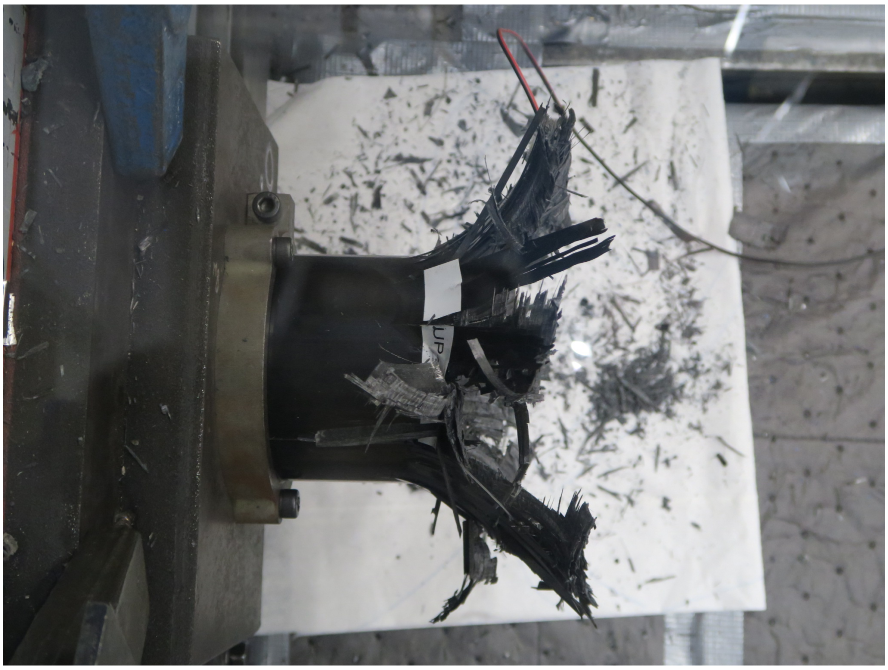
Modelling crash behaviour in future lightweight composite vehicles – Step 2



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Project in Traffic safety and automated Vehicles

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Kort om FFI

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1 Sammanfattning

Strukturella (kolfiber)kompositer har stor potential att både öka säkerheten och sänka vikten på, och därmed utsläppen från eller elförbrukning hos, fordon. Detta p.g.a. kompositers fördelaktiga strukturella egenskaper (styvhet, styrka och energiupptagning) i förhållande till deras vikt. Avgörande för att introducera strukturella kompositer i fordon är dock tillgången till tillförlitliga och effektiva beräkningsverktyg som är anpassade för industriell tillämpning. Detta är något som fortfarande saknas, vilket har varit utgångspunkten för detta projekt.

Projektets syfte har därför varit att utveckla nya materialmodeller och numeriska metoder för att öka den industriella förmågan att genomföra krocksimuleringar av fordon med strukturella delar av kompositmaterial. Detta har lett till vidareutveckling av en materialmodell som beskriver skadetillväxten i individuella kompositskikt, beroende på vilken skademekanism som aktiveras. En ny modell för att inkludera töjningshastighetsberoende har också tagits fram, en modell som dock hittills främst har förmågan att korrekt beskriva effekten på materialets styvhet. Dock är grunden lagd för att även gå vidare till att modellera töjningshastighetsberoende skadeutveckling.

Utöver ren materialmodellsutveckling har det även inom projektet utvecklats en adaptiv metod för att mer effektivt simulera progressivt kompositbrott, där adaptiv förfining av modellen sker i de delar av komponentmodellen där skadeutveckling sker. Den adaptiva metoden har implementerats i en industriell tillgänglig programvara (LS-DYNA) för att möjliggöra industriell användning, dock än så länge i ett proof-of-concept stadium. Den adaptiva modellen har visat potential i flera mindre numeriska exempel, men slutgiltig utvärdering och anpassning till industriella behov återstår.

För att utvärdera potentialen hos utvecklade materialmodeller och numeriska metoder så har det inom projektet genomförts omfattande instrumenterad provning. Totalt har 46 kolfiberbalkar, 36 krockrör och 10 metall- och kompositbalkar provats, både kvasistatiskt och dynamiskt Den mekaniska provningen har också kompletterats med detaljerad fraktografi för att identifiera skademekanismer och deras omfattning, men också kvalitén på ursprungsmaterialet. Tillsammans utgör dessa experimentella resultat en väldigt värdefull bas för vidare modellutveckling, och saknar troligtvis motstycke internationellt.

Totalt sett så bedöms det att projektet tagit avsevärda steg mot en ökad förmåga att simulera det strukturella beteendet hos kompositkomponenter i krock. Projektarbetet har även resulterat i en generellt ökad kompetensnivå kring modellering och simulering av kompositer hos medverkande projektparter. Genom projektet har grupperingen av akademiska parter och företag också etablerat sig som en ledande aktör i Europa inom detta forskningsområde.

Fortfarande återstår dock viktig forskning och samverkan innan industrin har full förmåga att använda simuleringsdriven produktutveckling av kompositkomponenter för krock. Detta innefattar både en ytterligare höjning av kompetensnivån hos industriföretagen, men också fortsatt forskning för att adressera de forskningsfrågor som kvarstår.

2 Summary

Structural composites or Carbon Fibre Reinforced Plastics (CFRP) can be designed to have higher strength, stiffness and also energy absorption capability per unit weight than steel and aluminium, and are therefore in increasing demand from the automotive industry. The driving forces behind this important shift in technology are both the ambition to reduce the environmental impact from the transport industry, in terms of lower emissions and reduced energy consumption per kilometre, and the evident safety benefits from introducing a lighter, but also stronger material with better energy absorption capability compared to conventional metal materials currently used.

Crucial for the introduction of CFRP in structural parts is however to have predictive, robust and efficient Computer Aided Engineering (CAE) tools such that crashworthiness can be assessed with good accuracy via Finite Element (FE) simulations. The purpose of the current project has therefore been to develop and validate simulation technologies (material models and numerical methods) that allow the industry partners to simulate the crash behaviour of CFRP components in crash situations. Thus, focus has been both on the accuracy and predictive capabilities of material models that describe the progressive failure of composites plies and interfaces, and on the computational efficiency to enable the simulation of larger components and automotive structures.

An improved material model and an adaptive shell modelling concept has been developed in this project. The material model proves to behave well in idealised load cases, and also compete well with other existing damage models, such as the one implemented in Digimat. However, remaining research that needs to be conducted should address the model mesh sensitivity and robustness with respect to various element formulations. The adaptive shell model was implemented and verified against a number of test cases with very promising outcome. Unfortunately, however, the gain in simulation time was lower than initially expected. In addition, the results obtained when this adaptive model was applied to the simulation of larger components were surprisingly different from results obtained with traditional simulation techniques. This is something that requires additional research.

To evaluate the potential of the material models and numerical methods developed in the project, there has also been extensive testing. In total 46 CFRP beams, 36 CFRP crash tubes and 10 beams with a hybrid design involving both high-strength steel and CFRP have been tested, both quasi-statically and dynamically. This mechanical testing has also been coupled with detailed fractography, to investigate te failure mechanisms and their extent, as well as the initial quality of the components. Together, this unique step of results (internationally!) constitute a very valuable basis for model and method development,

All in all, the project has taken significant steps towards a more accurate and efficient modelling of composite structures in crash. The project has also led to a increase of competence level when it comes to the industrial modelling of composite structures in crash, mainly through the large investment in time put on modelling and simulating the component tests, and through the strong interaction during the assessment phase of the new CAE tools that have been developed. Through the project, the consortium has also established a leading position on composites-related crash safety research in Europe. This has been achieved both through the arrangement of the first international workshop in crashworthiness of composites in 2018, but also through well-recognised journal publications, conference presentations and assignments as external reviewers at relevant international PhD defences.

But there are also remaining research to be made before the models and methods developed in this project can be fully adopted in industry. This will require further research and extensive collaboration between academia and industry

3 Background

Structural composites, and particularly Carbon Fibre Reinforced Plastics (CFRP), can be designed to have higher strength, stiffness and also energy absorption capability per unit weight than steel and aluminium, and are therefore in increasing demand from the automotive industry. The driving forces behind this important shift in technology are both the ambition to reduce the environmental impact from the transport industry, by lower emissions and reduced energy consumption per kilometre, and the evident safety benefits from introducing a lighter, but also stronger material with better energy absorption capability than conventional metal materials currently used.

Crucial for the introduction of CFRP in structural parts is however to have predictive, robust and efficient Computer Aided Engineering (CAE) tools such that crashworthiness can be assessed with good accuracy via Finite Element (FE) simulations. A major challenge is however that, in contrast to metallic materials where crash energy is absorbed via plastic deformation, the energy in crash protective CFRP components is absorbed via a much more complex failure process. The complexity is due to the fact that CFRP components typically contain many layers, or plies, with different fibre orientation. For each ply the failure mechanisms, strength and toughness are different along or across the fibres, and differ in tension and compression. Furthermore separation ("delamination") and friction between plies is common. As a consequence of this complexity, there are today no predictive and efficient enough CAE tools available to the industry for crash analysis.

The lack of such tools, and knowledge of how to use them, are important aspects that are currently hindering the Swedish automotive industry to introduce CFRP in structural parts. Several Swedish companies, e.g. Volvo Cars, NEVS, Gestamp Hardtech and AB Volvo, have identified a need for validated and robust CAE crash tools for CFRP structures already within a few years.

To address this challenge, a national consortium with 10 partners led by Chalmers was formed around the project *Modelling crash behaviour in future lightweight composite vehicles – Step 1* (denoted *FFI-Crash 1 in short),* which started in October 2013. Thereby, a focused effort was initiated with the ultimate goal to, in a ten year perspective, establish confidence in crash predictions of composite vehicles to a level comparable with the state of the art for conventional metallic structures.

Although *FFI-Crash 1* delivered significant improvements to the modelling of CFRP failure, it was at the end of that project clear that a number of challenges remained to be addressed. First of all, the material model to describe the progressive failure of individual composite plies needed to be further developed and validated. A limitation of the model from *FFI-Crash* 1 was that it was developed and adapted only for solid (continuum) finite elements. Thus, there was a clear need to adapt the model so that it also fits to much more computationally efficient shell elements. Another aspect is that both research literature and results from the testing in *FFI-Crash 1* indicate that strain-rate effects often have an important role in the crash behaviour of CFRP components. Thus, another important focus for the current project was to include the strain-rate behaviour.

A second important aspect that needed to be addressed (and still is!) is that most approaches to model progressive failure of composite components are using separate continuum (3D) elements for each ply (cf. e.g. [1-3]), in order to allow for proper modelling of delamination, which may be detrimental to the structural performance. However, this is an approach which is completely unrealistic for larger simulation models, such as car crash models, as this requires too much computer memory and leads to too long simulation times. Thus, there is an obvious need for numerical procedures that include the relevant mechanisms more efficiently. It is crucial to model what can be relied upon as to give reasonable results, but without having to wait weeks for the results.

One approach to achieve increased efficiency was prototyped in *FFI-Crash 1*, which for idealised test cases indicated significant time savings in the simulations. In short, this approach allows for adaptive refinement of a single-element layer model in areas where delaminations may occur. However, to make such an adaptive technology feasible for impact and crash analysis of larger components or entire cars it needed to be made available in a speed-optimised and mature FE-software (such as LS-DYNA). Additionally, the implementation of the adaptive approach in a commercial software makes it accessible to industry.

4 Purpose, research questions and method

The purpose of the project has been to develop and validate simulation technologies (material models and numerical methods) **that allow the industry partners to simulate the crash behaviour of CFRP components in crash situations**. Thus, focus has been both on the accuracy and predictive capabilities of material models that describe the progressive failure of composites plies and interfaces, and on the computational efficiency to enable the simulation of larger components and automotive structures.

More specifically, the project has aimed to answer the following research questions:

- *What is the influence of strain-rate effects on the response and performance of structural composites in crash applications? How do we best model these effects?*
- *How much better predictions of the safety-protective capabilities of composite components can we achieve by developing improved models for crash, compared to what is currently available to the automotive industry?*
- *How much computational efficiency can we gain compared to traditional ply-by-ply modelling of composites by adopting an adaptive shell concept to model progressive failure in composites in crash? Is it sufficient to enable crash simulations of entire cars?*

4.1 Method

To meet the needs listed above, the project has been divided into five work packages (WPs):

WPA: Ply damage modelling incl. dependence on strain-rate and temperature
Work package leader: Robin Olsson, RISE SICOMP

The main task of WPA has been to develop a model that is capable of describing the strain-rate dependence of CFRP, including the effects on stiffness, strength and damage evolution.

As input to the model, available research literature has been reviewed, see details in Deliverable DA.1 [4]. Based on the outcome of this review, additional tests to quantify the strain-rate dependence of CFRP were defined and conducted both at AB Volvo [5] and at the University of Patras in Greece (the latter via the collaboration with the EU-project ICONIC).

The collected data was used as a starting point for the modelling. Focus has been on composites reinforced by carbon fibres, and strain-rate dependence has only been considered for the polymer component of the composite. A model based on micromechanics and a tailor-made homogenisation procedure was used to develop a model that combines the linearly elastic material behaviour of the carbon fibres with a viscoelastic-viscoplastic behaviour of the polymer matrix, cf. Deliverable D A.2 [6] and D A.3 [7].

WPB: Efficient progressive failure analysis using adaptive shells
Work package leader: Mats Landervik, DYNAmore Nordic

The main task of WPB has been to further develop the adaptive concept from *FFI-Crash 1* and to implement this concept in the commercial finite element solver LS-DYNA to enable industrial use. Also, the material model from FFI-*Crash 1* has been adapted for use with continuum shell elements (with a 3D stress-strain relation but with arbitrary element shape.

It turned out that the material model from *FFI-Crash 1* contained a combination of too severe simplifications and implementation errors, whereby a significant portion of this WP has been devoted to the improvement and verification of the material model. The modifications have included a reformulation of the model to allow for large strains (which means that fibre reorientation under shear is properly treated) and the incorporation of a proper, element-shape-dependent fracture toughness regularisation. The material model has been verified by subjecting the model to idealized load cases in tension, compression and shear in all loading directions [8].

The second part of this WP has been devoted to the implementation of the adaptive modelling concept in LS-DYNA. Here, Chalmers has collaborated closely with DYNAmore Nordic to implement a shell element that is capable of handling multiple delamination cracks (limited to 5 cracks per element due to internal limitations in LS-DYNA). The element implementation incorporates the improved material model from *FFI-Crash 1* to describe progressive ply failure, and a mixed mode cohesive law to model the interface degradation between the plies [9-10].

WPC: CAE tool implementation in the industrial design process
Work package leader: Rickard Östlund, Gestamp Hardtech

The first task of this WP was to develop routines and best-practice processes for how to model, simulate and optimise composite components for crash. In this process, two commercial software were used: LS-DYNA from LSTC and Digimat from e-Xstream. Thus, WPC started with that FS Dynamics, Escenda and Gestamp developed routines and processes to virtually (by simulation) assess the crashworthiness of composite components [11]. In this work, the test results and demonstrator geometries from *FFI-Crash 1* were utilised. In addition, ÅF (later AFRY) developed a methodology to optimise the fibre orientations of CFRP laminates, and MSC (via e-Xstream) assessed the predictive capabilities of Digimat (at that time) to predict the tests from *FFI-Crash 1* [12]. Based on the outcome of the initial Digimat benchmark, see more below, MSC also implemented a second set of material models to be used in WPD.

The second task of WPC was then to develop the design of three demonstrator components (a CFRP beam, a CFRP crash tube and a hybrid metal-CFRP beam), to be mechanically tested in WPD. To allow for a comparison with test results obtained in *FFI-Crash 1*, it was decided that the component geometries for the CFRP beam and CFRP crash tube should be the same as therein [13]. Simulations were however used to decide two different lay-ups (through-thickness order of fibre orientations) for the beam in order to promote two different types of principal failure mechanisms. Furthermore, three types of CFRP material systems were determined to be used: one unidirectional pre-preg system, one biaxial pre-preg system and one Uniweave NCF material system (the latter the same material system as in *FFI-Crash 1*). The purpose of the two different lay-ups and the three different material systems was primarily to widen the experimental results to be used for the assessment of the CAE tools in WPD.

Furthermore, the hybrid metal-CFRP component was designed as a steel hat-profile beam reinforced with a rectangular CFRP patch [14]. The CFRP system used was more or less the same as the unidirectional pre-preg system used for the CFRP beams. Furthermore, the optimisation procedure developed by ÅF was used to define three different lay-ups of the reinforcing CFRP-patch.

WPD: Methodology assessment and validation
Work package leader: Fredrik Edgren, Volvo Car Group

The first task of WPD was to manufacture the demonstrator components defined in WPC. CFRP beams and crash tubes were manufactured with the three different material systems, the two pre-preg systems at Volvo Cars and the Uniweave NCF system at RISE SICOMP [15]. In addition, the hybrid metal-CFRP beams were manufactured by Gestamp with their novel two-step manufacturing technology in which the residual heat from the hot forming of the metal part is used to cure and attach the reinforcing CFRP patch [16].

The second task of WPD was the mechanical testing of the demonstrator components. First, an experimental test plan was defined [17], which included both quasi-static and dynamic testing of all three types of components. The beams (both 45 CFRP and 10 metal-CFRP) were tested in a three-point bending setting. Additionally, for the CFRP beam, two different span lengths and various dynamic impact speeds were defined to establish a broad experimental basis for CAE tool validation. For the 36 CFRP crash tubes, both the quasi-static and dynamic testing was conducted as axial and oblique crushing/impact. For a summary of the test plan, please see Table 1.

***Table 1**: Experimental component tests in the project*

Component type	Material system	Composite lay-ups	Quasi-static (span length)	dynamic
CFRP beam	Uniweave NCF	Lay-up 1.1	3 (300mm) + 3 (400 mm)	6 (various speeds)
	UD pre-preg	Lay-up 1.1	3 (300mm) + 3 (400 mm)	10 (various speeds)
		Lay-up 3.1	3 (300mm) + 3 (400 mm)	
	Biax pre-preg	Lay-up 1.1 (mod)	3 (300mm) + 3 (400 mm)	5 (various speeds)
CFRP crash tube	Uniweave NCF	$[\pm 45]_{4S}$	3 (3 different angles)	6 (var. speed and angle)

	UD pre-preg Biax pre-preg	$[0/90]_{3S}$ $[0/90]_{5S}$	9 (3 different angles) 3 (3 different angles)	10 (var. speed and angle) 5 (var. speed and angle)
Hybrid beam	Usibor 1500P AS150 + CFRP patch	Lay-up A Lay-up B Lay-up C	2 2 2	8 (various speeds) 8 (various speeds) 8 (various speeds)

All experimental results are available on the file server of the project (accessible to all project partners), and they are also summarised in Deliverable D D.4 [18]. The second task was concluded by a detailed fractographic study to identify e.g. failure mechanisms and extent of delamination, as further input to the CAE tool evaluation. Also these results are available in D D.4.

The final task of WPD involved the evaluation of agreement between simulations and tests. For the hybrid beams, simulations were made using the material model from WPB to describe the behaviour of the CFRP-patch, together with validated material models for the steel already available at Gestamp Hardtech. The CFRP-patch was modelled with 3D continuum elements for each composite ply, separated by cohesive interface element to allow for the modelling of delamination growth. This in order to enable the assessment of the predictive capabilities of the ply material model from WPB. Comparisons were made with experimental results obtained from the hybrid testing [19].

A similar modelling strategy was used for the CFRP crash tubes, i.e. each composite ply was modelled with separate elements and with the same material model. In contrast to the hybrid beam, however, delamination growth was not included, and different types of finite elements were used to also allow the assessment of the effect of element formulation on the composite failure predictions. Both the tests with the unidirectional pre-preg material system and the Uniweave NCF material system were simulated, considering different dynamic impact angles. Comparisons were made with experimental results obtained from the dynamic crash tube testing [19].

The CFRP beams were modelled with different amount of model fidelity, with focus on one of the lay-ups for the beams made from the unidirectional pre-preg material system. The total amount of 24 composite plies were in different models modelled with 3, 6, 12 and 24 elements through the thickness, using a combination of continuum 3D elements and continuum shell elements (THSELL, ELFORM=5 in LS-DYNA). Most of the simulations were made in a dynamic setting, but also a low rate impact was modelled to compare with the quasi-static test results. In addition, the CFRP beams were also modelled with the adaptive modelling concept developed and implemented in WPB. In all cases, a mixed-mode cohesive law was included between each layer of finite elements to allow for the modelling of delamination initiation and growth. Comparisons were made with experimental results obtained from the quasi-static and dynamic testing [19].

The aforementioned cases with the CFRP beams and crash tubes were also numerically analysed with Digimat in combination with LS-DYNA, using similar modelling strategies as outlined above. This was made to be able to compare the response of two types of damage models with the experimental results.

Finally, the capabilities of the material model were also tested in a “real” industrial application, a pole intrusion load case of a composite door. This was done both to assess the robustness of the model in a larger simulation model, and the sensitivity of the results depending on the orientation of the finite element mesh.

WPE: Dissemination
Work package leader: Martin Fagerström, Chalmers

The results of this project has been disseminated via one PhD thesis [20], publications in international scientific journals (4 published/accepted papers) and at conferences (6 published papers), and via presentations at international scientific conferences (14 presentations) and other meetings (e.g. at SAFER - Chalmers Vehicle and Traffic Safety Centre).

To further position the consortium as a leading group in Europe, an international workshop on crash in composites was organised at Chalmers in 2018 [21]. The workshop gathered 65 participants, out of which 48 were external to the project, coming from different organisations and more than 10 countries. To our knowledge, this was the first focused meeting of this size that ever took place to discuss the challenges related to composites in crash. The workshop was highly appreciated by the partners and the ambition is to make this a reoccurring event as there are still many challenges that remain.

5 Main project goals

Goal 1: To develop an efficient CAE methodology for designing and assessing crash-worthiness of vehicles with protective structures in structural composite materials

Goal 2: To develop a leading competence in Swedish industry on the design and crashworthiness assessment of crash-protective composite structures

Goal 3: To establish a leading position on composites-related crash safety research in Europe

6 Results and fulfilment of goals

6.1 Project results

The most important results from the project are summarised per work package below:

WPA: Ply damage modelling incl. dependence on strain-rate and temperature

A literature review report of strain rate effects in structural composites (Deliv. DA.1)
An extensive review of experimental studies carried out to study the effects of strain rate on unidirectional composite materials and its constituents. The report mainly focuses on the review of pure fibres, pure resins and unidirectional composites, with an emphasis on carbon/epoxy and glass/epoxy material systems. The report contains clear evidence that mechanical properties such as stiffness, yield strength and failure strain are all strain rate sensitive, although to a various extent. Dynamic tests to provide input for modelling of the current materials were performed at Volvo AB and evaluated at RISE SICOMP [5]. Unfortunately, the results could not be used as planned for a number of reasons; limitations in loading rate and loading type of the equipment, large scatter in results and delay in delivery of the final test results. Nevertheless, the results qualitatively demonstrated clear strain rate effects. Specimens were also manufactured and delivered for testing at University of Patras in a related project. These results were delivered too late to be used in the modelling but provided a larger range of strain rates with less scatter and will be used in future model development.

A micromechanically based material model for strain rate effects in unidirectional composites (Deliv. DA.2 + Deliv. DA.3)
The key result from WPA is a micromechanically based material model that is capable of representing the transversely isotropic and strain-rate dependent stiffness response of unidirectionally reinforced carbon fibre composites [6]. A major novelty of this model is that it draws from computational homogenization, with matrix and fibre materials as subscale constituents for a representative volume element of the ply. The micromechanics of the strain rate dependent polymer matrix is represented by an isotropic pressure sensitive viscoelastic-viscoplastic prototype model. Despite the relatively simple modelling assumptions for the constituents, the homogenised model compares favourably to experimental data for an epoxy/carbon fibre-based composite, subjected to a variety of challenging uniaxial off-axis tests. Due to the delays and limitations in dynamic data for the in-house materials, the

model was validated by published data for a unidirectional prepreg material not tested within FFI-Crash 2. The model response clearly reflects observed strain rate dependencies on *stiffness* under both tensile and compressive loading. The model has also been extended to account for a rate-dependent damage evolution, but the validation of this still remains.

Thus, the project ambitions compared to what was stated in the project plan have not been fully met, primarily explained by the fact that the establishment of the rate-dependent modelling framework was more complex than anticipated at the time of application. Still, the model framework appears very promising and serves as a good basis for further research.

The ambition to also deliver an orthotropic damage model (Deliverable DA.4) was not possible to meet within the project, simply because the other tasks (including task B1) was more resource consuming than expected. This was realised at approximately half-time during the project and it was agreed among the project partners to rather focus on Deliverables A.2-A.3.

WPB: Efficient progressive failure analysis using adaptive shells

An improved material model for progressive ply failure, adapted for shell modelling (Deliv. DB.1)
A material model that describes and combines different failure mechanisms of unidirectional composites has been further developed and improved during the project. The model combines the separate failure modes of tensile and compressive failure for loading along the fibres, tensile and compressive failure for loading transverse to the fibres, and in- and out-of-plane shear failure.

The developments made during the project involve several improvements. Firstly, the model has been reformulated to account for finite deformation, something that is important for an accurate response in the case of significant shear deformation. Secondly, the regularisation of the damage evolution has been improved to properly account for the element geometry and crack orientation (something that is not generally considered for competing composite damage models). Thirdly, the implementation has been thoroughly tested which has led to the identification and correction of several implementation errors in previous versions.

The model has been tested for idealised loading situations, and the responses are summarised in Deliverable D D.5 [19]. It is clear that the model behaves as desired when used in combination with continuum elements in LS-DYNA. However, it appears that the model is sensitive to the correct deformation as input, which causes some issues when the model is used in combination with continuum shell elements in LS-DYNA. The latter is caused by that deformations are calculated in an approximate way for continuum shells, which leads to lower accuracy of these.

An adaptive shell modelling technology implemented as a user-element in LS-DYNA (Deliv. B.2-B.3)
An adaptive shell approach has been implemented as a user-element in LS-DYNA. The user-element can be used to describe a laminate (or a sublaminate) at three levels of refinement. In the initial stage, the laminate is described in the most coarse way. For this level, the element kinematics are similar to Mindlin theory, and each ply is represented by individual integration points through the thickness.

In the next level of refinement, each ply is described in a way analogous to separate elements through the thickness, fully connected at the composite interfaces. This allows for a better representation of the laminate, yielding a more accurate stress and strain prediction. The final level of refinement includes accounting for displacement discontinuities wherever there are delamination cracks.

The adaptive shell modelling concept shows good potential when applied to a number of test cases, see also Deliverable DB.2 [9] and the open-access journal papers [23-24]. It has also been applied to the CFRP beam impact loading case, for which it shows to be robust as well. However, the results obtained with the adaptive shell model shows some differences compared to high-fidelity models using standard finite element technology, see more in [19]. The reason for the discrepancy in results are unfortunately not known at this stage.

As for the handling of contact between delaminating plies, as well as to external objects, the ambitions of Deliverable D B.3 [10] could only be partially fulfilled. The contact between delaminating plies described by refinement of the user-element could be handled via retaining the compressive interface stiffness of the cohesive interface law. Unfortunately, however, the contact with external objects could not be treated in the way foreseen at the planning stage of the project. Thus, this remains an unresolved implementation task. A strategy for how this could be considered has been outlined in the project. The implementation of this requires, however, larger changes in the main source code of LS-DYNA, something which was not possible to achieve within the time and budget frame of this project.

WPC: CAE tool implementation in the industrial design process

Development of industrial design assessment routines and processes (Deliv. DC.1)
The work in the project has led to the definition of a number of modelling guidelines when it comes to modelling laminated composites in crash. These have all been summarised in Deliverable DC.1 [11]. Overall, the modelling activities in the project have led to an increased level of competence at the industrial project partners for how to model progressive failure of composites in large detail. However, a remaining challenge remains in developing modelling and simulation guidelines that are more adapted to the needs and available resources in industry, i.e. to identify how simplifications can be made to enable shorter simulation times without severely compromising with the accuracy. This remains a question for further research.

Design of weight efficient crash protection demonstrators (Deliv. DC.2)
Three demonstrators were designed (and later manufactured) in the project. The details of these demonstrator components are summarised in Deliverable DC.2. In the end, focus was less on defining the most weight-efficient components and more on defining components that were suitable to challenge the models and methods developed in the project.

Assessment and benchmark of Digimat
An initial assessment of the capabilities available in the software Digimat was made, in which results from simulations were compared with test results from FFI-Crash 1. The detailed outcome of this assessment if available in Deliverable DC.4, but in short it can be said that the capabilities in Digimat in the beginning of the project were far from sufficient to capture the results seen in the tests.

WPD: Methodology assessment and validation

Component manufacturing and test results (Deliv. DD.1-DD.4)
All three demonstrator components were manufactured and tested. This has resulted in probably the largest database of CFRP crash component testing there is. In total, 45 CFRP beams, 36 CFRP crash tubes and 30 hybrid beams were manufactured and tested. The test procedures, as well as the results are well-documented in Deliverable DD.4, and all the raw data is available to all project partners on the file server of the project. In the evaluation of the results, there are also detailed fractographic results which contain information on failure modes, amount of delamination in different tests etc.

This has naturally been a very important result for the model assessment made in the final part of the project, but these test results are also a very valuable outcome of the project in themselves as they can be used for future model development and validation. A significant part of the data has also been generated with the Uniweave NCF material, the data for which is fully open-access, which means that these test results can be shared with external research groups as well.

Evaluation of agreement between simulations and tests

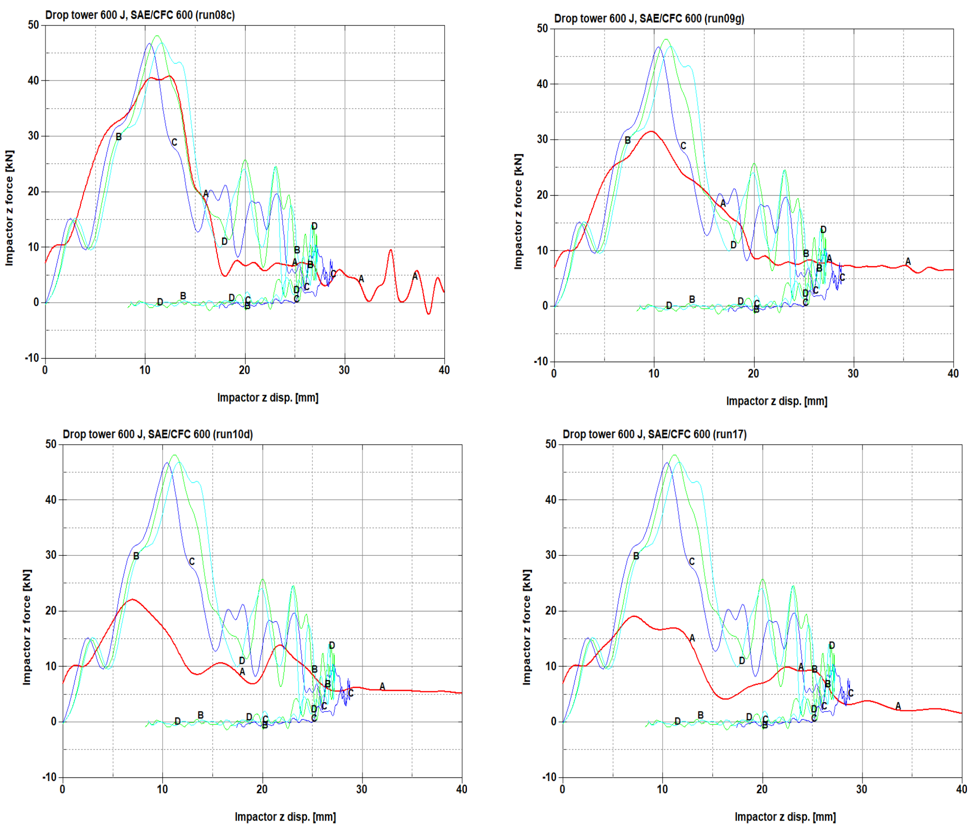
Assessment of damage model from WPB
The material model developed in WPB was assessed against a portion of the test results conduced in WPD. In the comparison with the CFRP beams, most of the work was focusing on the dynamic impact (impact energy 600J) of the UD pre-preg beam with a span length of 400 mm. The results show that the response obtained with the model using 3 elements through the thickness, see Figure 1 (left) below, is closest in agreement with the experimental results, even though this model also shows a bit too brittle results. Unfortunately, however, when refining the model (which should give higher accuracy), the

simulated results deviate more from the experimental results. This is explained by that more delamination can be allowed through the thickness of the simulation model, something which leads to a softer response. Interestingly, however, the extent of delamination growth in the plane of the beam corresponds very well with the observations made in the fractographic studies, see Figure 2. Still, the unexpected softening of the results upon a higher model resolution through the thickness is something that needs to be addressed in further research.

The comparisons for the CFRP tubes was made for the UD pre-preg tubes at different impact speeds and impact angles. All results are summarised in Deliverable DD.5. Unfortunately, the model results show a severe sensitivity to the type of element formulation used (both solid elements and continuum shell elements were compared). For some cases, the material model also shows unphysical behaviour, which is something that was not possible to explain by the time the project ended.

The comparisons between simulated and experimental results for the hybrid beams show that the additional stiffness provided by the CFRP patch is well captured also in the numerical model. However, the numerical model shows a lower maximum force compared to the experiments, again most likely explained by the fact that the simulations predicted more delamination and more separation between the steel beam and the CFRP patch than what is occurring experimentally. This is also confirmed by numerical results obtained when delaminations and steel-CFRP debonding are suppressed in the numerical model.

Finally, the damage model from WPB was also tested in a pole intrusion (of a door) load case at VCG, to assess how well the damage model works in larger simulation models. For the initial door model, the results obtained with the damage model developed in WPB corresponds much better with experimental observations, compared to existing models used in car projects at VCG. These results are very



promising. However, when a second numerical model was created, for which the model discretisation was changed such that the main mesh lines were oriented at 45 degrees compared to the first model, the simulated failure pattern changed significantly. This highlights a significant mesh dependency of the damage model, something which is also essential to address in further research.

Figure 1: Simulated and experimental force-displacement curves for the UD pre-preg CFRP beam with a span length of 400 mm and impacted with an impactor with energy 600J. Model results (in red) with 3, 6, 12, and 24 elements through the thickness (left to right), compared to experimentally measured results.

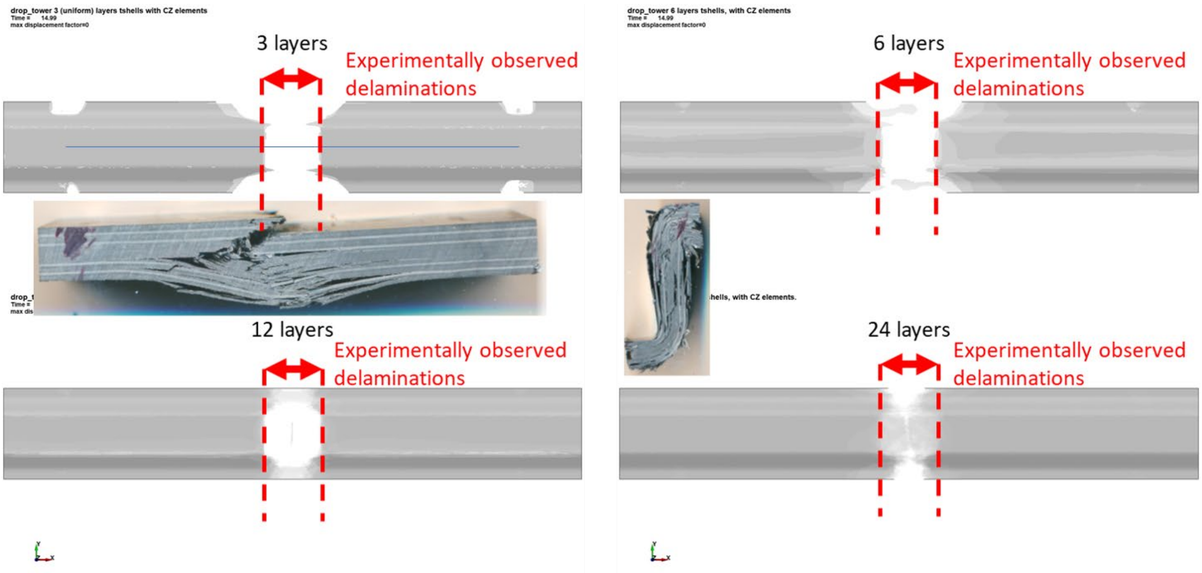


***Figure 2**: Simulated amount of in-plane delamination for the UD pre-preg CFRP beam with a span length of 400 mm and impacted with an impactor with energy 600J. Model results with 3, 6, 12, and 24 elements through the thickness (top left to bottom right) compared to experimentally measured in-plane delamination growth.*

Assessment of damage model developed in Digimat

In parallel to the developments in WPB, e-Xstream was implementing an alternative ply damage model based on the work by Maimí et al. [24], along with an alternative mixed-mode cohesive zone law following Turon et al. [25]. The results from simulations using these material models to simulate the impact response of the CFRP beam and the crushing response of the CFRP tube were compared with experimental results. The outcome of the comparison is summarised in Deliverable DD.5 [19]. In short it can be said that a similar trend of a too soft response was obtained also for these models, although in this case the discrepancy between simulated and experimental results was even larger than for the damage model developed in WPB.

Assessment of the adaptive shell modelling concept

Besides being successfully tested in a number of test cases, the developed adaptive shell model was also applied to the modelling of the CFRP beams. The numerical results are compared with the experimental results in Deliverable DD.5 [19]. On the positive side, the model is robust also for larger models like this. Surprisingly, however, the results obtained differ from the results obtained with the traditional finite element models with different levels of fidelity. This discrepancy remains to be investigated in further research.

6.2 Project goal fulfilment

Goal 1

The first goal for the project goals has been to develop an efficient CAE methodology for designing and assessing crashworthiness of vehicles with protective structures in structural composite materials. To meet this, an improved material model and an adaptive shell modelling concept has been developed. The material model proves to behave well in idealised load cases, and also competes well with other existing damage models, such as the one implemented in Digimat. However, remaining work to be done is to tackle its mesh sensitivity and robustness with respect to various element formulations

The adaptive shell model was implemented and verified against a number of test cases with very promising outcome. Unfortunately, however, the gain in simulation time was lower than initially expected.

Partly, this is explained by the fact that the adaptive concept had to be implemented in a proof-of-concept way as full access to the source code of LS-DYNA was not possible (and such an implementation would also have required much more resources). But the moderate efficiency gain is also explained by that a significant amount of the simulation time is spent on evaluating the material response at model integration points, and the amount of these points.

All in all, the project has taken significant steps towards a more accurate and efficient modelling of composite structures in crash, but there is also remaining research to be made before the models and methods developed in this project can be fully adopted in industry.

Goal 2:
The second goal of the project has been to develop a leading competence in Swedish industry on the design and crashworthiness assessment of crash-protective composite structures. The competence level on the modelling side has indeed been raised significantly among the industrial partners, mainly through the large investment in time put on modelling and simulating the component tests, and through the strong interaction during the assessment phase in WPD. However, as the CAE tools developed in this project are still not fully developed for industrial use, the component design aspect still requires more collaborative work.

Goal 3:
The third and final goal of the project was to establish a leading position on composites-related crash safety research in Europe. This has been achieved both through the arrangement of the first international workshop in crashworthiness of composites in 2018, but also through well-recognised journal publications, conference presentations and assignments as external reviewers at relevant international PhD defences.

6.3 Contribution to FFI goals

Active safety systems have the potential to reduce accidents and are currently penetrating the automotive industry at increasing speed. Nevertheless, the risk of accidents will still remain in a foreseeable future. Thus, we need to ensure improved passive crash safety also for future lightweight composite vehicles.

This project has therefore been well aligned with the national and international road maps on traffic safety and lightweight technology for the future. The development of CAE tools and methodologies for design of crashworthy composite components are emphasised in road maps from both FFI Traffic Safety and Automation [26] as well as from SAFER (Vehicle and Traffic Safety Centre at Chalmers) [27]. Similarly, ERTRAC Safety roadmap explicitly mentions predictive numerical simulation of the mechanical performances of new materials (such as composites) as a key area towards a 50% more efficient road transport system by 2030.

The current project has spanned several areas under FFI Traffic Safety and Automation, 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 developing the major elements of a crash simulation methodology, we have paved the way for 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 when fully developed 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 have actively contributed 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 have taken steps towards a much 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.

7 Dissemination

7.1 Knowledge and results dissemination

To avoid confusion by translation, the table below has been filled in Swedish

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	Nya, förbättrade modeller för att beskriva brottprocessen i kompositmaterial har utvecklats. Stark samverkan mellan akademiska och industriella parter har också lett till kompetensöverföring i båda riktningar viket stärkt den gemensamma kunskapen
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	Även om resultaten I mångt och mycket är lovande, så krävs fortsatta forskningsinsatser för att nå hela vägen till full industriell användning. Därför diskuteras nu en fortsättning på projektet med flertalet av de parter som ingått i konsortiet
Föras vidare till produktutvecklingsprojekt		Ej fullt moget ännu
Introduceras på marknaden		Ej moget ännu
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		Ej tillämpbart

7.2 Publications

The results of this project has been disseminated via one PhD thesis [20], publications in international scientific journals (4 published/accepted papers) and at conferences (6 published papers), and via presentations at international scientific conferences (14 presentations) and other meetings (e.g. at SAFER - Chalmers Vehicle and Traffic Safety Centre). All these are listed below:

PhD Thesis

Johannes Främby (2020) Methods for efficient modelling of progressive failure in laminated fibre-reinforced composites, *PhD Thesis at the Department of Industrial and Materials Science at Chalmers University of Technology*.

Journal papers

- Larsson R, Singh S, Olsson R, Marklund E (2020). A micromechanically based model for strain rate effects in unidirectional composites. *Mechanics of Materials*; paper 103491
- Främby, Fagerström and Karlsson (2020) An adaptive shell element for explicit dynamic analysis of failure in laminated composites Part 1: Adaptive kinematics and numerical implementation, *Engineering Fracture Mechanics*, paper 107288.

- Främby and Fagerström: An adaptive shell element for explicit dynamic analysis of failure in laminated composites Part 2: Progressive failure and model validation, Engineering Fracture Mechanics (accepted)
- Costa, S.; Fagerström, M.; Olsson, R. (2020). Development and validation of a finite deformation fibre kinking model for crushing of composites, *Composites Science and Technology*, Vol 197, paper:108236.

Conference papers

- Främby, Johannes; Fagerström, Martin; Brouzoulis, Jim: Modelling of progressive matrix cracking induced delaminations using an enriched shell element formulation, *In Proceedings of the 21st International Conference on Composite Materials*, 2017.
- S. Costa; M. Fagerström; R. Gutkin; R. Olsson: VALIDATION AND IMPROVEMENTS OF A MESOSCALE FINITE ELEMENT CONSTITUTIVE MODEL FOR FIBRE KINKING GROWTH. *In Proceedings of the18th European Conference on Composite Materials*, 2018.
- Östlund and Hedström: Press hardened B-pillar with CFRP patch, Simulation & Crash test, *Proc. 7th International Conference on HOT SHEET METAL FORMING OF HIGH-PERFORMANCE STEEL*, Luleå, Sweden 2019.
- Främby, Johannes; Fagerström, Martin; Karlsson, Jesper: AN ADAPTIVE METHODOLOGY FOR EFFICIENT MODELLING OF ARBITRARY DELAMINATIONS DURING CRASH SIMULATIONS*. In Proceedings of the Twenty-second International Conference on Composite Materials*, 2019.
- Singh V, Larsson R, Marklund E, Olsson R (2019). Effect of strain rate at compressive and tensile loading of unidirectional plies in structural composites. *Proc. 7th ECCOMAS Thematic Conf on the Mechanical Response of Composites*. Girona, Spain:177-183.
- Främby, Karlsson and Fagerström: An adaptive thick shell element for crashworthiness assessment of laminated composites. *Proc. 16th International LS-DYNA® Users Conference*, 2020.

Additional conference presentations

- Främby, Johannes; Fagerström, Martin; Brouzoulis, Jim: Prediction of matrix induced delaminations using an enriched shell element approach, *In Proceedings of the 6th ECCOMAS Thematic Conference on the Mechanical Response of Composites,* 2017.
- Fagerström et al.: Computationally efficient modelling of failure in laminated composites by utilising adaptive shell elements, *LIGHTer International Conference*, 22 Nov 2017, Göteborg, Sweden.
- Landervik: Swedish research project: Modelling crash behaviour in future lightweight composite vehicles, *Proc. Information Day ENVYO and Composite Analysis*, 2018.
- Olsson R. "Crash modelling and experiments at Swerea SICOMP". Workshop on crash behaviour of composites. Chalmers University of Technology (Sweden), 13 - 14 Sept 2018.
- Fagerström, Främby, Oddy, Brouzoulis, Costa: Crash modelling at Chalmers and in Swedish crash projects. Workshop on crash behaviour of composites. Chalmers University of Technology (Sweden), 13 - 14 Sept 2018.
- Främby, Johannes; Fagerström, Martin; Molker, Henrik: Element-Local Stress Recovery In Linear Shells *In Proceedings of the Seventh ECCOMAS Thematic Conference on the Mechanical Response of Composites: COMPOSITES 2019*, 2019.
- Singh V, Larsson R, Marklund E, Olsson R. "Strain rate dependency of unidirectional composite plies in compressive loading". 1st European Conference on Crashworthiness of Composite Structures – ECCCS-1. Queen's University Belfast, 19-21st November 2019.
- M. Fagerström, J. Främby, S. Costa, R. Olsson, J. Karlsson, F. Edgren and G. Petersson: MODELLING AND TESTING THE CRASH BEHAVIOUR OF COMPOSITE VEHICLES COMPONENTS. 1st European Conference on Crashworthiness of Composite Structures – ECCCS-1. Queen's University Belfast, 19-21st November 2019.

8 Conclusions and further research

An improved material model and an adaptive shell modelling concept has been developed in this project. The material model proves to behave well in idealised load cases, and also competes well with other existing damage models, such as the one implemented in Digimat. However, remaining research that needs to be conducted should address the model mesh sensitivity and robustness with respect to various element formulations. It should also be considered to add the more advanced kinking model developed by RISE in collaboration with Chalmers in a parallel project.

The adaptive shell model was implemented and verified against a number of test cases with very promising outcome. Unfortunately, however, the gain in simulation time was lower than initially expected. Partly, this is explained by the fact that the adaptive concept had to be implemented in a proof-of-concept way as full access to the source code of LS-DYNA was not possible (and such an implementation would also have required much more resources). But the moderate efficiency gain is also explained by that a significant amount of the simulation time is spent on evaluating the material response at model integration points, and the amount of these points.

All in all, the project has taken significant steps towards a more accurate and efficient modelling of composite structures in crash, but there is also remaining research to be made before the models and methods developed in this project can be fully adopted in industry. This needs further research and extensive collaboration between academia and industry

The project has also led to a raise of competence level when it comes to the industrial modelling of composite structures in crash, mainly through the large investment in time put on modelling and simulating the component tests, and through the strong interaction during the assessment phase

Through the project, the consortium has established a leading position on composites-related crash safety research in Europe. This has been achieved both through the arrangement of the first international workshop in crashworthiness of composites in 2018, but also through well-recognised journal publications, conference presentations and assignments as external reviewers at relevant international PhD defences.

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