THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

in

Solid and Structural Mechanics

Failure prediction of orthotropic Non-Crimp Fabric reinforced composite materials

HENRIK MOLKER

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2016

Failure prediction of orthotropic Non-Crimp Fabric reinforced composite materials
HENRIK MOLKER

THESIS FOR LICENTIATE OF ENGINEERING no 2016:02
ISSN 1652-8565

Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31 772 1000

Cover:
Predicted failure initiation with proposed failure criteria. Fore more details, see chapter 5.

Chalmers Reproservice
Gothenburg, Sweden 2016

Failure prediction of orthotropic Non-Crimp Fabric reinforced composite materials
Thesis for the degree of licentiate of engineering in solid and structural mechanics
HENRIK MOLKER
Department of Applied Mechanics
Chalmers University of Technology

Abstract

The automotive industry needs to reduce the energy consumption to decrease the impact on the environment. One part of this is to reduce the weight of cars, thereby reducing the fuel consumption. A promising way to be successful with this is to introduce carbon fibre composites in the structural parts. This as carbon fibre composites have outstanding properties. However, design of cars are made in a virtual environment while composite designs are today made using guidelines that require large amounts of testing.

The automotive industry needs an efficient design methodology for carbon fibre composite structures that can be used in the virtual development. In addition to this, the automotive industry needs new material systems and production methods to be able to produce in large scale at a profitable cost.

In this thesis, the basis for a design methodology for composite structures within the automotive industry is given. A methodology that uses numerical models at multiple scales is proposed. Assessing failure on full scale models cannot be done as analysis of composite structures needs to be done with more detailed models due to the different failure mechanisms. An approach with global models for screening for critical locations and local higher fidelity models for verification is outlined.

The first step in the methodology is to find accurate failure modes for the intended material systems. A strong candidate material for the automotive industry is Non Crimp-Fabric (NCF) reinforced composites. Compared to Uni-Directional (UD) reinforced composite materials, NCFs have been found not to be transversely isotropic but orthotropic. This is valid for both stiffness and strength. Current state-of-the-art failure criteria are based on the assumption of transverse isotropy. In this thesis and the appended papers a set of criteria for assessing failure initiation of NCF reinforced composites are proposed. The proposed failure criteria are compared and verified against data from literature and numerical models. It have also been implemented into a commercial finite element code and verified against physical testing.

Keywords: Design methodology; Carbon fibre composite; Non crimp-fabric; Failure initiation; Orthotropic

Preface

During 10 years of work within finite element simulations there has always been a thought about the possibilities of doing a PhD. From time to time more pronounced. However, as time goes by life changes and one gets more settled in.

Who figured that my wife, by chance, would find a job advert with the title ”*Industrial Ph.D. Candidate - CAE for composite structures*”. – Does not this include all the key and buzz words that you have mentioned from time to time? And frankly, it did. Together with the fact that it was in the city that we recently moved back to made the choice even easier. Now, half way through, I am very happy to have gotten this opportunity.

This project is funded by the Volvo Industrial PhD Program (VIPP) and the Swedish Research Council (VR) 2012-4320, whose financial supports are greatly acknowledged. The work has been carried out at Volvo Car Corporation in Gothenburg with weekly visits at Swerea Sicomp AB in Mölndal and Chalmers University of Technology in Gothenburg.

Without the guidance and support from my supervisors Prof. Leif Asp and Dr. Renuad Gutkin the work would not have been as successful has it has been. Leif for painting the background and large structures of composites on my composite picture with the big airbrush and Renaud for clarifying things with the fine brush and for highlighting the details. Together I think that we have accomplished a nice piece of work. Also thank you to Dr. Magnus Oldenbo who initiated this project at VCC and made all the hard work to make it happen and giving me a great canvas to start on.

My colleagues at VCC and Dr. Annika Lundberg for getting me into the automotive world to understand the demands and needs thereof and a nice work environment. Also a thank you for the discussions with VIPP-college Per Mårtensson in the fields of composites.

Finally for the support and understanding from my wife Anna and our kids Erik and Axel. For allowing me to get back, at least partially, to academia, with study periods, deadlines and times of writing. And to my parents, brother and parents in law for your never ending support and belief in me.

Gothenburg February 2016

Dissertation

This licentiate dissertation includes a short description of where the research conducted fits within automotive industry and a presentation of the appended papers.

Paper A

Orthotropic criteria for transverse failure of non-crimp fabric reinforced composites
Molker, H., Wilhelmsson, D., Gutkin, R., Asp, L. E.

Accepted September 2015. Journal of Composite Materials. Available online: doi:10.1177/0021998315605877

Molker created the analytical criteria and comparisons towards existing data. Wilhelmsson contributed with the part regarding finite element simulations at the meso-scale and method for assessing failure envelopes from the representative volume element. Molker wrote the paper together with Wilhelmsson and with assistance from Gutkin and Asp.

Paper B

Implementation of failure criteria for transverse failure of orthotropic Non-Crimp Fabric composite materials
Molker, H., Gutkin, R., Asp, L. E.

Submitted paper: Composite Part A, Selected for Special Issue 2016.

Molker performed the implementation and performed the experimental tests. Molker wrote the paper with assistance from Gutkin and Asp.

Contents

1 Energy consumption of cars

During the last decade, the automotive industry has increased the focus on the weight of cars. This is directly driven by current and future legislation regarding emissions as shown in Figure 1 [1,2]. Light cars are also important for electric vehicles, where range is closely related to weight, especially for small urban cars [3].

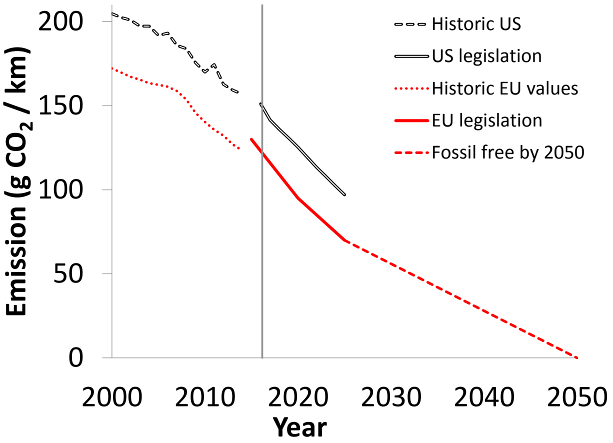

Figure 1. Historic and European legislation on CO_2 emissions. The trend for reaching a fossil free car by 2050 is also added.

Over the last decades, the annual weight increase has been about 10 kg/year, independent of size and manufacturer as illustrated in Figure 2 [4,5]. Up until about the years 2000-2010 the weight of new car models have increased steadily, but since then the focus on weight have increased. However, to be able to fulfil future demands on low energy consumption and emissions, the weights must be decreased. In addition, other features are entering cars of today that are increasing weight. To be successful with weight reduction of the total car, the structural mass needs to be decreased considerably.

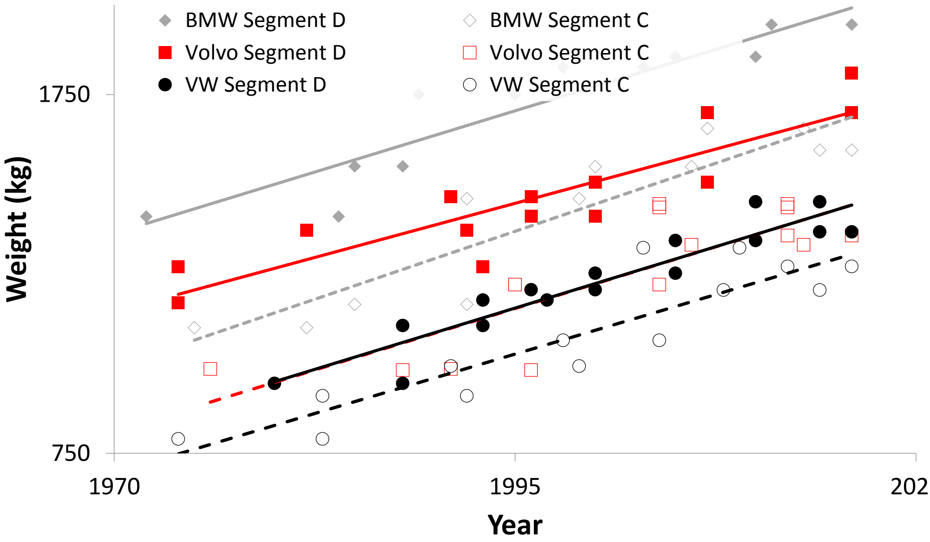

Figure 2. The trend of weight increase of cars during the last decades are shown for three different brands, BMW (diamond), Volkswagen (circle) and Volvo (square) and two sizes of cars, segment C (unfilled markers and dashed lines) and D (filled markers and solid lines).

The materials used today are mainly advanced steels of different grades, and light-weight metals such as aluminium or in some cases magnesium. These materials have been used for some time and have been optimised for present designs. The possible weight reductions with these materials are limited. As in other industries and segments, a class of materials that stands out when it comes to specific strength and stiffness are composite materials and especially continuous carbon fibre based composites, as shown in Figure 3.

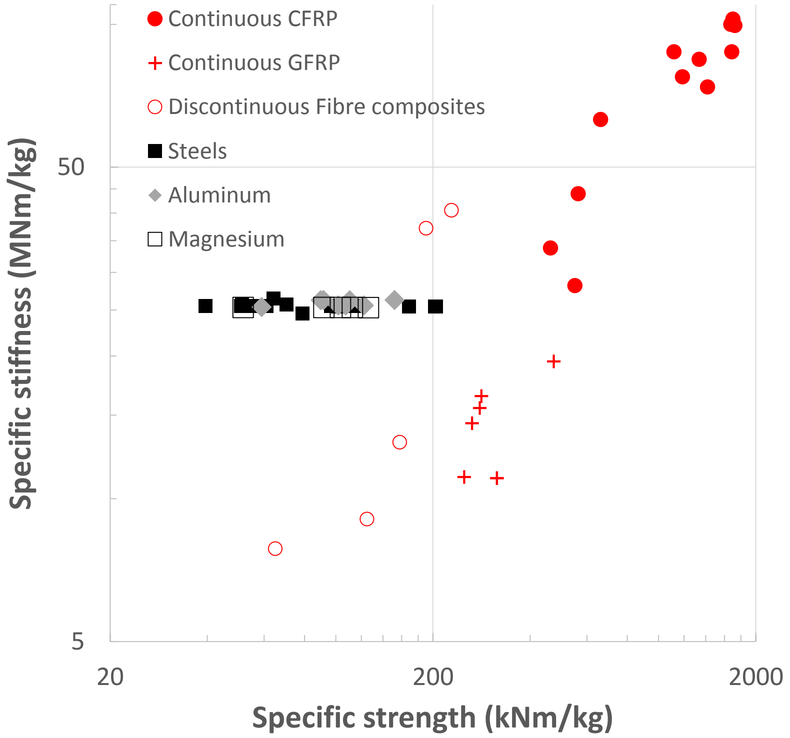

Figure 3. Chart over specific stiffness and specific strength for different material groups used for structural parts [6,7].

1.1 The battle to reduce energy consumption

Composites are more expensive than other structural materials and have therefore historically only been used in industries where the appreciation of low weight has been high, e.g. space, aircraft and racing industries [8]. Until recently, the main focus for reduction of emissions and fuel consumption of cars has been on improvements of the engine and drivetrain. However, as further reductions in this area become more expensive, the appreciation of low weight materials increases within the automotive industry [8]. To reach the anticipated structural mass needed by 2025 and beyond, carbon fibre composites are needed [8].

2 Composites within passenger cars

Cars made from CFRP materials are considered to be 50% lighter compared to steel alternatives and 30% lighter compared to aluminium alternatives with similar performance. Hence, composites are an outstanding alternative for reducing the structural mass. Reduction of the structural mass can also result in secondary savings, e.g. smaller powertrain, smaller brakes, etc.

With the present knowledge of composite materials, the use of carbon fibre reinforced composites is limited to certain areas of passenger cars. This is related to the knowledge of composites regarding their failure mechanisms. Failure in composite materials differs between different material systems. The initiation of failure is also better understood compared to failure progression, including all active failure modes [9]. Therefore it is likely to first see composite materials in stiffness designed structures and last in crash designed structures.

This can be seen already today in high performance cars made from composites, where the main monocoque or module is made out of carbon fibre, while front and rear crash structures are made from steel or aluminium which is shown in Figure 4. It is also true for cars produced in larger series where front and rear structures are made in metal, while the passenger cell is made from composite material, see in Figure 4.

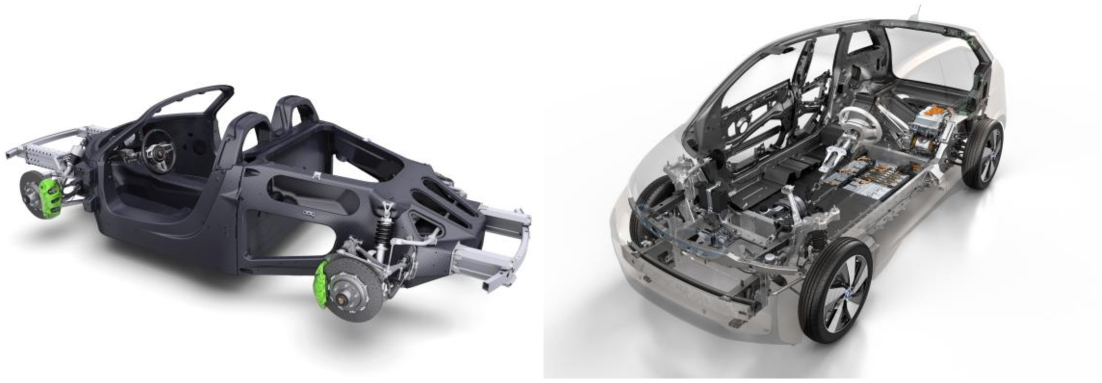

Figure 4. Left: Body structure of Porsche 918 with a CFRP main structure and metal front and rear structures [10]. Right: BMW i3 with front and rear structures in metal and the passenger cell in CFRP [11].

2.1 Expected types of composite materials for structural components

Composites come in a wide range of different systems, both in materials used and architecture. The type selected for a specific structure depends on the prerequisites in terms of trade between performance, cost and properties [12].

Typically, structural composites are made from fibres that are embedded into a matrix material. The fibres are traditionally made from either glass or carbon, where glass is the cheaper alternative and carbon the one with superior structural performance. The matrix material is in most cases a polymer, either a thermoset or thermoplastic. One of the most common is a family of thermosets called epoxy.

The fibres are divided into different categories depending on the length. The two basic classes are Discontinuous Fibre Composites (DFC) or Continuous Fibre Composites (CFC). Materials based on CFC typically have better mechanical performance compared to DFC based materials. Structurally designed systems with CFC are more complex and have a higher manufacturing cost associated with them compared to DFC systems. However, for structural composites CFC are found to be the preferred choice when looking at performance versus cost [12].

Structurally designed components made from CFC are laminated, either by Uni-Directional (UD) tapes or with textiles of fibre bundles. Within the laminate, different laminas or plies (of tape or textile) with different directions are stacked on top of each other. The number of different directions and number of plies in each direction is chosen to best fulfil the performance requirements on that component.

Traditional manufacturing of structural composites using pre-preg tape-based UD systems is a time and labour intensive process. Manufacturing using dry textiles that can be pre-formed and infused with resin in automated processes can overcome these obstacles. A class of textiles that are known as Non-Crimp Fabric (NCF) reinforced composites possess properties that are of interest for the automotive industry. NCF composites are also suitable for manufacturing with a Resin Transfer Moulding (RTM) processes. This makes them a strong candidate for the automotive industry [13].

2.2 Research scope

The research within this project is focused on efficient design methodology for composite vehicle structures through numerical simulations. The term design methodology can include many different aspects depending on within which field it is used. In the general form it is to find the best solution that complies with a certain specification [14]. In this case design methodology refers to how a composite structure with a specific lay-up should be evaluated with respect to mechanical requirements, e.g. stiffness and strength. This would only be a subset of the steps in a more general form.

3 CAE based development of composites

Development of cars is today based on a methodology that have evolved over the last decades. The design and development of cars is driven by CAE and virtual tools. This makes it possible to, from a limited number of material tests, define appropriate material cards according to existing material models in the commercial codes that are used in durability analyses. The models and methodology to assess different structures and features have been developed gradually over the years and physical tests on all levels in the Rouchon pyramid have been replaced by numerical models as illustrated in Figure 5.

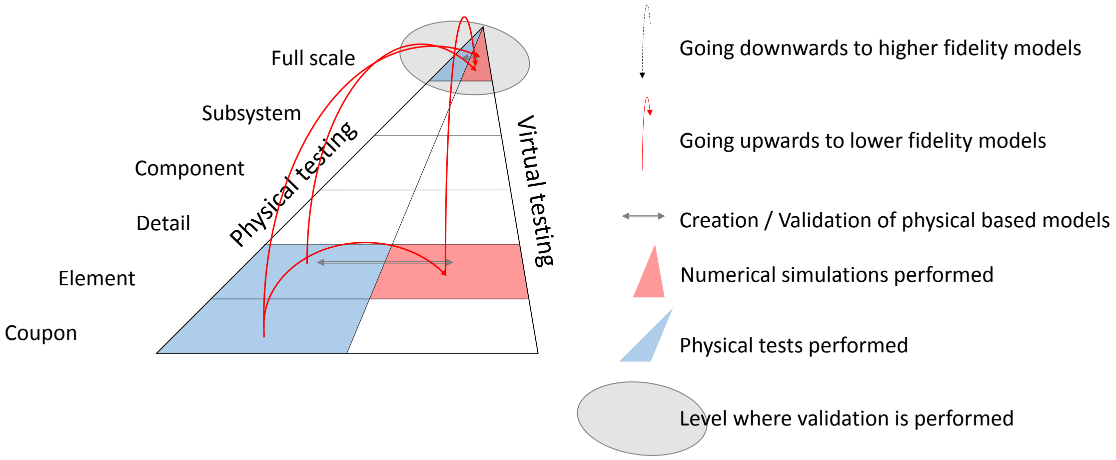

Figure 5. Rouchon's pyramid of test. The base of the pyramid represents tests of parts with low complexity, i.e. material coupon tests, while the top represents full scale tests. On the left side, physical tests are performed, on the right side, numerical simulations are performed.

This means that the car industry today can develop vehicles based on physical testing on the lower left hand side in the pyramid and then design, size and verify the performance of both subsystems and complete cars using CAE.

Ideally validation is done on a complete car or full assemblies of structures using data from coupon tests only.

A never-ending development within the automotive industry is the reduction of lead times not only of CAE analyses but also of complete car development projects. As more physical testing is replaced by virtual testing, the need for robust numerical methods increase. This also applies in new areas, where new failure modes are addressed. This requires efficient methods so that the increased number of analyses that needs to be performed can be done without increasing the overall time.

3.1 Designing with composites today

Structural design of composites must today rely on validation tests to a much larger extent than metal designs do. Within the aerospace industry, a building block approach is used to address validation [15,16]. The building block approach is used to ensure that secondary loads are not critical for the design, i.e. that no unexpected failure modes occur. This is related to the many different failure modes that exists in composite designs. In this approach, tests are performed on all levels, material, element, component and full scales. Verifications made according to this approach are very costly and time consuming.

Having physically based models that can predict all failure modes or identify which areas that might be critical can replace a large amount of testing by numerical simulations. However, as failure occurs at much smaller scales than usual simulations resolve two or three orders of magnitude less than what is feasible to model the understanding of simplifications needed is of utmost importance.

A solution to the contradictions between shorter lead times and the increased amount of testing needed for composite structures as well as larger numerical models, is therefore needed. Lack of efficient methodologies for composite design has been identified as a potential show-stopper for their introduction in the automotive industry [17]. Developing a methodology that is based on physical models to be used at different levels of complexity and effectively select which level of complexity that is required where would make it possible to efficiently evaluate composite structures. The overall aim of the research within this PhD project is to find a framework for efficient design methods for composite structures.

3.2 Wishbone model for virtual testing of aircraft structures

Within aerospace at Airbus, a methodology called the Wishbone model [18] has been proposed for virtual testing of aircraft structures. This model consists of two different parts, arranged in the form of a wishbone as shown in Figure 6.

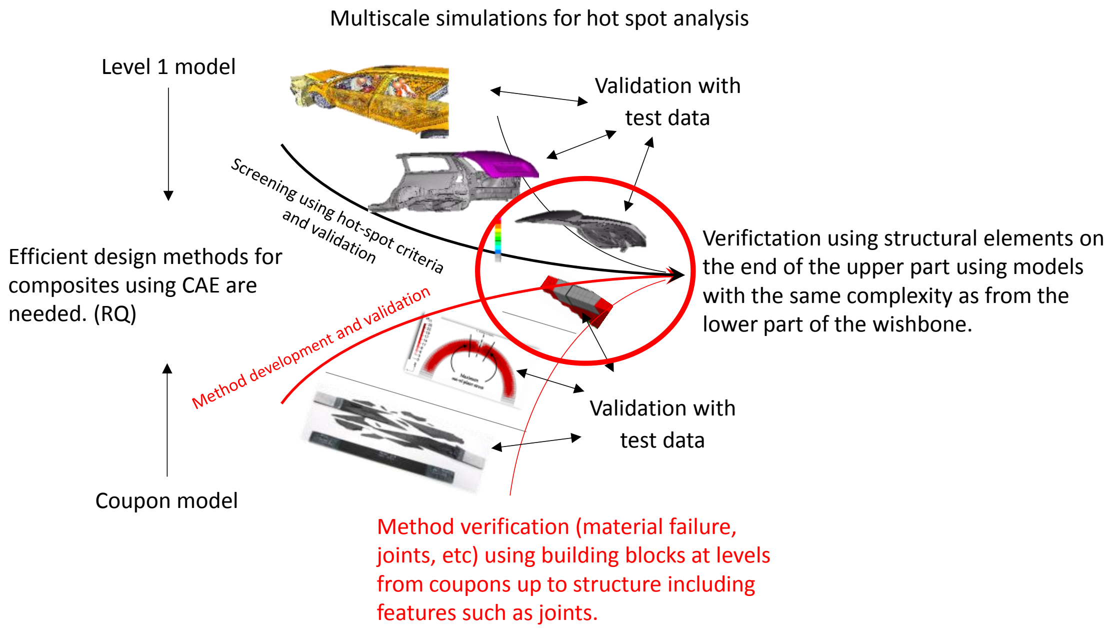

Figure 6. Design methodology based on the Wishbone model for virtual testing within aerospace.

The lower part in Figure 6 is made up of method development and validation, e.g. models for material failure, bondlines and fasteners. Starting with very detailed models at coupon level and moving towards coarser structural models consisting of one or more components. The main purpose is to demonstrate that the detailed analysis and gradually coarser modelling methods can provide consistent and accurate results on all levels of structural features.

The upper part of Figure 6 consists of multi-scale modelling. At the top, a full scale model, Level 1, that can predict the overall non-linear behaviour as well as the local non-linear behaviour, is created. Local is at the size and granularity where critical locations can be identified. The global scale in aerospace is an order of magnitude greater compared to the automotive industry. For each zoom-in, the model of the local area is refined and more accurate modelling methods can be employed. The different modelling and analysis methods at all levels need to be verified with structural testing. Detailed analysis is then performed with models at the common level for both the method development and validation together with the multi-scale part.

3.3 Design methodology of structural composites for automotive components

Finding an efficient path through Rouchon's pyramid is not that easy for composites. The first ingredient needed is predictive tools, based on the physical behaviour, for the materials that are to be used. As described in section 1, this might not be the same type of composites that the aerospace industry have used, and models for new material systems, i.e. NCF reinforced composites are then needed. This is further addressed in chapters 5.

The major challenge is to understand how models for material failure, and the information needed for such models, can be used in subsystem models or large full-scale models without missing any failure modes.

The overall idea is to use full-scale models, or subsystem models, that are enhanced to predict the full stress tensor so that full 3D hot-spot criteria can be used. Full 3D stresses are needed for composite materials as the strength differs in all direction. For metals the strength is the same, but for composite materials the out-of-plane strength can be one to two orders of magnitude less than the in-plane strength. Global criteria will be used to screen the design for potentially critical locations with active failure modes. Global-local analyses need to be employed to break these areas down to a scale where appropriate modelling methods can be used for verification of the design using state-of-the-art failure criteria.

Global-local modelling techniques are available already today [19]. However, what is handled is the application of constraints to a local model based on displacements from the global model. Different approaches for this are available, e.g. submodelling [19] and mesh superpositioning [20]. All these processes are however based on that the local model exist and its placement is manually decided by the user. The full process of evaluation of the global model, identification of critical hot spots, creation of local model, load application, solution and evaluation of local models, still need to be developed.

It is also important to use models that can transfer CAE-based data and results from one scale to another. This can be information on how to predict in-situ strength depending on lamina location and thickness or the effect of blocking of plies when holes are analysed. The ability to use such models can reduce the need of physical tests at intermediate levels.

Composite models include more information than corresponding models for metal, i.e. information on stacking sequence and fibre angles. To handle this information correctly, it is necessary to have automated processes for creation of both global and local models. There is no room for manual transfer of data between scales for two reasons; first the time aspect and second the robustness.

When a framework for prediction of material failure is established, the same framework can be used for addressing other failure modes, e.g. bondlines, fasteners, fatigue etc. With global hot spot criteria the critical locations can be identified. These can then be resolved with higher accuracy models and verified.

4 NCF composites

Textile composites possess a number of advantages compared to tape-based composites [21]. The main advantage is that textiles typically can be thicker, with fibres in more than one direction in the fabric, and thereby can reduce the number of lay-up steps needed. Furthermore, textile reinforced composites are typically made with dry preforms and then infiltrated/infused with resin in a secondary step. This reduces requirements on handling and storage compared to pre-impregnated systems. The cost is further decreased since fewer production steps are needed.

Non Crimp-Fabric (NCF) reinforced composites are made with a textile, see Figure 7 (a). The textile have its name from the fact that there is much less crimp compared to common textiles with e.g. weaves, see Figure 7 (b). Crimp is a measure of the yarn length compared to fabric length, defined by Backer [22] as:

$$C = \frac{l_\mathrm{y} - l_\mathrm{f}}{l_\mathrm{f}}, \tag{1}$$

where C is the crimp, l_y is the length of the yarn in the fabric and l_f is the length of the fabric.

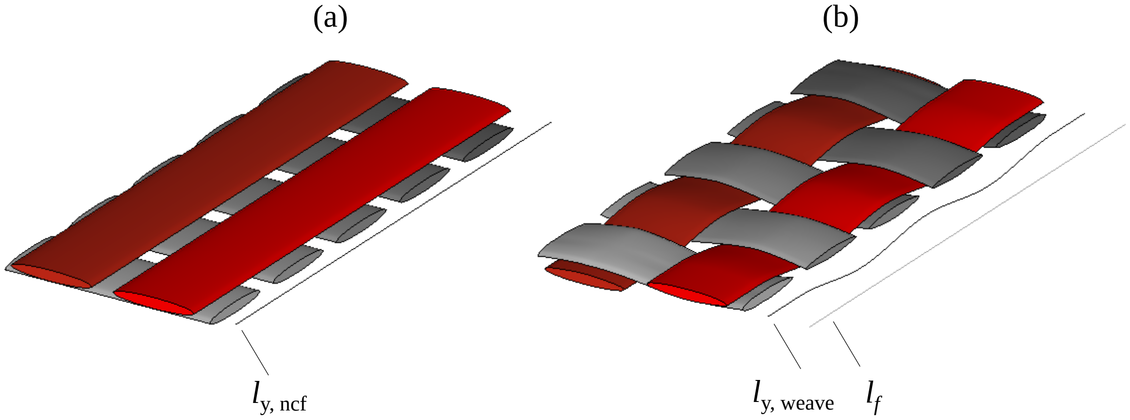

Figure 7. Illustration of a biaxial NCF (a) and plain weave (b) with the yarn length, l_y, and the fabric length, l_f. The circle represents the cross section of a fibre bundle and the grey straight or wavy rectangle represents the side view of a bundle. Images generated using TexGen [23].

Crimp, which is a direct result of the waviness of the fibres, reduces the mechanical properties of the composite. Especially the compressive strength is reduced. A textile with small crimp is therefore favourable.

NCF reinforcements have the advantages of textiles, such as easier production, lower cost and thicker net shaped components [24], while the reduced mechanical properties of weaves are partially recovered with NCFs due to the reduced crimp. Also NCFs can be more tailored compared to weaves. This as NCFs are made from isolated unidirectional layers as shown in Figure 8 (a), stacked on top of each other to produce a multi-axial fabric as Figure 8 (b), and then held together by stitching, knitting or warp/weft insertion [25].

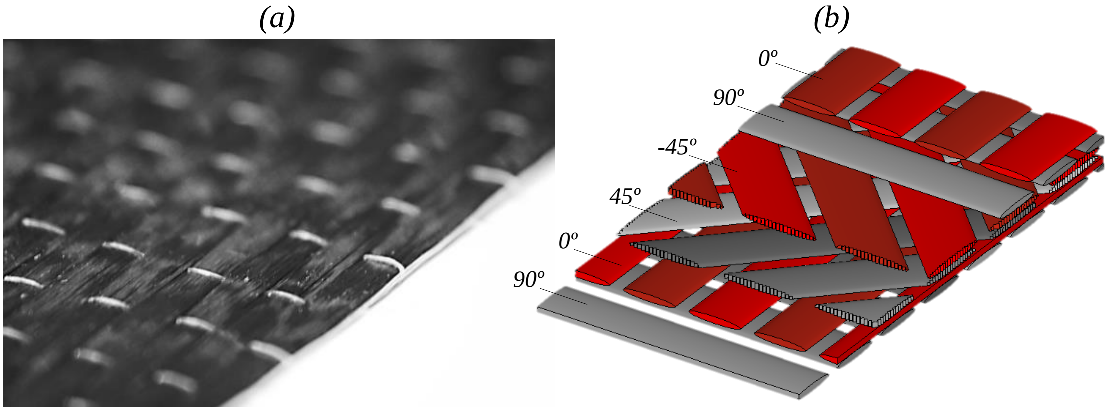

Figure 8. (a) Image of a uni-weave NCF. (b) Illustration of a multi-axial NCF [90/0/45/-45/90/0].

4.1 Applications of NCF reinforced composites

NCF reinforced composites are today found in different industries. Within aerospace, they can be found in the A380 rear bulkhead and A400M cargo door [26]. Common for these structures are that they are designed for stiffness and strength and subjected to internal pressure, resulting in tensile membrane loads. Thereby they are not limited by the decreased compressive properties of NCFs compared to pre-preg tape based UD composites. In automotive industry NCF reinforced composites can be found in the composite structure of BMW i3 [27] and roofs of the BMW M3 [28]. Within the wind turbine industry NCF reinforced composites are common in both blades and nacelles [29]. In maritime industry NCF reinforcements can be found in ship hulls, e.g. the Swedish navy corvettes of Visby class [30] sandwich hull .

4.2 Mechanical properties of NCF reinforced composites

Properties of NCF composites are known to be slightly decreased compared to pre-preg tape based composites [31]. This is due to the meso-structure with stitching or binding yarns, resin rich areas and waviness of the fibre tows. In-plane properties, both stiffness and strength have been studied [Edgren] [31], while the effect of the meso-structure on the out of plane properties are not as well understood.

NCF composites have been found to be orthotropic both from an elastic point of view [7] and from a failure perspective [7,32]. Orthotropic means that the material have three orthogonal principle axes along which the properties are defined., see Figure 9 (a). This is not the case for traditional UD reinforced composites that are transversally isotropic. For UD reinforced composites, one plane (with the normal along the fibre direction) can be defined as an isotropy plane, as shown in Figure 9 (b). This means that the properties in the 2-3 plane are the same. For most other common engineering materials the properties are the same in all direction. These materials are known as isotropic, see Figure 9 (c).

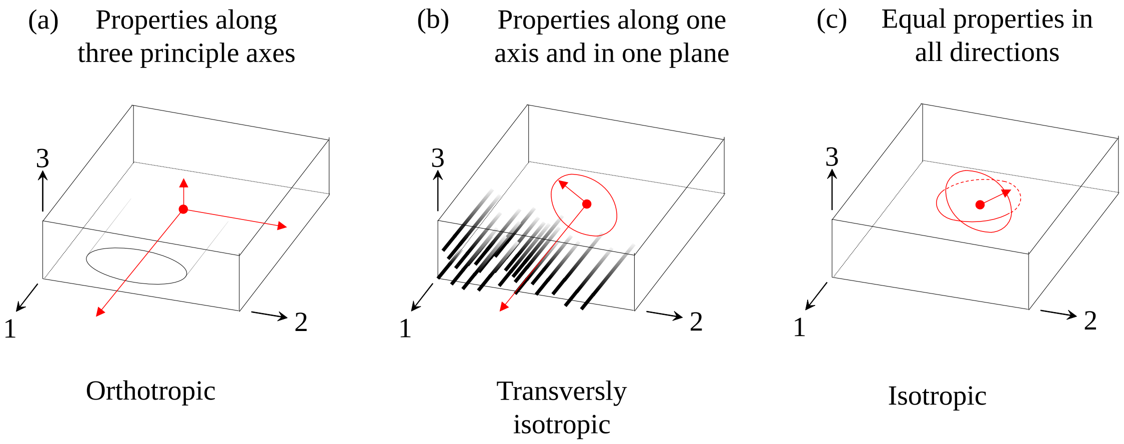

Figure 9. Illustration of directions with different properties. (a) Orthotropic material with properties defined along three principle axis. (b) Transversely isotropic material with properties defined along one axis and one plane. (c) Isotropic material with material properties that are independent of direction.

Defining orthotropic material properties in commercial finite element software is not a problem for stiffness. The stiffness matrix can be defined using laminate theory [33] if the ply properties are known.

The effect on failure is somewhat different. This since an additional failure mode has been observed that does not exist for UD reinforced composites. This is found for transverse matrix related failure, where the behaviour is not transversally isotropic.

5 Assessing failure of composites

Composite materials are quite different from most engineering materials used. Failure initiates due to different mechanisms under different loading conditions. This is in contrast to most metals where failure is due to slip motions within the crystalline lattice structure, which is independent on loading condition.

The fact that structural fibre reinforced composite materials consists of two different materials (fibre and matrix) means that the failure mechanisms relate to each of them. Since the properties of these constituents are very different, the failure modes differ dramatically too.

5.1 History of failure assessment

Assessment of the strength of fibre composites started in the 1950's [34]. The common approach to assess failure is to calculate a failure index for each ply within the laminate. The failure index, *FI*, is based on the current stress state and evaluated against an allowable stress. Failure is predicted to initiate when the index is greater or equal to unity. This is known as "First Ply Failure", which can be defined as the first change of stiffness of the laminate [33].

The earliest failure theories were based on maximum stress or strain in the main direction. Taking combined stress states into account were first done in theories based on anisotropic yielding of metals and did not consider different failure modes, e.g. the Tsai-Wu criterion [35]. Adressing different failure modes in a failure criteria was first introduced by Hashin [36] in the early 1980's. Since then, more refined criteria, based on the physical behaviour of the different failure modes have been proposed, e.g. Puck [37] and LaRC05 [38], two criteria that have performed well in the World Wide Failure Exercises [39]. Common for these failure theories are that they are developed for UD composites, like tape based pre-preg systems.

Physically based failure criteria for NCF composites are still lacking. Because of the orthotropic nature of the failure, this development constitutes a clear scientific challenge. So far, studies have focused on one particular failure mechanism [40,41] and the objective of the work done in **Paper A** and **Paper B** is to achieve a 3D physically based set of failure criteria able to predict all the relevant failure modes.

5.2 State-of-the-art failure criteria for UD reinforced composites

The different failure modes typically addressed by state-of-the-art failure criteria can be divided into three different categories for UD reinforced fibre composites: fibre tensile failure, matrix related failure and fibre kinking failure (compression in the fibre direction). The failure is for all failure categories evaluated on a fracture plane and based on the tractions on this plane.

Fibre tensile failure, shown in Figure 10, is governed by the strength of the fibres, X_T, and the stress in the fibre direction, σ_{11}, is used to evaluate the criterion:

$$FI_{\mathrm{FT}} = \frac{\langle \sigma_{11} \rangle_{+}}{X_{\mathrm{T}}} = 1. \tag{2}$$

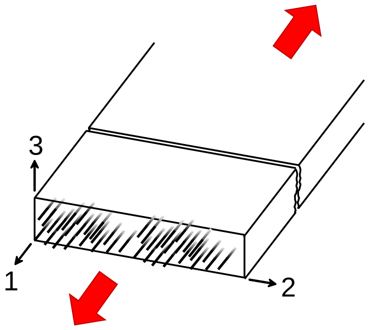

Figure 10. Illustration of tensile fibre failure for a UD composite material.

Matrix related failure is governed by the properties of the matrix material. Many common matrix materials, e.g. epoxy, show brittle failure. Under transverse compression, the matrix material fails at an inclined fracture plane, as illustrated in Figure 11, suggesting that the failure is driven by shear forces. Several failure criteria, e.g. Puck [37] and LaRC05 [38], a modified Columb-Mohr criterion is used for matrix related failure. As the fracture plane angle for matrix materials tends to be larger than 45°, it is likely that friction on micro cracks increases the allowable shear stress [42]. The shear stress on the fracture plane are divided into transverse, τ_T and longitudinal, τ_L. The shear strength on the fracture plane is also divided into transverse, S_T and longitudinal, S_L. The friction stress from the micro cracks are calculated from the normal stress, σ_N, and a friction coefficient in transverse-, η_T, and longitudinal direction, η_L. The matrix compression criterion for LaRC05 [38] is written as:

$$FI_{\mathrm{M}} = \left(\frac{\tau_{\mathrm{T}}}{S_{\mathrm{T}}^{\mathrm{is}} - \eta_{\mathrm{T}} \sigma_{\mathrm{N}}} \right)^2 + \left(\frac{\tau_{\mathrm{L}}}{S_{\mathrm{L}}^{\mathrm{is}} - \eta_{\mathrm{L}} \sigma_{\mathrm{N}}} \right)^2 = 1. \tag{3}$$

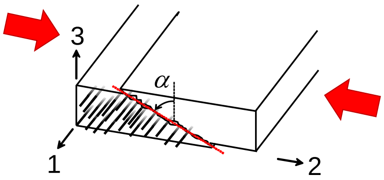

Figure 11. Illustration of compressive matrix failure for a UD composite material.

These criteria then need to be evaluated for any potential fracture plane, i.e. with varying α. This can either be done by checking a number of potential failure planes [ref], e.g. every 15°, or by an iterative optimisation algorithm [43].

For matrix tension, as shown in Figure 12, a quadratic relationship between the normal stress and shear stresses have been found to capture failure initiation [42]. The matrix tension criterion for LaRC04 [44] evaluates the tractions on the fracture plane, τ_T, τ_L and σ_N compared to the allowables, S_T^{is}, S_L^{is}, Y_T^{is} and is written as:

$$FI_M = \left(\frac{\tau_T}{S_T^{is}}\right)^2 + \left(\frac{\tau_L}{S_L^{is}}\right)^2 + \left(\frac{\sigma_N}{Y_T^{is}}\right)^2 = 1. \tag{4}$$

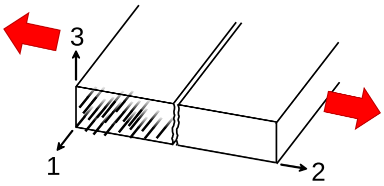

Figure 12. Illustration of tensile matrix failure for a UD composite material.

Fibre compressive failure, known as fibre kinking, is a matrix controlled failure mode, shown in Figure 13. The failure is initiated due to local misalignments of fibres causing shear stresses. This then increase the fibre misalignment and at some point cause matrix failure in a different coordinate frame, denoted with superscript m. The fibre compressive criterion for LaRC05 [38] is written as:

$$FI_{KINK} = FI_{SPLIT} = \left(\frac{\tau_{23}^m}{S_T^{is} - \eta_T \sigma_{22}^m}\right)^2 + \left(\frac{\tau_{12}^m}{S_L^{is} - \eta_L \sigma_{22}^m}\right)^2 + \left(\frac{\langle \sigma_{22}^m \rangle_+}{Y_T^{is}}\right)^2 = 1. \tag{5}$$

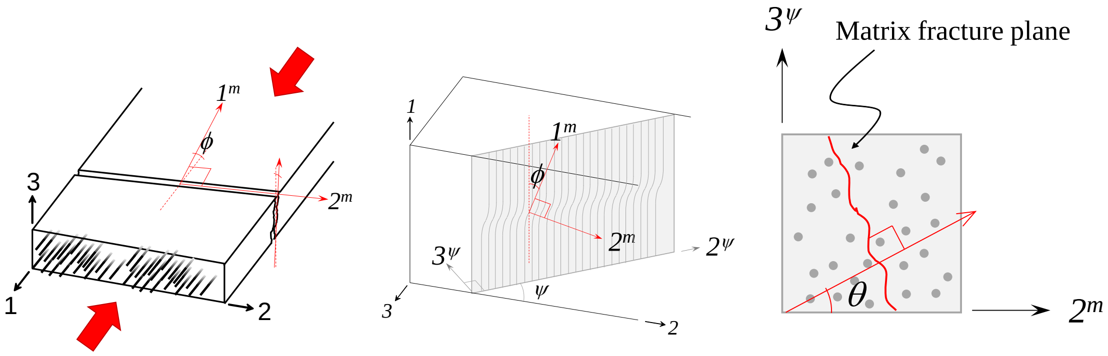

Figure 13. Illustration of fibre kinking failure.

The plane within the composite ψ depends on the current stress state and is between 0 and 180 degrees. The misalignment frame *m* is dependent on the initial fibre misalignment and material properties of the matrix and rotated ϕ degrees from the fibre direction. The matrix fracture plane has to be calculated for any potential fracture plane θ, as for matrix compression.

The combination of the different modes and their respective criteria creates a complete failure initiation criterion. Failure is then initiated if any of the failure indices become unity with the corresponding failure mode and potential fracture plane as a result.

5.3 *Failure initiation in NCF reinforced composites – Paper A*

The tensile strength in the out-of-plane direction of NCF reinforced composites have been found to be as low as 40% of the tensile transverse strength in the in-plane direction. This means that failure predictions used with available failure criteria for UD composites will not be accurate for all load conditions. Such criteria are based on the in-plane strength, as this is the easiest one to measure. This would overestimate the out-of-plane tensile strength and is thus non-conservative.

For transverse failure in NCF reinforced composites two different failure modes have been identified. At the interface between the fibre bundle and the surrounding matrix failure occurs at a plane parallel to the ply, this failure is denoted as interbundle failure and shown in Figure 14, bundle I. Inside the fibre bundle failure occurs as in UD-composites and failure criteria such as LaRC05 [38] are accurate. This mode is denoted as intrabundle failure as shown in Figure 14, bundle II.

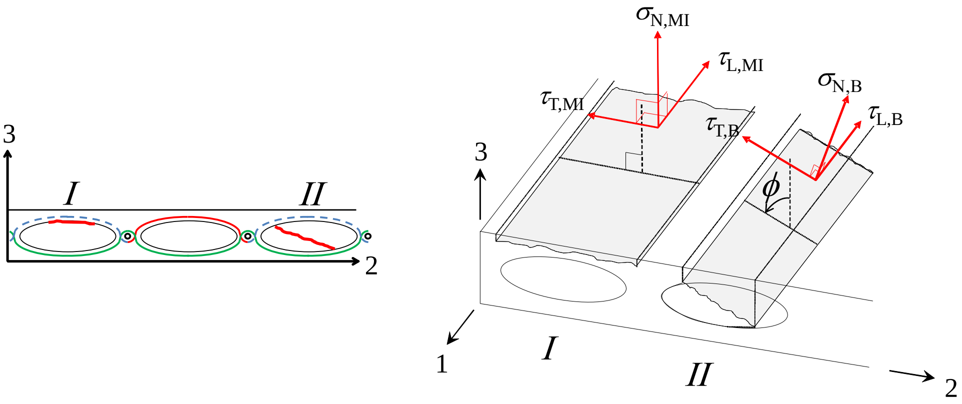

Figure 14. Transverse matrix related failure modes in NCF reinforced composites. Bundle I suffers interbundle failure, and Bundle II suffers intrabundle failure.

Available failure criteria for orthotropic 3D reinforced composites, e.g. by Juhasz [45], are developed for composites with reinforcements in the out-of-plane direction. The criteria then identifies different failure modes compared to those found in NCF reinforced composites. However, the number of material parameters in the model is large and the model is sensitive to properties that are hard to measure.

In **paper A,** a set of physically based criteria for transverse matrix related failure is proposed. The criteria are based on the LaRC05 criteria [38] and have an additional criterion for the interbundle failure. The interbundle failure occurs for out-of-plane tensile load and is based on the matrix tensile failure criterion. It is evaluated for a plane parallel to the ply and uses the out-of-plane tensile strength Z_T.

Since experimental data for out-of-plane properties are hard to find in the literature, the proposed criteria have been verified using a finite element based meso-mechanical model. The numerical model includes failure criteria for each constituent; the LaRC05 criteria [38] for the fibre bundle and the Raghava yield criterion [46] for the matrix. In this model, different aspects, i.e. fibre bundle shape, thermal stresses, compressive strength and non-linear material properties are studied for different stress combinations in the transverse plane.

In the study presented in **Paper A** it is found that the proposed failure criteria for transverse matrix related failure can capture the orthotropic strength of NCF reinforced composites. The predictions by the analytical failure criteria show good agreement with both experimental data and numerical simulations made with a meso-mechanical numerical model.

5.4 Failure assessment of NCF reinforced composites in CAE – Paper B

In **Paper B**, the set of failure criteria for transverse failure in NCF reinforced composites that were proposed in **Paper A** are implemented into the commercial finite element code Abaqus [19]. The implementation is done in a user defined function, UVARM [19]. This function is evaluated for all applicable material points at every time steps. The implementation predicts failure mode, failure index and fracture plane for the current stress state.

Validation of the criteria is performed with physical experiments on corrugated specimens. Two different lay-ups have been used for the same experimental setup, illustrated in Figure 15. Calculations are made with the proposed set of criteria and the LaRC05 set of criteria [38], a state-of-the-art set of criteria for transversely isotropic materials.

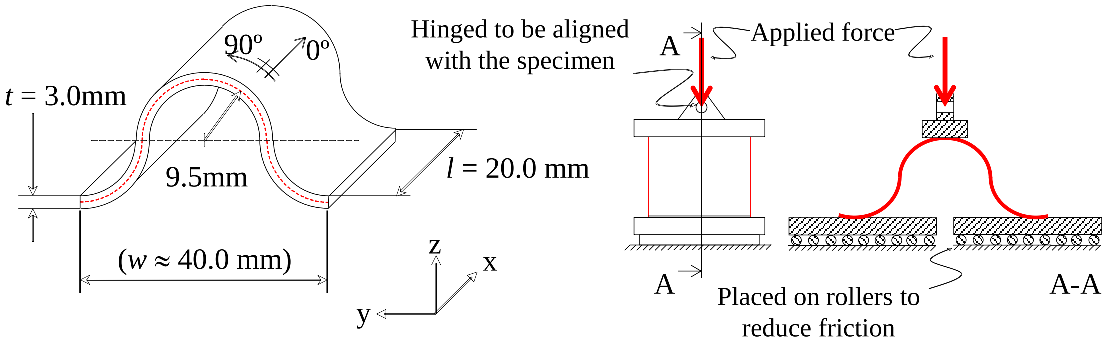

Figure 15. Experimental test. Left: Illustration of test specimen. Right: Setup of experiment with load application and constraints.

One conclusion from the validation is that the proposed failure criteria can accurately predict the failure mode. Something that criteria based on the assumption of transverse isotropy properties cannot do. Such criteria would overestimate the strength of the component, leading to a non-conservative design.

Based on the known material data [7] it is found that the out-of-plane strength is subject to volume effects [47]. In **Paper B**, a discussion on the sensitivity to the strength value and differences between test specimens is presented.

Another conclusion in **Paper B** is that characterisation made on one type of specimen and one standard for material characterisation will not be valid for the design of features with large stress gradients with different design. Characterisation of a material has to be made on specimens that are similar to the design that they will be used on with the same manufacturing process and knowledge about the bounds for the validity is needed.

6 Conclusions and outlook

The development of physically based criteria for failure initiation in NCF reinforced composite provides the basis for reaching the final goal: development of a design methodology. Knowledge of how the existing failure modes can be predicted with high fidelity models is vital for finding how failure can be addressed in large models.

6.1 What is missing to assess composite structures efficiently?

The limitation of today's modelling practice with shell elements is that they lack the full 3D stress tensor which is needed. This makes the use of 3D solid models necessary since the through the thickness stresses are needed to asses onset of ply failure and delamination. In order to have an efficient design methodology, it is necessary to find a way to replace high fidelity models with reduced models, but that still are able to predict all possible failure modes.

When such reduced models are available, they can be used for hot spot identification. These hot spots can then be analysed in more detailed models with improved accuracy for verification. The creation of an automated flow of models for hot spot analyses is also important to make a design methodology efficient.

Having both global and local analysis methods, the process of merging these into an automated process is needed. A process where data from a CAD model is used to create the needed models and where appropriate modelling techniques are used at each scale.

6.2 Validity of material data

Apart from establishing a design methodology that makes it possible to use global models, it is necessary to understand the material system and what kind of testing that is required to characterise it. Since several different lay-ups will be used, it is important to understand under what constraints the existing material data are valid. Knowledge of thickness and lay-up dependencies will be crucial to be able to accurately predict failure initiation.

Projects such as PAVE [48] is therefore of great importance to understand what tests are actually needed to obtain valid material data. In the long term, this will avoid experimental tests on intermediate levels in Rouchon's pyramid of tests. However, to validate methods for modelling and calculation of allowables, experimental tests will be needed at many different scales.

7 References

[1] icct org. Global_PV_data_20150803.xlsx n.d. http://www.theicct.org/sites/default/files/info-tools/pvstds/Global_PV_data_20150803.xlsx (accessed January 1, 2016).

[2] Statens offentliga Utredningar. Fossilfrihet på väg, del 1. Stockholm: 2013.

[3] Barnard RH. Road Vehicle Aerodynamic Design: An Introduction. 3 rev ed. MECHAERO PUBLISHING; 2010.

[4] Weight of cars. www.wikipedia.com (accessed February 15, 2016).

[5] Weight of cars. http://www.ultimatespecs.com/car-specs (accessed February 15, 2016).

[6] MatWeb, Your Source for Materials Information n.d. http://www.matweb.com/index.aspx (accessed January 1, 2016).

[7] Bru T, Hellström P, Gutkin R, Ramantani D, Peterson G. Characterisation of the mechanical and fracture properties of a uni-weave carbon fibre/epoxy non-crimp fabric composite. Data in Brief 2016;6:680–95.

[8] Heuss R, Müller N, Sintern W, Starke A, Tschiesner A. Lightweight, heavy impact - How carbon fiber and other lightweight materials will develop across industries and specifically in automotive. McKinsey. 2012.

[9] Andersson M, Liedberg P. Crash behavior of composite structures. Chalmers University of Technology, 2014.

[10] Porsche Media Gallery. Porsche Media Gallery 2013. http://press.porsche.com/ (accessed February 15, 2016).

[11] BMW Group PressClub Global. BMW Group Press Global 2013. https://www.press.bmwgroup.com/ (accessed February 15, 2016).

[12] Mårtensson P, Zenkert D, Akermo M. Method for the cost-efficient and weight-efficient material diversity and partitioning of a carbon fibre composite body structure. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2015.

[13] Verpoest I, Thanh TC, Lomov S. The TECABS Project: Development of Manufacturing, Simulation and Design Technologies for a Carbon Fiber Composite Car. Proceedings of the 9th Japan International SAMPE Symposium, 2005, p. 56–61.

[14] Eckert C, Clarkson J. Introduction. In: Clarkson J, Eckert C, editors. Design Process Improvement, London: Springer; 2005, p. 1–33.

[15] Tenney DR, Davis Jr JG, Pipes B, Johnston N. NASA Composite Materials Development: Lessons Learned and Future Challenges. NATO RTO AVT-164 Workshop on Support of Composite Systems, 2009.

[16] Military Handbook - MIL-HDBK-17-1F: Composite Materials Handbook, Volume 1 - Polymer Matrix Composites Guidelines for Characterization of Structural Materials.

[17] Josefson L, Nilsson-Ehle A. SAFER Project report, Slutrapport SEVS Phase 1,. 2010.

[18] Ostergaard MG, Ibbotson AR, Roux OL, Prior AM. Virtual testing of aircraft structures. CEAS Aeronautical Journal 2011:83–103.

[19] Dassault Systèmes. ABAQUS Documentation. 6.14 ed. Providence, RI, USA: 2014.

[20] Gigliotti L, Pinho ST. Multiple length/time-scale simulation of localized damage in composite structures using a Mesh Superposition Technique. Composite Structures 2015;121:395–405.
[21] Pastore CM. Opportunities and challenges for textile reinforced composites. Mechanic's of Composite Materials 2000;36.
[22] Backer S. Fibrous materials. In: McClintock FA, Argon AS, editors. Mechanical behavior of materials, MA: Addison-Wesley Publ.; 1966.
[23] Nottingham of University. TexGen 2016.
[24] Ogale V, Alagirusamy R. Textile preforms for advanced composites. Indian Journal of Fibre & Textile Research 2004;29:366–75.
[25] Schnabel A, Gries T. Production of non-crimp fabrics for composites. In: Lomov S, editor. Non-Crimp Fabric Composites Manufacturing, Properties and Applications, Cambridge: Woodhead Publising Limited; 2011, p. 1–37.
[26] Middendorf P, Metzner C. Aerospace applications of non-crimp fabric composites. In: Lo, editor. Non-Crimp Fabric Composites Manufacturing, Properties and Applications, Cambridge: Woodhead Publising Limited; 2011, p. 441–8.
[27] Dry Composites. BMW i3: first mass produced composite car in production. http://www.drycomposites.com/bmw-i3-first-mass-producedcomposite- (accessed May 20, 2015).
[28] Sköck-Hartmann B, Gries T. Automotive applications of non-crimp fabric composites. In: Lomov S, editor. Non-Crimp Fabric Composites Manufacturing, Properties and Applications, Cambridge: Woodhead Publising Limited; 2011, p. 461–80.
[29] Adolphs G, Skinner C. Non-crimp fabric composites in wind turbines. In: Lomov S, editor. Non-Crimp Fabric Composites Manufacturing, Properties and Applications, Cambridge: 2011, p. 481–93.
[30] Summerscales J. Composites manufacturing for marine structures. In: Graham-Jones J, Summerscales J, editors. Marine Applications of Advanced Fibre-Reinforced Composites, Cambridge: Woodhead Publishing; 2015, p. 19–55.
[31] Lomov SV., Troung T, Verpoest I. Mechanical properties of non-crimp fabric (NCF) based composites: stiffness and strength. In: Lomov S, editor. Non-Crimp Fabric Composites Manufacturing, Properties and Applications, Cambridge: Woodhead Publising Limited; 2011, p. 261–88.
[32] Olsson R. Experimental observations on the orthotropic transverse strength of Non-Crimp Fabrics composites. Mölndal, Sweden: 2015.
[33] Zenkert D, Battley M. Foundations of Fibre Composites, FLYG, paper 96-10. Second edition. Stockholm: 2012.
[34] Hinton MJ, Kaddour AS, Soden PD. The world-wide failure exercise: Its origin, concept and content. In: Hinton MJ, Kaddour AS, Soden PD, editors. Failure Criteria in Fibre-Reinforced-Polymer Composites: The World-Wide Failure Exercise, Elsevier Ltd.; 2004.
[35] Tsai SW, Wu EM. A General Theory of Strength for Anisotropic Materials. Journal of Composite Materials 1971;5:58–80.
[36] Hashin Z. Failure Criteria for Unidirectional Fiber Composites. Journal of Applied Mechanics 1980;47:329–34.

[37] Puck A, Schürmann H. Failure analysis of FRP laminates by means of physically based phenomenological models. Composite Science and Technology 2002;62:1633–62.

[38] Pinho S, Darvizeh R. Material and structural response of polymer-matrix fibre-reinforced composites. Journal of Composite Materials 2012;46:2313–41.

[39] Kaddour AS, Hinton MJ. Maturity of 3D failure criteria for fibre-reinforced composites: Comparison between theories and experiments: Part B of WWFE-II. Journal of Composite Materials 2013;47:925–66.

[40] Marklund E, Asp LE, Olsson R. Transverse strength of unidirectional non-crimp fabric composites: Multiscale modelling. Composites Part B: Engineering 2014;65:47–56.

[41] Edgren F, Asp LE, Joffe R. Failure of NCF composites subjected to combined compression and shear loading. Composite Science and Technology 2006;66:2865–77.

[42] Pinho ST, Iannucci L, Robinson P. Physically based failure models and criteria for laminated fibre-reinforced composites with emphasis on fibre kinking. Part II: FE implementation. Composites Part A: Applied Science and Manufacturing 2006;37:766–77.

[43] Wiegand J, Petrinic N, Elliott B. An algorithm for determination of the fracture angle for the three-dimensional Puck matrix failure criterion for UD composites. Composites Science and Technology 2008;69:2511-17.

[44] Pinho ST, Carlos DG, Camanho PP, Iannucci L, Robinson P. Failure Models and Criteria for FRP Under In-Plane or Three-Dimensional Stress States Including Shear Non-Linearity. NASA/TM-20. Hampton: NASA Langley Research Center; 2005.

[45] Juhasz J, Rolfes R, Rohwer K. A new strength model for application of a physically based failure criterion to orthogonal 3D fiber reinforced plastics. Composite Science and Technology 2001;61:1821–32.

[46] Caddell RM, Raghava RS, Atkins AG. Pressure dependent yield criteria for polymers. Materials Science and Engineering 1973;13:113–20.

[47] Wisnom MR. Characterisation of the mechanical and fracture properties of a uni-weave carbon fibre/epoxy non-crimp fabric composite. Composite Science and Technology 1999;59:1937–57.

[48] LiGHTer. Del 2. Projektsammanfattning - PAVE: Probabilistisk analys och verifiering av kompositstrukturer. 2015.

Glossary

BIW	Body in White
CAE	Computer Aided Engineering
CFRP	Carbon Fibre Reinforced Composite
GFRP	Glass Fibre Reinforced Composite
Coupon	Test specimen for material characterisation.
Lamina	Single layer of composite material, also called ply.
Laminate	All laminae stacked on top of each other makes a laminate.
Lay-up	Order of laminae within a laminate
In-situ	Accounting for variation of a property due to the position within a laminate.
NCF	Non crimp-fabric
Pre-preg	Preimpregnated material
RTM	Resin transfer moulding. Manufacturing process where resin is injected into a mould with dry fibres.
Thermoset	Plastic material that are crosslinked and can not be reshaped at elevated temperature.
Thermoplastic	Plastic material that are not crosslinked and can reshaped at elevated temperature.

Nomenclature

C	Crimp, meassure of waviness.
l_y	Length of the yarn in a fabric.
$\mathrm{l_f}$	Length of fabric.
σ_{11}	Stress in the 1-direction.
X_T	Basic strength in tension in the 1-direction.
τ_T	Transverse shear on the fracture plane.
τ_L.	Longitudinal shear on the fracture plane.
σ_N	Normal stress on the fracture plane.
S_T	Transverse shear strength.
S_L.	Longitudinal shear strength.
η_T	Transverse friction parameter.
η_L	Longitudinal friction parameter.
Y_T	Basic strength in tension in the 2-direction.
m	Reference to misaligned coordinate system for fibre kinking.
σ_{22}	Stress in the 2-direction.
is	In-situ.
Z_T	Basic strength in tension in the 3-direction.