THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN SOLID AND STRUCTURAL MECHANICS

On efficient modelling of progressive damage in composite laminates using an equivalent single-layer approach

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Abstract

In order to reduce the weight and subsequently the fuel consumption of their vehicles, the automotive industry is currently very active in research to incorporate laminated composites of Carbon Fibre Reinforced Plastics (CFRP) into structural components. This effort is a reaction to the increasing demands from regulatory bodies aimed at reducing the CO_2 emissions from the transportation sector.

Historically composite materials have mainly been used in the aerospace industry, whereby CAE-based design and development tools for composite structures have been developed primarily to the specific needs and requirements in this industry. Even if many of the methodologies used to develop aerospace composite structures are directly transferable to the automotive industry, the assessment of crashworthiness of automotive vehicles has no clear equivalence within aerospace. Thus, it is crucial to develop numerical tools which are able to asses the crashworthiness performance of vehicles made of composite materials. However, in order to be usable in the automotive product development process these tools must be both computationally efficient and be able to make an accurate prediction of the crash response. For an accurate prediction, predominant failure mechanisms such as delaminations must be captured by the simulation models.

In this thesis, we will present a route towards full scale vehicle crash simulations based on a computationally efficient adaptive methodology. To model the delamination propagation in the laminates, we propose an equivalent single-layer (ESL) shell formulation with adaptively refined delamination enrichments using the eXtended Finite Element Method (XFEM). By combining the proposed formulation with a stress recovery technique, we can increase the accuracy of the transverse stress distributions of the shell model, and thus the prediction of delaminations. In this way, we balance the delicate issues of model accuracy and efficiency in the context of progressive delamination failure analyses in laminated composites.

The work presented in this thesis lays the ground work for achieving computationally efficient and accurate predictions of the crashworthiness performance of composite components in simulations. This is an absolute requirement in the automotive development process today if these materials are to be have a widespread use in future automotive vehicles.

Keywords: CFRP, crash simulation, XFEM, adaptive delamination modelling

to Anna and Rio

Preface

After finishing my Master's degree at Chalmers I was eager to get to work as a CAE-engineer. This despite knowing that my thirst for knowledge and perfectionist personality probably would be better of in academia. Two years in, I (by chance) attended a meeting where the idea for a research project was discussed. The project combined my interest for crash simulations and composite materials. Well, not being ready to go back to school I merely watched the process to get funding from the outside. However this process took some time. So much time that I during that I realised that I needed to be one of the intended PhD students performing the research. Now six years after leaving Chalmers I'm back, ready to have my half time[1] seminar.

I am glad that I was accepted to be a part (and accepted to take a leave of absence from ÅF) of this research project called *Modelling crash behaviour in future lightweight composite vehicles — Step 1.* It is funded by the Swedish Strategic Vehicle Research and Innovation Programme on Vehicle and Traffic Safety and co-funded by the industrial partners, which is gratefully acknowledged. The work has been carried out between October 2013 and May 2016 at the Division of Material and Computational Mechanics at Chalmers University of Technology.

I would like to thank my supervisors Associate Professor Martin Fagerström, Dr Jim Brouzoulis and Professor Ragnar Larsson for their support and guidance on my path through the academic jungle. I especially owe the deepest gratitude to Jim who has had to endure my demanding questions every now and then. Also the colleagues at both Chalmers and and Swerea SICOMP deserve a great thanks. Finally, I want to express my love to Anna (the girlfriend) and Rio (the dog) for supporting me in this endurance.

Gothenburg, April 2016
Johannes Främby

[1]Well ok, licentiate, even though no other than people with licentiate degrees seem to know what it is.

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	Johannes Främby, Jim Brouzoulis and Martin Fagerström. Assessment of two methods for the accurate prediction of transverse stress distributions in laminates. *Composite Structures*, 140:602-611, doi: 10.1016/j.compstruct.2015.12.036. Reprinted with permission.
Paper B	Johannes Främby, Martin Fagerström and Jim Brouzoulis. Adaptive modelling of delamination initiation and propagation using an equivalent single-layer shell approach. *To be submitted*

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work, *i.e.* planning, developing theory, making the numerical implementations, performing simulations and writing of the papers, all with the assistance of the co-authors.

Contents

Part I
Extended Summary

1 Introduction

In the 2011 European Union White Paper on transport it is stated that the CO_2 emissions from the transportation sector shall be reduced by 60 % in 2050 compared to 1990. This type of statement is part of a global trend where the emissions of green house gases from transportation are being targeted by regulatory bodies. Since the emission of CO_2 is directly linked to the fuel consumption, decreasing fuel consumption is crucial.

An important factor for the vehicle fuel consumption is the weight of the vehicle. In the investigation by Park *et al.* [1] it was reported that an estimate of 75 % of the fuel consumption of a passenger car can be directly related to its weight and that a 6-8 % increase in fuel economy can be realized for every 10 % reduction in vehicle weight.

The relationship between weight and emissions can also be found in the regulations on emissions. For example, Figure 1.1 shows the EU legislation for CO_2 emissions from European passenger cars, where the target emissions are related to vehicle weight such that a car of average weight should emit no more than 95 gCO_2/km from the year 2021. In the case of electric vehicles, the driving range is closely related to weight, especially for urban cars where the driving cycle includes many accelerations and decelerations. Thus low vehicle weight is equally important for these types of vehicle.

Park *et al.* [1] also concluded that replacing steel materials in structural components with plastic, Fibre Reinforced Plastic (FRPs) and especially laminated composites of continuous Carbon Fibre Reinforced Plastics (CFRP) have the potential of effectively reducing the weight of vehicles. This is due to the high specific stiffness and strength of these materials (stiffness and strength per unit weight), which is illustrated in Figure 1.2. Similarly, in the report by Heuss *et al.* [2] it was estimated that CFRP has the potential of reducing the weight of vehicles by 50 % compared to steel and that the emission reductions from improving the drivetrain efficiency will not alone be sufficient in order to fulfil regulatory demands past 2021. It should also be mentioned that the reduction of the structural mass can result in secondary savings, *e.g.* smaller power-train, brakes, *etc.*

Driven by these conditions, the automotive industry is currently very active in research to incorporate composite materials like CFRP into structural components, in order to reduce the weight of their vehicle fleet.

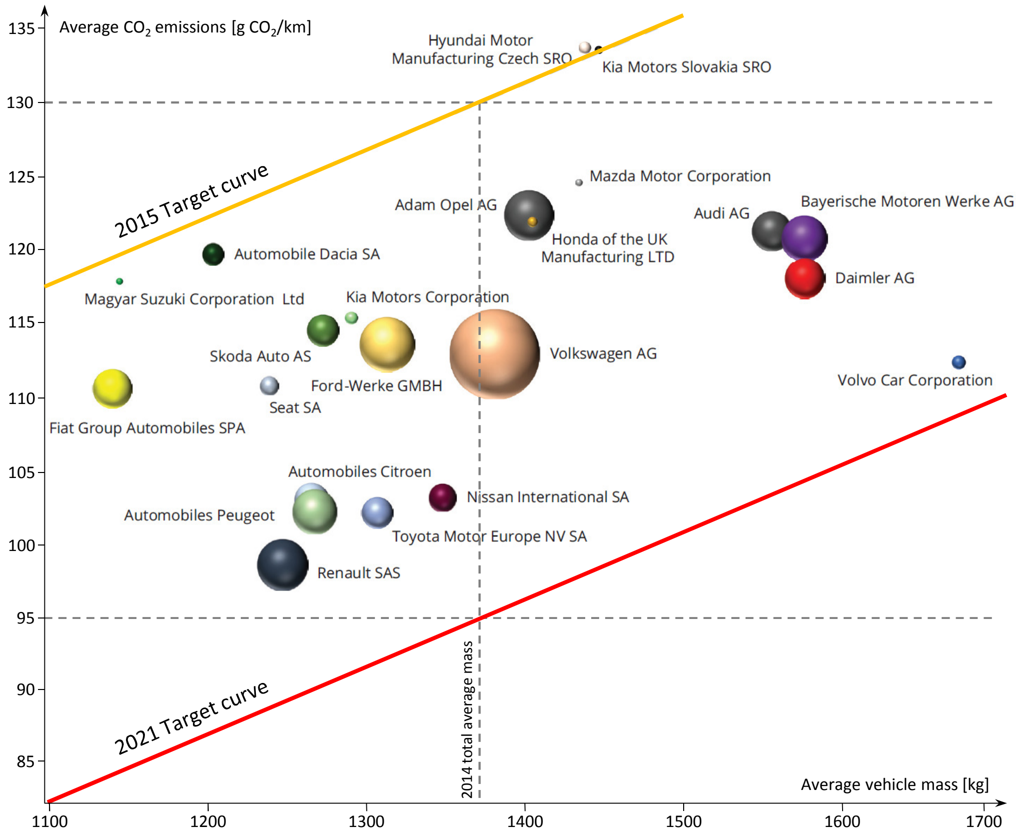


Figure 1.1: Average emission (per km) versus vehicle mass (only manufacturers with > 100,000 new vehicles registered) compared to EU 2015 and 2021 emission targets (based on the 2014 average vehicle mass). The size of the bubble is proportional to the number of new vehicles registered in the EU-28 in 2014. For reasons of scale, data for Jaguar Land Rover Limited is not shown on the chart (its average mass is 2044 kg and its average CO_2 emissions are 165 gCO_2/km). Adapted from EEA techical report 16/2015 [3].

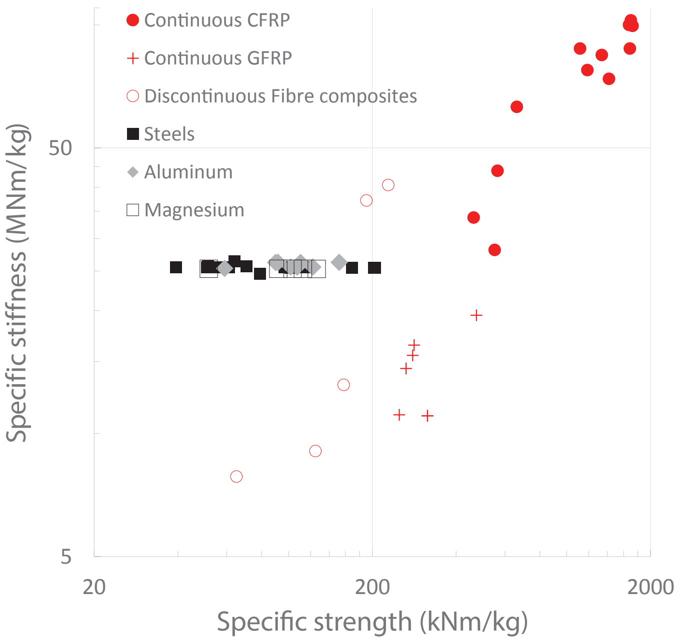


Figure 1.2: Chart over specific stiffness and specific strength for different material groups. *NB:* logarithmic scale. © 2016 Henrik Molker. Reprinted with permission from thesis by Molker [4].

2 Challenges for introducing composites in automotive structures

Compared to traditional materials used in the automotive industry, *e.g.* advanced steels of different grades and light-weight metals such as aluminium and magnesium, the cost of raw material to construct composite structures is very high. Besides this, the production of these materials require long manufacturing cycles and the cost of manufacturing a part made from CFRP can be 570 % to that of the steel version [2]. Therefore composite materials have historically mainly been used where the price per saved kilogram is high, *i.e.* the aerospace industry but also in sport applications or high-end consumer products. This has led to computer aided engineering (CAE) based design and development tools for creating composite structures tailored to the specific needs and requirements in the design of aerospace structures.

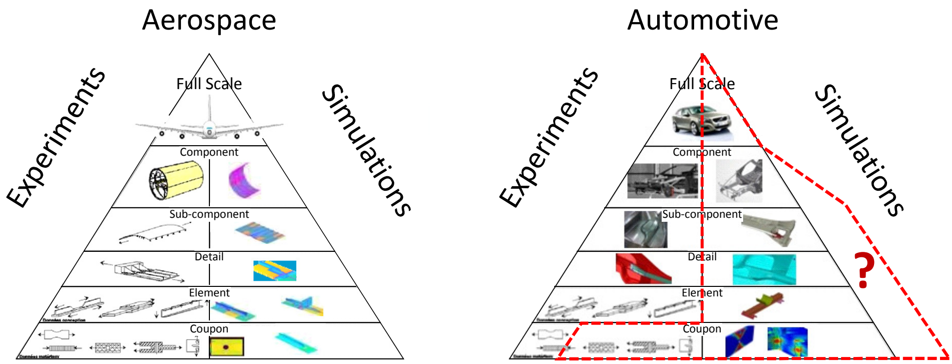
Within the aerospace industry a building block approach is used to ensure that secondary loads, associated with the many potential failure modes in composite materials, are not critical for the design. This approach relies heavily on validation test on different structural scales: material coupon, element, detail, subcomponent and component levels, as illustrated in Figure 2.1a. Development using this approach is therefore very costly and time consuming.

On the contrary, the development of automotive vehicles today is almost exclusively driven by CAE, and especially using numerical finite element (FE) tools. Basically the only experimental testing performed (besides the full vehicle crash tests like the NCAPs) is on or close to the material coupon level, from which data is used to define the properties of material models used in simulations further up the scale. If composite materials are to become wide spread in automotive vehicle structures the product development process of such components needs to be in line with that of the automotive industry. This is illustrated in Figure 2.1b, where it is indicated that the development of composite automotive structures can only rely on a limited amount of physical testing performed only on the material scale.

2.1 Particular needs in the automotive industry

Even if many of the methodologies used to develop aerospace composite structures are directly transferable to the automotive industry, the assessment of crashworthiness of automotive vehicles has no clear equivalence within aerospace. The design of aerospace structures is generally made in relation to the initiation of failure and not to the subsequent progression, a phenomenon which needs to be captured in crash simulations. An effect of using design methods from aerospace in the design of automotive vehicles can be observed when examining modern passenger cars made of composite materials, as exemplified in Figure 2.2. Here the main passenger protection compartment, which is designed to be stiff and prevent intrusion in the event of a crash, is made of composite materials, while the crash absorbing structures are typically made from metal.

The split CFRP/metal design is a consequence of the lack of numerical FE tools



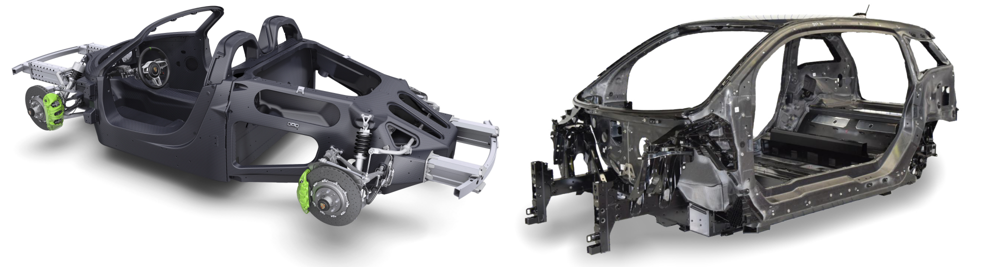
(a) (b)

Figure 2.1: Rouchon's pyramid of test for the development of composite structures in (a) the aerospace industry and translated to (b) the automotive industry, where the red line indicates the ambition to perform limited amount of physical testing only on the material scale and perform (additional) simulations on superior levels, including full scale. Adapted from [5] and [6].

capable of assessing the crashworthiness performance of composite materials and not because these materials are inappropriate to use in crash protection structures. On the contrary, as concluded by *e.g.* Hamada *et al.* [7], composite materials can show superior specific energy absorption, which in axial compression can be higher or significantly higher compared to aluminium and steel grades normally used in crash structures.

It has been shown, cf. *e.g.* Hull [8] and Grauers *et al.* [9], that this beneficial material characteristic is the consequence of a very complicated fracture process in the material, involving many competing failure mechanisms, *e.g.* fibre kinking (and breaking) in compression, compressive matrix failure and significant (mixed-mode) delamination, which is illustrated by an example in Figure 2.3. Most of these failure modes are not present in the failure of metal structures, which is why these characteristics cannot be captured with existing FE models intended for crash simulations of metallic structures. The challenges in developing models which are appropriate for performing crash simulations of automotive composite structures are indeed many and complex and will be the topic of the next section.

We end this section by referring to the EU report European Roadmap to Safe Road Transport [10], where they conclude that the development of FE tools for the accurate prediction of the crash response of vehicle structures in laminated composites are crucial for structural composites to have a widespread use in future automotive vehicles.



(a) (b)

Figure 2.2: Examples of body structures with a CFRP main passenger compartment and metal front and rear crash protection structures in (a) the Porsche 918 Spyder [11] © 2016 Porsche Cars North America and (b) the BMW i3 © 2015 FKA.

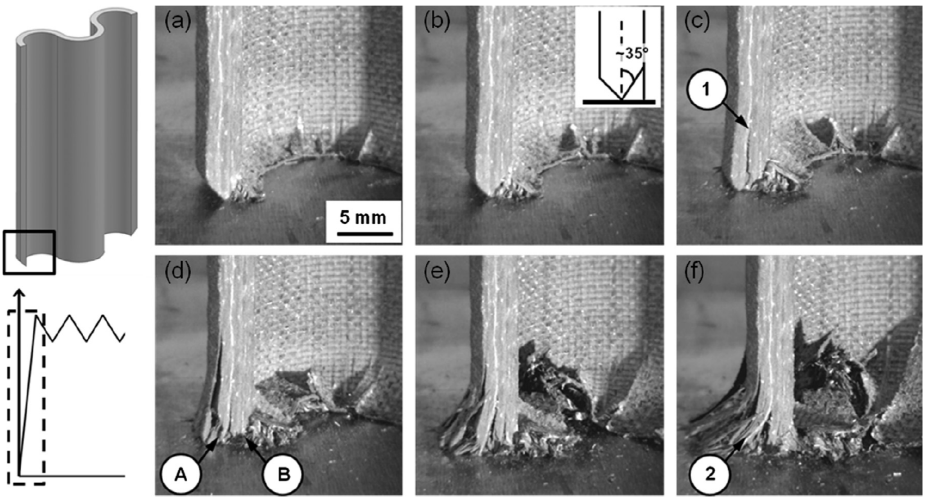


Figure 2.3: Example from [9] on crushing of laminated composites; including bending of plies Ⓐ, compressive failure Ⓑ, delamination in mode I ① and in mixed mode ②. The upper left image illustrates the test geometry and the location of the specimen in (a-f). The lower left image illustrates the corresponding location in a typical force versus displacement curve. © 2013 Elsevier Ltd. Reprinted with permission.

3 Research challenges for crash modelling of composites

The experimental example in Figure 2.3 illustrates the many competing failure mechanisms active during crushing of laminated composites. The crushing zone is schematically illustrated in Figure 3.1, where the bending and compressive failure modes on the laminate scale are the results of a combination of different intralaminar failure modes on the ply scale.

The ply scale failure modes are associated with the anisotropic and heterogeneous architecture of the composite layers, which for unidirectional (UD) composites can generally be divided into two major categories:

- Longitudinal failure modes occurs from loads mainly parallel to the fibres:
  - Tensile failure (Figure 3.2a) – most of the load is carried by the fibres up to the strength of these followed by catastrophic failure;
  - Compressive failure (Figure 3.2b) – likely the most complex failure mode due to shear failure of the matrix and friction between crack surfaces with subsequent finite rotation the fibres in so-called kink bands.
- Transverse failure modes occurs from loads mainly perpendicular to the fibres:
  - Tensile failure (Figure 3.2c) – stress concentrations in the matrix material around fibre inclusions lead to low failure strength in this mode;
  - Compressive failure (Figure 3.2d) – complex failure mode involving shearing of the matrix and friction between crack surfaces.

In addition, when stacking plies (of composite material) in a laminate, the interfaces between the plies can be the origin of interlaminar failure, *i.e.* delamination. This problem is pronounced if there is an difference between fibre angles of adjacent plies, which is almost always the case in laminated structures.

Interlaminar crack growth can be classified according to the direction of the load with respect to the crack front, as illustrated in Figure 3.3. In most cases it is difficult to define the in-plane orientation of the crack front, making it impossible to distinguish between mode II and III growth. Therefore a common practise is to treat mode II and III crack growth as one and the same shearing mode.

In the progressive failure of composites, microscopic intra- and interlaminar failure can easily lead to failure on the laminate level, which is why all of the above mentioned failure modes must be taken into account when simulating crash in composites. However, as mentioned previously, since intra- and interlaminar failure modes are not present in the failure of metals, they cannot be captured using existing material models intended for crash simulations of metallic structures. Furthermore the material models that are in-fact developed for crash analysis of composite materials are often sensitive to model parameters or include non-physical, *e.g.* curve-fitting, parameters, cf. *e.g.* Feraboli [13].

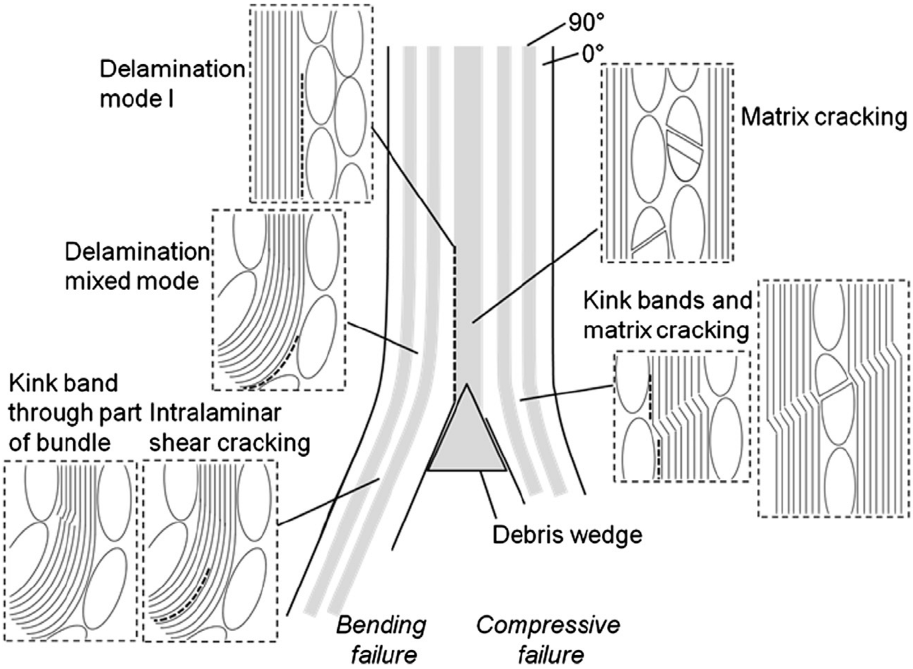


Figure 3.1: Schematic illustration of a crushing zone in a laminated composite from [9]. The failure includes both bending and crushing failure on the laminate scale as well as inter- and intralaminar failure on the ply scale. © 2013 Elsevier Ltd. Reprinted with permission.

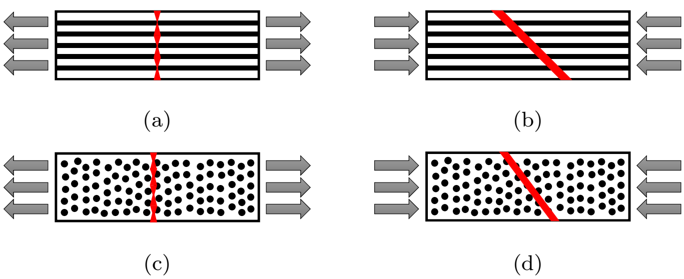


Figure 3.2: Longitudinal (a) tensile and (b) compressive failure and transverse (c) tensile and (d) compressive failure in UD composites.

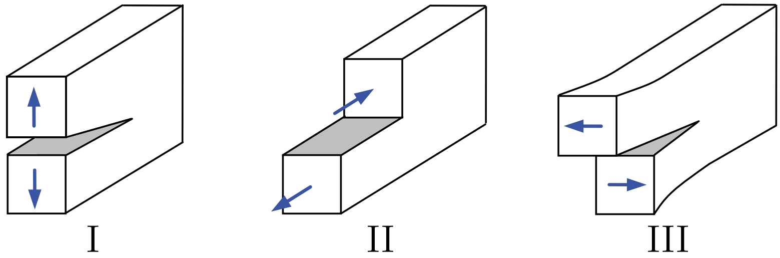


Figure 3.3: Schematic illustrations of crack growth in (I) peeling (II) shearing and (III) tearing mode, from [12]. © 2008 Elsevier Ltd. Reprinted with permission.

To complicate the problem further, when assessing the crashworthiness performance of automotive vehicles, the crash simulations must to a large extent be performed on large FE models of the full scale vehicle. Even considering state-of-the-art simulations, when most of the structure is modelled using equivalent single-layer (ESL) shell elements, the number of elements are in the order of millions. This in combination with the long time frame that needs to be simulated (typically in the range of 100-300 ms) means that crash simulations are solved using large computer clusters, where there is a practical limit on how many computer cores the simulation can be split to. Thus there is a requirement to keep the size of the FE models limited - preferably such that the CAE-engineer can have the results from a crash simulation over night.

Even if using a ply material model that can take all the intralaminar failure modes into account, ESL shell elements are not able to describe the kinematics of delamination crack growth. This means that one of the governing failure mechanism, in the sense that propagating delaminations significantly influence the overall deformation pattern and thereby, indirectly, the occurrence of the other failure mechanisms, is not accounted for, cf. Grauers *et al.* [9]. It is therefore clear that in order to achieve accurate predictions of the crashworthiness performance of laminated composites in simulations, the delamination process needs to be explicitly accounted for in an accurate way without compromising the computational efficiency too much.

The numerical approaches to modelling delaminations in crash simulations can generally be divided into two categories where the focus is on either efficiency *or* accuracy[1]. With focus on efficiency, ESL models with one element through the thickness (cf. Figure 3.4a) are used together with phenomenological material models which are not based on the physical mechanisms but rather mimicking the total failure process including the effects of delamination, cf. *e.g.* Feraboli [13]. With more focus on accuracy, layerwise (LW) models are adopted. In these the laminate is modelled with many elements through the thickness, up to a degree where the individual plies are represented by separate elements (cf. Figure 3.4b), having the interfaces modelled by means of an interface cohesive law in the form of interface elements or similar, cf. *e.g.* Tan *et al.* [16] or Greve and Pickett [17]. Although this approach is able to accurately describe the failure process in laminated composites, it is due to substantial computational cost infeasible to use for full scale crash

[1]We acknowledge that this is in no way an exhaustive description on the subject of modelling laminated structures and refer to the reviews by Carrera [14], Orifici etal [12] or Kreja [15] for further reading.

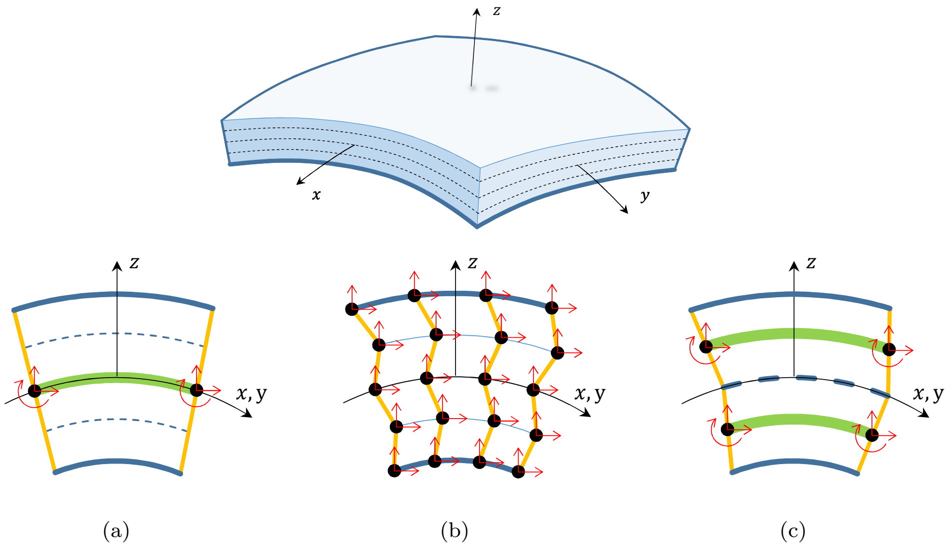


Figure 3.4: Examples of modelling approaches for laminated composites: (a) ESL model where the kinematics of the entire laminate are represented as degrees of freedom on a mid-surface (green line) having delaminations accounted for by using phenomenological material models; (b) LW model where each ply is represented by separate degrees of freedom and interconnected by cohesive laws; (c) A combination of using ESL (or LW) models to represent sub-laminates and interconnect these with cohesive laws at one or a few chosen interfaces.

simulations.

A third option is therefore the combination of the two where sub-laminates are modelled with separate elements (cf. Figure 3.4c), which are connected by cohesive interface laws, cf. *e.g.* Hörmann and Wacker [18] (one delamination) or Bussadori *et al.*[19] (2-4 delaminations). However, this approach will then make *a priori* assumptions on which interfaces that will be able to delaminate during simulations and can not be truly predictive for the general case.

A major research challenge for crash failure analysis of laminated composites is thereby to find a modelling approach which is both sufficiently accurate in predicting the structural response *and* computationally efficient – a challenge addressed in this research.

3.1 Research scope

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 in this research is to maintain the numerically efficient ESL shell formulation and refine this by local extension of the element formulation, when the damage state no longer can be represented by the simplified ESL model. We will therefore continue the work by Brouzoulis and Fagerström [20] where they use the eXtended Finite Element Method (XFEM) [21, 22] to enable mesh independent representation of arbitrary delaminations by introducing kinematic enrichments locally in the vicinity of propagating delaminations. This way, the increased computational cost, associated with the analysis of progressive damage in laminated composites, is limited both with respect to time frames and to the pertinent areas of the FE model.

In order to predict the areas in need of refinement an accurate prediction of the delamination driving transverse (out-of-plane) stress components must be made. However, a known drawback of traditional ESL shell element formulations is the low accuracy of the predicted transverse stress components [23]. In this thesis we will therefore address the following challenges:

1. Develop a technique to improve the prediction of stress components in equivalent single-layer shell models;

2. Develop an adaptive technique, which locally can describe delamination failure using local extension of the FE element formulation.

We acknowledge that this thesis only address the issue of effectively modelling delaminating composite structures, while problems like physically based ply material models are not covered. However, the current work is part of a larger project which also addresses other aspects in the development of suitable crash simulations models. A brief overview of this project will be given in the Subsection below.

3.2 Research project

The research discussed in this thesis is part of the project *Modelling crash behaviour in future lightweight composite vehicles — Step 1.* The goal of the research is to develop computational efficient numerical FE tools for the accurate prediction of the crash response of composite structures. The project is split into four work packages, as illustrated in Figure 3.5, where the main research is conducted by two PhD students in work packages A and B respectively:

A Development of physically based constitutive models for the modelling of progressive damage in composite plies;

B Development of numerically efficient FE models which can describe the kinematics of progressively failing laminated composites.

In this thesis we will focus on work package B and in the next chapter we will present the main challenges and developments.

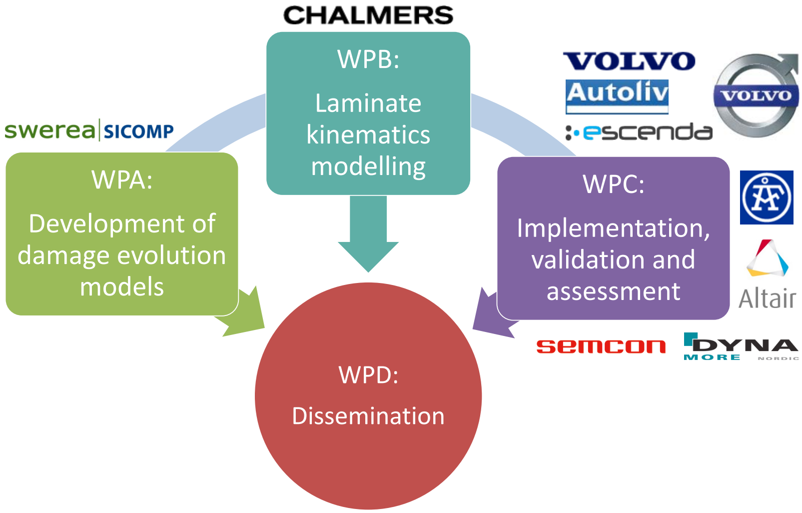


Figure 3.5: Schematic illustration over the work packages in the research project *Modelling crash behaviour in future lightweight composite vehicles — Step 1*.

4 Proposed methodology for failure modelling of composite laminates

The challenges addressed in the current research was summarised in the research scope (Subsection 3.1) as: Improvement of the prediction of stress components in ESL shell models and development of an adaptive methodology which is able to locally refine the model. We therefore propose a methodology involving the following steps:

1. The laminated structure is built up by a single layer of shell elements through the thickness;
2. The interlaminar transverse stresses, calculated using a stress recovery technique, are used in an interlaminar failure criterion in order to predict delaminations;
3. In predicted critical areas the model is then locally refined by inserting delamination enrichments and associated cohesive zone models;
4. If the initiated delaminations propagate, the enrichments are expanded such that the fracture process can be accurately resolved.

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.

Details regarding the research leading to the proposed methodology can be found in the two papers appended to this thesis. In the sections below we will give a summary of the work performed and the main conclusions drawn therein.

4.1 Improvement of prediction of transverse stress distributions in equivalent single-layer shell models - Paper A

Due to its computational efficiency we have chosen to adopt a solid-like ESL shell formulation. This is based on first-order shear deformation theory (FSDT) with a second-order expansion of the deformed configuration in the normal direction, leading to a 7-parameter displacement formulation. In Paper A, we address the potential of two different concepts for obtaining better prediction of the through-the-thickness distribution of the transverse stresses; a crucial issue since the accuracy for a single-layer approach in this respect is normally low.

First, we have investigated the potential of using a multiscale approach as a possible remedy to the problem. A long term idea of adopting such an approach is to enable a model-adaptivity procedure, cf. *e.g.* Oden and Vemaganti [24], 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 [25] for simulating deformations of thin-walled porous structures by coupling the macroscopic shell model to a mesoscopic 3D element representation of the heterogeneous material structure. Due to their promising results, our intention in Paper A 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 presented in Paper A is however that, the concept proposed in [25] is not a suitable approach to increase the level of accuracy of the predicted transverse stress distributions.

The reason is because the average deformation is not guaranteed across the scales, even though energy equivalence is maintained. We believe this to be an interesting finding since similar boundary conditions have been adopted also by other authors, although normally with in-plane Periodic Boundary Conditions (PBCs), cf. [26, 27, 28]. We emphasise however that not even in the case of PCBs, deformation equivalence across the scales can be guaranteed. The consequences of this are uncertain since the mentioned papers do not discuss *e.g.* transverse shear or the effect of a varying RVE-size.

As an alternative method, we have identified a suitable, and seemingly robust, post-processing procedure which allows accurate predictions of the transverse stress distribution to be made. This procedure is based on a nodal recovery of the in-plane stress components, averaged over neighbouring elements, followed by an integration of the transverse stress components using the 3D equilibrium equations. The stress recovery method is computationally inexpensive, and if the only goal is to improve the prediction of the transverse stresses in analyses of laminated composites, we conclude it to be more suitable compared to a multiscale approach.

4.2 Adaptive modelling of delamination in an equivalent single-layer shell formulation - Paper B

In Paper B we continue the work from Paper A by further developing the stress recovery method. Instead of a nodal recovery of the in-plane stress components, we approximate the in-plane derivatives of the in-plane stress using a polynomial fit to the stress values in the integration points. The recovered transverse stresses are then used to locate critical areas where the adopted ESL shell formulation should be locally refined, by local extension of the formulation, such that the kinematics of delamination can be captured.

Furthermore, In Paper B we propose the four step methodology presented in the beginning of this chapter. The focus of the paper is on the parameters associated with identifying, introducing and extending the enrichment areas; especially on the impact of these parameters on the resulting deformation behaviour in structural problems.

We can conclude that the delamination enrichment must be large enough to allow the fracture process to be accurately resolved and thus propose a suitable size to achieve this. Besides this, the size of the enrichment must be large enough to facilitate a long enough delamination propagation in each load step.

The methodology is based on the approach by Brouzoulis and Fagerström [20] where an ESL shell model is enriched using the XFEM. However, we emphasise that the concept is general and can easily be applied to other element formulations and refinement methods, *e.g.* the phantom node [29] or the floating node [30] and even methods based on isogeometric analyses [31].

The proposed methodology is very computationally efficient because the number of active enrichments during the simulation is limited, both with respect to to time and location. Even for small problems where all interfaces finally become enriched, close to 50 % computational time is saved compared to the case where all interfaces are enrichments during the entire simulation.

5 Conclusions and outlook

If structural composites are to become common in future automotive vehicles it is crucial to develop FE tools which are both computationally efficient and can accurately predict the crash response of vehicle structures made from laminated composites. To be able to make an accurate prediction, important failure modes such as delaminations must be captured by the simulation models.

In this thesis we have presented an adaptive methodology which achieves this in a computationally efficient way such that full scale vehicle crash simulations may become feasible. The methodology is based on a numerically efficient ESL shell formulation, which is adaptively refined with delamination enrichments using the XFEM when the damage state no longer can be represented by the simplified ESL model. This way, the increased computational cost, associated with the analysis of progressive delamination failure in laminated composites, is limited both with respect to time frames and to the pertinent areas of the FE model.

Ahead we will combine the methodology with a constitutive model which is able to 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.

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