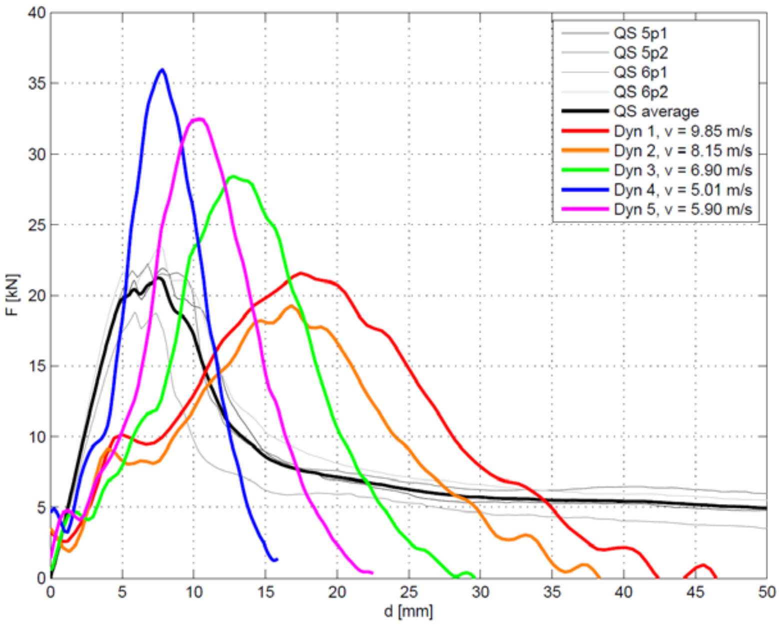


Figure 20. Force displacement curved from quasi-static and dynamic beam tests

The resulting peak forces indicate a negative rate dependency which was not expected. However, the quasistatic tests does not follow this trend. More information on this is found in [6].

6.7 Fractography

All results from the fractography are summarised in [13], available on the project server.

6.7.1 Beams

For the beams with the smallest extent of damage, the matrix cracks stopped less than 4 mm away from the impact location along the beam length. This distance was 9 mm for the specimen with the highest damage

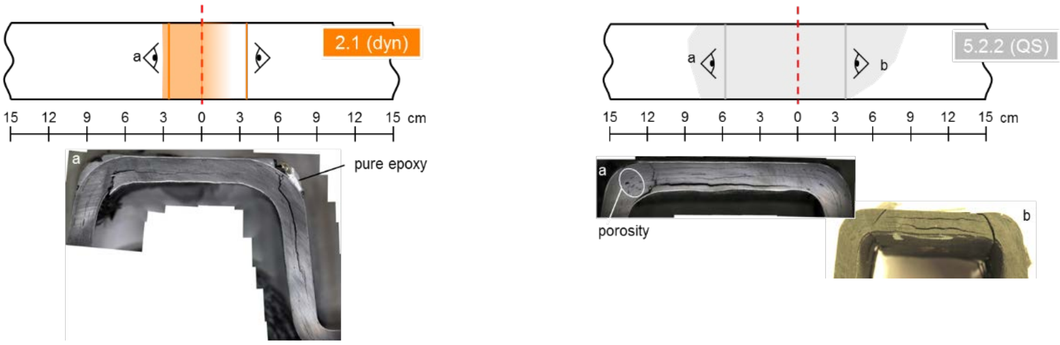


Figure 21 Results from A-scan of two of the tested beams

extent, see Figure 29. The failure seemed to have initiated in the shoulders of the beams, most likely because of the combination of high mechanical stresses and porosity from manufacturing, see Figure 30.

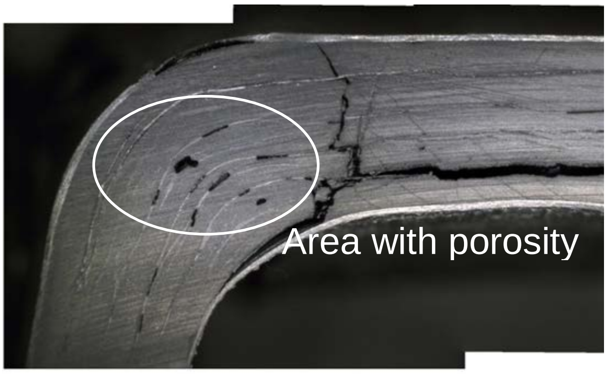
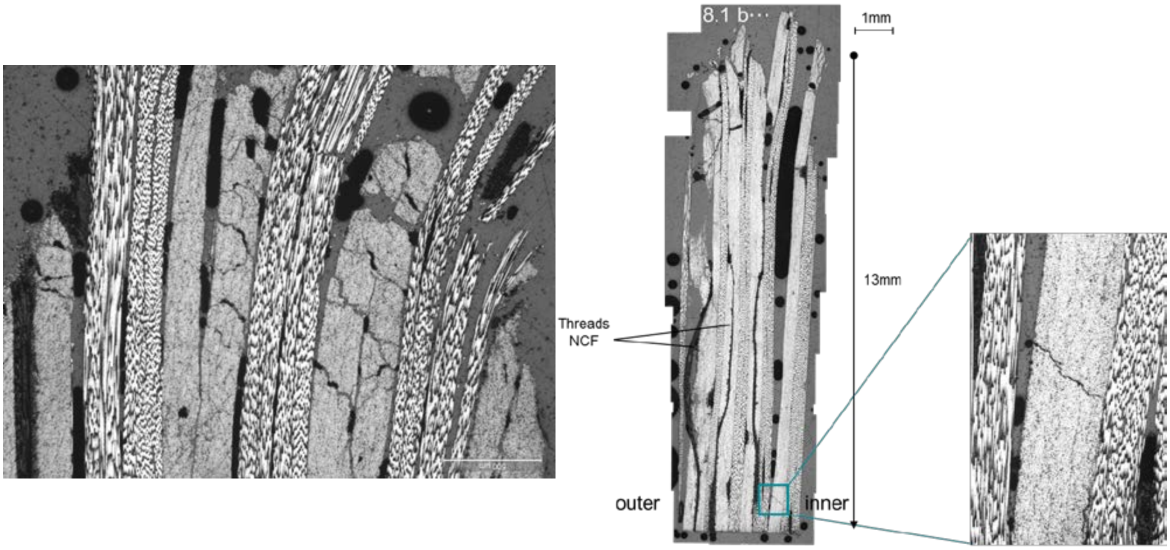


Figure 30. Image on existing porosity at the beam shoulders resulting from the manufacturing

6.7.2 Crash boxes

Delamination and intralaminar failure mechanisms were visible from the micrographs of the cross-sections, see Figure 31a. No clear pattern appeared in the amount and location of delaminations between specimens. The deepest delamination measured stopped more than 15 mm below the crush front, see Figure 31b. Finally, the deepest delamination seemed to correlate with the presence of wrinkles from the manufacturing of the tubes.



a) b)

Figure 31. Delaminations and intralaminar failure observed from the microscopic studies of the crash boxes

6.8 Material model benchmark

The benchmark study shows that both material models (built-in LS-DYNA material model 261 and the first version of the model delivered form work package A) physically captures the failure behaviour in the dynamic crushing of a three-point bending test of a beam, see Figure 32. However, since the failure behaviour in the experiment was unknown, it is hard to draw any conclusion whether the failure behaviour corresponds to the experiments or not. The correlation of the force-displacement response, as well as the absorbed energy, was poor between the simulation results and the experimental test. In the benchmarking test of the crushing of the corrugated specimen, it was however possible to see a correlation in the force-displacement relation. Although, the drop in force due to damage in the simulations was not as clear as in the experiment.

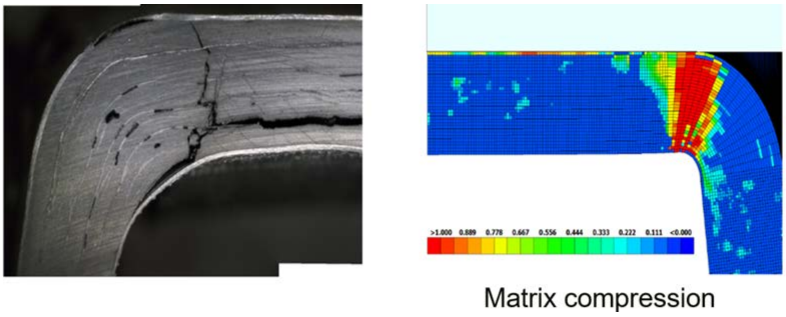


Figure 22 Comparison between experiment (fractography to the right) and modelling results (with SICOMPs material model to the left)

The overall conclusion is that the new material model appears to be more robust than MAT261. However, in order to have a reliable material model in crash simulations, such that testing can be reduced, further development of physically based material models will be required.

6.9 DYNAMore Nordic course activities

The LS-DYNA training course Introduction to Composite Modeling was attended by 20 persons from nine partner organisations. It has thus helped to spread the knowledge in composites FE modeling and the current state-of-the-art to a broad audience. Additionally, the course Introduction to LS-DYNA was attended by three Master students within the project and the course Material Modelling and User Defined Material in LS-DYNA was attended by the two PhD students.

7 Dissemination

An important part of the project has been to disseminate the results. This has been done via different type of publications (cf. Subsection 7.2 below), 7 presentations at international conferences and integration of some of the results into the teaching on Masters and PhD student level at Chalmers.

7.1 Knowledge and results dissemination

The table is kept in Swedish to avoid any misunderstandings due to translation

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	x	Forskning inom krockmodellering av kompositstrukturer är helt avgörande för att möjliggöra införandet i strukturella komponenter i framtida fordon. Trots det är verksamheten internationellt begränsad varvid behovet av forskning är stort. Därför har forskningen inom detta projekt bidragit avsevärt till ökad kunskap inom området och ökade möjligheter till framtida pålitlig lättviktsdesign med kompositer. Resultaten från projektet har spridits genom ett flertal konferens och tidskriftsartiklar samt vid flera konferenspresentationer
Föras vidare till andra avancerade tekniska utvecklingsprojekt	x	Modellen utvecklad i WPA kommer användas och fortsätta utvecklas i det parallella projektet Compcrash 2 som finansieras av energimyndigheten. Fortsättning på detta projekt har också sökts och är under utvärdering. Resultat och modeller från detta fortsättningsprojekt beräknas sedan kunna användas i produktutvecklingsprojekt från 2020.
Föras vidare till produktutvecklingsprojekt		
Introduceras på marknaden		
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

The current project has specifically benefited from a strong interaction with two related projects, i.e. the European project MATISSE on modelling and testing of composite components in crash and the national project Compcrash focused on material characterisation and failure mechanism identification for composites in crash situations.

Besides project specific achievements, this project has been a means to coordinate the research on crash modelling of composites among the partners of the consortium, since many of the partners have been, are and will be involved in related projects which will benefit from results and knowledge of this project.

We hope to continue this coordinated Swedish effort and have therefore also applied for a continuation within the FFI programme to further continue developing the models and methods developed in this project, all according to the initial 10 year plan. At the same time, a new project called Compcrash 2 (funded by the Swedish Energy Agency) has recently started which builds directly on the findings of the current project summarised in this report. Compcrash 2 also addresses the remaining aspects of work package A (see above in Section 5) which had to be postponed due to lack of resources.

On European level, we foresee that the recently started Marie Curie Sklodowska Initial Training Network on crash modelling of composites (called ICONIC) will also benefit from the results of the current project. There, SICOMP is a partner with 2 PhD students currently being recruited. Similarly, Chalmers is in discussions within a new EARPA led proposal towards the current call *MG 3.2-2017 Protection of all road users in crashes* where composite modelling may be included and therefore also this project (if granted) will benefit from the results of the current project.

7.2 Publications

The project has contributed with the following contributions

7.2.1 Licentiate of engineering theses

Främby J (2016). On efficient modelling of progressive damage in composite laminates using an equivalent single-layer approach. Chalmers University of Technology.

7.2.2 Journal papers

Gutkin R, Costa S, Olsson R (2016). A physically based model for kink-band growth and longitudinal crushing of composites under 3D stress states accounting for friction. *Compos Sci Technol. In press.*

Costa S, Gutkin R, Olsson R (2016). Mesh objective finite element implementation of a model for kink-band growth and longitudinal crushing of composites accounting for friction. *Compos Struct; To be submitted.*

Främby J, Brouzoulis J, Fagerström M (2016). Assessment of two methods for the accurate prediction of transverse stress distributions in laminates. *Compos Struct;* 140:602-611.

Främby J, Brouzoulis J, Fagerström M (2016). Adaptive modelling of delamination initiation and propagation using an equivalent single-layer shell approach. *Inter. J Numer. Meth. Eng., Submitted*.

7.2.3 Conference publications

Främby J, Brouzoulis J, Fagerström M, Larsson R (2014). A fully coupled multiscale shell formulation for the modelling of fibre reinforced laminates. *16th Eur. Conf. on Compos. Materials*. Seville. Spain.

Costa S, Gutkin R, Olsson R (2016). Finite element implementation of a model for longitudinal compressive damage growth with friction*. 17th Eur. Conf on Compos. Materials.* Munich. Germany

Främby J, Fagerström M, Brouzoulis J (2016). Delamination initiation and propagation modelling with an enriched shell element formulation. *17th Eur. Conf on Compos. Materials*. Munich. Germany.

7.2.4 Technical reports

Costa S. (2015). Material model implementation – Version one. CR15-037 (confidential). Swerea SICOMP. Mölndal.

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7.2.5 Master thesis reports

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Gradin W, Karlsson F (2016). Modelling and simulation of composites crash tests for validation of material models using LS-DYNA. Master thesis at Chalmers University of Technology.

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8 Conclusions and continued research

A novel material model has been developed and implemented in commercial finite element software. It is able to handle triaxial load cases and has been shown to perform much better than previously existing models for a number of numerical test cases, and for a few experimental validation cases. It was however also shown in the final assessment phase discovered that more work is needed both for increased accuracy in general and complex multiaxial load cases and for increased numerical stability.

The material model offers the potential for improved crash analysis of composite structures, but has not yet been applied to analysis of larger components. Use of the model in analyses of larger structures requires further improvement of the numerical efficiency and robustness of the material model, as well as further collaboration on the implementation in more efficient FE shell elements. These aspects are to be considered in the future research planned.

Remaining questions include the proper modelling of the final material behaviour at very large strains and the difference in the in-plane and through-thickness transverse properties of the composite plies. Furthermore, the experiments in WPC have indicated potential influence of the deformation velocity, which needs to be addressed in further development of the model.

The adaptive shell methodology developed within work package B The proposed has shown to be computationally efficient because the number of active enrichments during the simulation is limited, both with respect to time and location. Even for small example problems, with delamination cracks growing more or less in the whole domain considered, more than 50 % computational time is saved compared to the case where all interfaces are enriched during the entire simulation. In full vehicle crash simulations the computational save of this methodology is therefore expected to be much bigger since only limited amount of the vehicle structure will experience delamination.

Furthermore, in its current form the adaptive shell methodology has only been assessed considereding elastic ply material, whithout any damage. Ahead we will therefore combine the methodology with the constitutive model from work package A in order to also describe the progressive damage within the composite plies. Thus we will create an FE model which is able to represent both the kinematics and the material physics of progressively failing laminated composites in a numerical efficient way. This will have implications for the analysis of progressive damage in laminated composites in general, and the crashworthiness analysis of automotive vehicles in particular. We even dare to say that achieving this is a prerequisite if structural composites are to have a widespread use in future automotive vehicles.

As a final conclusion, even if the research work in work packages A and B has taken a somewhat different direction compared to what was initially planned, the main goals of each of these WPs are considered to be met. Considering the work packages C and D, all activities planned have more or less been executed as expected and generally with a successful outcome.

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