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

On matrix-driven failure in unidirectional NCF composites

A theoretical and experimental study

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Cover:
Above: Micrograph of waviness out-of-plane for an NCF composite; Below: Measurements of waviness in the micrograph.

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Abstract

With ever increasing traffic levels, the civil aircraft industry is in constant need of new technologies to make air travel environmentally sustainable. One such technology is light materials to reduce the energy consumption in flight. Currently, up to 53 weight percent of the Airbus A350XWB aircraft is made from carbon fibre reinforced polymer (CFRP) material, mainly in the fuselage and wings. There are other areas in the aircraft where components traditionally made from metals can be replaced with composite material, for instance the cold and moderately high temperature parts of the engines. CFRP fanblades were successively introduced in a civil aircraft engine (GE90) in 1994 and there is now an interest to increase the use of CFRP deeper into the engine.

The current research project is carried out in response to an industrial need of cost-effective CFRP components in load carrying parts of the engine. The preferred route is an automated, out-of-autoclave manufacturing method using resin transfer moulding (RTM) with a non crimp fabric (NCF) as reinforcement. Carbon fibre/Epoxy composites reinforced with NCF offer potential cost savings over tape based prepreg materials, with good mechanical properties - close to that of prepreg type composites. For this reason, NCF-reinforced composites provide an interesting alternative to prepregs for the aerospace industry. One limiting factor for their use in primary structures is their relatively low strength in compression. The overall goal of this research project is to further understand the compressive behaviour of NCF composites and to develop a strength assessment method for the aerospace industry.

In the first part of the project, we increase the fundamental understanding of the composite material on a meso-scale level, where the NCF have a specific architecture, consisting of fibre tows in various configurations. A new failure criterion has been developed to take into account the orthotropic properties in the transverse (2-3) plane. Local interaction between two bundles out-of-plane was simulated with a finite element model and it was proved to be one possible explanation for the reduced strength out-of-plane. In the second part of the thesis, we investigate the influence of intrinsic material variations on the performance of an NCF composite loaded in compression. These intrinsic variations to the material have been identified as potentially likely to occur in future aero-engine composite structures. In conjunction with the compression test campaign, a method to measure fibre misalignment angles out-of-plane has been developed based on microscopy and a Matlab script. The fibre waviness was found to have a strong adverse effect on the compressive stiffness and strength of the material. The measured compressive strength was reduced to half when the mean fibre misalignment angle was doubled.

Keywords: NCF composite, compressive failure, compressive testing, aerospace

till Hania, Leonora och Frank.

Preface

This work has been performed at Chalmers University of Technology in Göteborg, Sweden, during the period of December 2013 to August 2016. Most of the work so far has been done at Chalmers Johanneberg and the experimental work has mainly been done in the laboratory at Swerea Sicomp, Mölndal.

This research project has been performed within the Swedish Aeronautical Research Program (NFFP), Project 2013-01119, jointly funded by the Swedish Armed Forces, Swedish Defence Materiel Administration and the Swedish Governmental Agency for Innovation Systems. In addition, Sweden's innovation agency, VINNOVA, is gratefully acknowledged for funding via LIGHTer SRA1. GKN Aerospace Sweden is gratefully acknowledged for funding 50 % of this project.

During 2013 there were a number of PhD positions announched from Chalmers focusing on composites. I realized that it was good opportonity to join this research group. I am still very happy and proud to be a part of this group of people, which spans across academia, research institute and industry. I am thankful to Prof. Ragnar Larsson (Chalmers), Dr. Fredrik Edgren (GKN Aerospace) and Prof. Leif Asp (Chalmers) for selecting me among others as a PhD candidate for this position.

The reason I came back to academia from industry as a mechanical engineer working with simulation, was to work with composite materials and in particular strength of carbon fibre reinforced composites. This material has fascinated me ever since I first encountered it in bicycle frames back in the late 90's. It was this exotic material with a huge pricetag and superior strength-to-weight ratio. Times are different now and it seems that this type of composite material finally can be manufactured at reasonable costs, which opens up new possibilities.

I am very grateful to my main supervisor Prof. Leif Asp. You have really been there for me as a mentor, supporting, guiding and reviewing my work. I am also thankful to my co-supervisor Dr. Renaud Gutkin, for his support in general and expertise within compressive failure. I hope that we can continue with the good collaboration that we have had so far.

I would like to thank my mother and father for the love and support. I am thankful to Rena Zielinska who could help our family during the final months of preparation of this thesis. Finally, I would like to thank the love of my life, Hania, kochanie moje. You encouraged me to apply for this PhD position and you have supported me since then.

Thesis

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

Paper A	Molker H., Wilhelmsson D., Gutkin R, Asp L.E. Orthotropic criteria for transverse failure of non-crimp fabric-reinforced composites, *Journal of Composite Materials*, 2016, 50(18), 2445-2458.
Paper B	Wilhelmsson D, Gutkin R, Edgren F, Asp L.E. Numerical analysis of the orthotropic transverse strength of NCF reinforced composites. *Texcomp-12 Conference*, 2015, Raleigh NC, USA
Paper C	Wilhelmsson D, Asp L.E., Gutkin R, Edgren F. Compressive strength and waviness characterisation of unidirectional NCF composites. *Manuscript form*

Paper A: Molker developed the analytical criteria in Paper A and compared to existing work. Wilhelmsson developed the meso-scale finite element model and postprocessing technique. Molker wrote the paper together with Wilhelmsson and with supervision from Gutkin and Asp.

Paper B: Wilhelmsson developed the meso-scale finite element model and postprocessing technique. Wilhelmsson wrote the paper with supervision from Gutkin, Edgren and Asp.

Paper C: Input to the experimental work was supplied by Edgren. Planning and execution of the experimental testing was done by Wilhelmsson with supervision from the co-authors. The method for fibre angle measurement was suggested and developed by Wilhelmsson. The preparation and execution of microscopy was done by Wilhelmsson. The paper was written by Wilhelmsson with supervision from Asp and review from Gutkin and Edgren.

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Part I
Extended Summary

1 NCF composites in aerospace

Carbon Fibre Reinforced Polymers (CFRP) are associated with high specific strength and stiffness. They also have desirable properties such as high damping and high energy absorption [1]. More recent discoveries show that CFRP even have the ability to store electrical energy [2]. The high specific strength and stiffness result in lighter cars and aircraft with a reduced CO_2 footprint.

Historically, this type of high performance composites were first used for military aircraft. This application has been driven by performance, being relatively insensitive to cost. The most common type of CFRP in aerospace applications is pre-impregnated tapes that consist of unidirectional fibres for best performance. These prepreg plies are stacked to form the desired layup and the laminate is then cured in an autoclave. A composite of this type has superior performance, which comes at a relatively high cost.

There are many other industries expanding their use of high performance composites in order to be competitive, like automotive and wind power. The challenge for these industries is to find a good balance between mechanical properties and costs. They are in need of rational manufacturing techniques, which are based on raw materials with lower price such as dry carbon fibre textiles and resin. These materials can then be processed with techniques suitable for large scale manufacturing.

Production for large volumes may be done with Resin Transfer Moulding (RTM), which is a manufacturing technique where a dry fibre textile preform of desired layup is placed in a closed metal tool and infused with resin under heat and pressure. There are many variants but the main difference compared to tape based composites is that the resin is added to a dry textile preform.

There are a number of techniques for textile preforming. Among these, three can be mentioned, i) Tape based prepreg composites, which hold the fibres in placed by semi-cured resin. ii) Textile weaves, where the integrity comes from contact forces from the weaving pattern. iii) Non crimp fabric (NCF) composites, where the fibres are held in place with a thread, either as single unidirectional plies or as a stitched multi-layered configuration. The main benefit with (iii) compared to (ii) is that the fibres become less wavy with an increased strength and stiffness, approaching that of tape based composites (i).

GKN Aerospace, which lead the current project, is focusing on an NCF, similar to the prepreg lamina, but where the fibres are kept in place by a glass/polyamide weft yarn instead of semi-cured resin. This type of NCF offers good performance, design freedom, draping capabilities and low cost. This textile is illustrated in Fig. 1.1.

NCF composites differ from prepregs, mainly on the meso-scale, where the fibres are arranged in bundles of typically 12,000 fibres. This architectural difference implies that the laminate is no longer transversally isotropic as a UD prepreg but rather orthotropic. This is a topic which has been studied in paper A and B. The threads, which hold the fibre

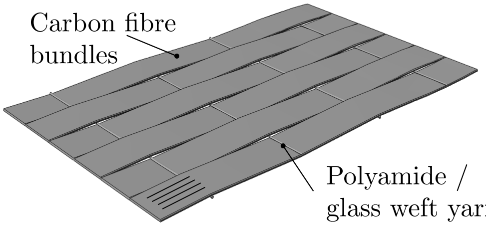


Figure 1.1: Illustration of a unidirectional NCF.

tows affect their shape by the stitch/weave pattern, material and tension. The threads or yarns also contribute to the strength of the laminate which could be a feature worth capturing in models. Obviously, NCF composites have to be homogenized in a different manner compared to tape based composites to capture the behaviour on a meso scale.

The aerospace industry is drawn to NCF composites but there are a number of reasons why prepregs are still used: i) There are no verified sizing methods for NCF composites as there are for prepregs. ii) The compressional strength of NCF composites is lower than for prepregs. The main reason for this is that NCF types have a greater fibre waviness than prepregs. iii) The statistical deviations of strength for NCF composites are greater then for prepregs. The meso-scale architecture of stitched fibre tows results in a less organized structure when compared to prepregs. Statistical approaches have been used successfully in [3] and this kind of statistical approach will be an essential component of future strength predictive capabilities also for NCF composites.

These reasons motivate further research on NCF composites in the project and hopefully this will lead to verified design methodologies such that the aerospace manufacturers can use NCF composites for components loaded in compression. One of the greatest challenges as indicated above, is in compression [4], where the initial fibre misalignment angle is a variable of great importance and uncertainty. The effect of the fibre misalignment angle on stiffness and strength has therefore been studied in the experimental work of paper C.

The ultimate goal for this PhD project is a design tool for GKN Aerospace, where they can asses any compressionally loaded components made from NCF composite materials with an arbitrary lay-up and geometry. Aero-engine components, e.g. outlet guide vanes, are complex in shape, which require high gradient ply-drops. These ply-drops cause 3D stress fields in the structure. A hybrid, composite/metal fan frame demonstrator can be seen in Fig. 1.2 with outlet guide vanes from a NCF reinforced composite material.

This licentiate thesis focuses on matrix initiated failure in NCF composites and the PhD project is focusing on compressive failure of complex NCF composites. Compressive failure is matrix governed which motivates a broader initial study in the project where the latter part will be focusing exclusively on compression and in particular complex aero-engine components.

Figure 1.2: A hybrid composite/metal fan frame for a commercial aircraft engine that was development by GKN Aerospace as demonstrator [5].

2 Matrix driven failure

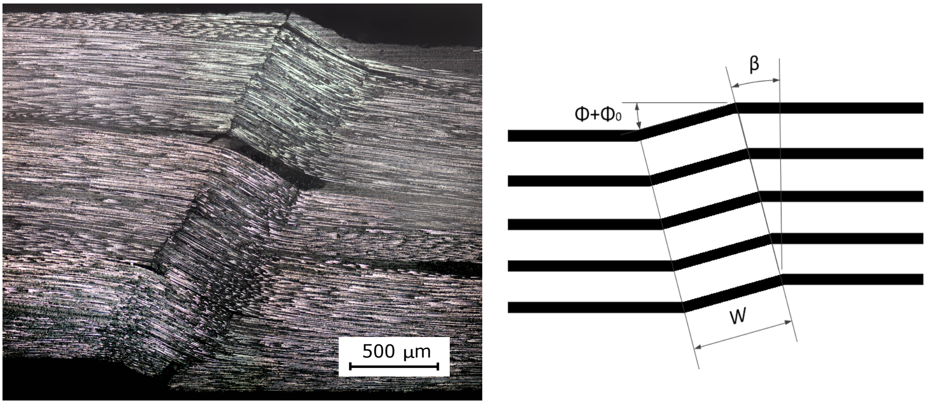
2.1 Failure mechanisms

A fibre reinforced polymer is based on two constituents and failure can be initiated either, within a fibre, somewhere in the matrix or at the interface. The failure mechanisms are however complex due to the heterogeneity on both the micro- and meso-scales. The competing failure mechanisms for a composite ply undergoing compressive loading are kink-band formation, fibre failure, splitting, buckle delamination, elastic microbuckling and shear-band formation [6]. All failure modes are directly dependent on the matrix behaviour except for longitudinal tensile loading where the fibre tensile strength governs the failure mode.

The dominant failure mechanism in longitudinal compression for polymer based composites like carbon-fibre / epoxy is by kink-band formation where the name comes from the shape of the failed fibres. It is also referred to as plastic micro-buckling [6], but is well known today that it is not an instability phenomenon and it is thus more correct to refer to it as kinking or kink-band formation.

The kinking phenomenon is governed by the matrix ability to support the fibres and is largely affected by the shear yield limit of the matrix, τ_y, and the initial fibre misalignment angle ϕ_0. A kinking failure is depicted in Fig. 2.1 from the work in Paper C alongside its schematic illustration with its key parameters. The additional fibre misalignment angle which comes from loading is denoted ϕ, the kink-band angle β and the kink-band width w.

Advanced fractography and numerical models have in recent years contributed with more detailed knowledge of this mechanism and its sequence of events. Pimenta et al. [7] employed these methods to study the different stages of fibre kinking for a T800/924 carbon-epoxy UD prepreg. It can be seen in Fig. 2.2 that three different domains are identified and four material related changes take place. 1) The matrix deforms linearly in the *elastic domain* until onset of matrix yielding. The load is increased a small amount and the peak load is reached. 2) The *softening domain* contains a point where the matrix



(a) (b)

Figure 2.1: (a) A micrograph from the experimental study in Paper C, which shows a kink-band formation out-of-plane for a laminate with 2 mm thickness. Note that not all fibres have been broken in the kink-band. (b) Definition of the geometric parameters for a kink-band.

is fully yielded and micro cracks start to form in the matrix. 3) Shear-bands form on the compressive side of the fibres, which then fail in *the fibre failure domain* due to bending or shear depending on the additional fibre angle ϕ, see Fig. 2.3.

Kink-band formation is dominant for longitudinal compression but there are transitions to other failure modes. Gutkin et al. [9] observed from experiments that initial fibre misalignment angles less then 2° results in fibre shear failure without kinking and large angles dominated by shear will result in splitting along the fibres, see Fig. 2.4. This behaviour was then reproduced with a micro mechanical Finite Element (FE) model. The transition between kinking and splitting is not as well defined, but [9] and [10] shows that it is close to pure shear for a CFRP, i.e. at 45°.

NCF composites behaves different to tape based composites since the meso-scale architecture is different. The fibre tows experience the same failure mechanisms internally as a UD prepreg laminate since they are transversely isotropic within. Disparity appears at the tow level where homogenized tows can be viewed as large fibres that interacts with other large fibres, i.e. tows. A study was made in Paper A where a localized interaction between two bundles where analysed with FEM and this showed a significant strength reduction. There are resin rich regions between the tows which have a meso-scale size and thus are very large compared to the size of a single fibre. At the scale of the fibre tow, there are two failure modes similar to the ones found in UD prepreg, i.e. inter fibre failure (IFF) and fibre failure (FF). At the meso scale a new failure mode is added, namely inter bundle failure (IBF). One example can be seen in Fig. 2.5 from [11], where the crack is propagating in the laminate transverse direction of a 45° ply. In addition, kink-bands in fibre tows are formed. These form in plies with significantly higher off-axis orientation angles than for prepreg composites, even in 45° plies, see Fig. 2.5. In such cases the kinking crack extends normal to the compressive load, whereas the individual kink-bands

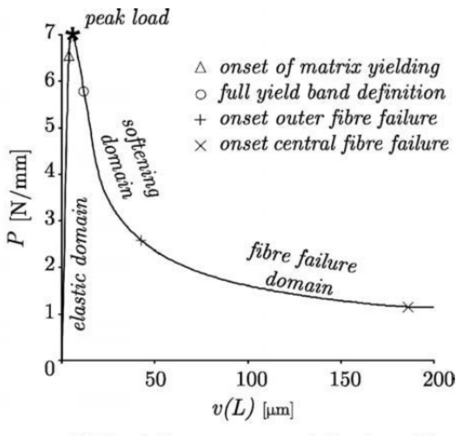


Figure 2.2: Load-displacement curve showing the sequence of events for kinking [7].

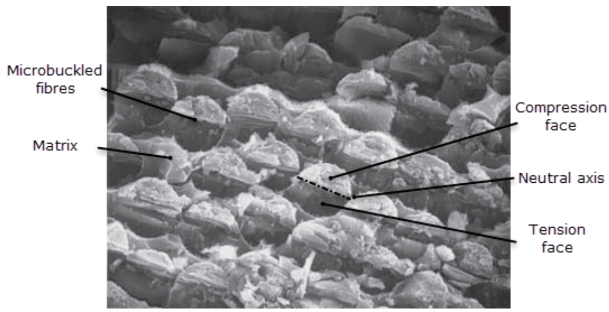


Figure 2.3: Failed fibres due to kinking (x2.5k) [8].

form normal to the fibre tow orientation forming a saw tooth pattern, see Fig. 2.5. This behaviour is beneficial from a fracture toughness point of view and would not occur in a UD prepreg. The heterogeneity on a meso scale also results in an increased damage tolerance of the composite.

Kinking can occur on different length-scales, especially in an NCF composite. A mesoscopic kink-band can be seen in Fig. 2.1 (a) where the kink-band extends through the whole laminate thickness of 2 mm. An example of microscopic kink-band can be seen in Fig. 2.6, where a fibre tow with a thickness of 200 μm have kinked out-of-plane from one of the specimens tested in Paper C.

2.2 Failure criteria

Generally speaking, modelling the stiffness of a composite is rather easy, whereas predicting the onset and propagation of failure and damage is difficult, particularly in compression. The pioneering work by Rosen in 1965 treated compressive failure of a fibre composite as

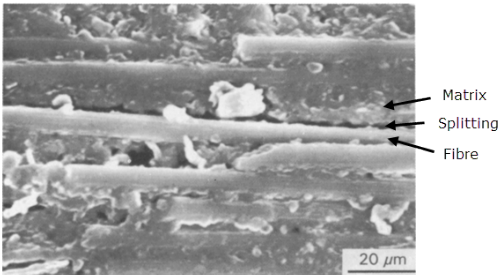


Figure 2.4: Electron micrograph from [10] showing splitting.

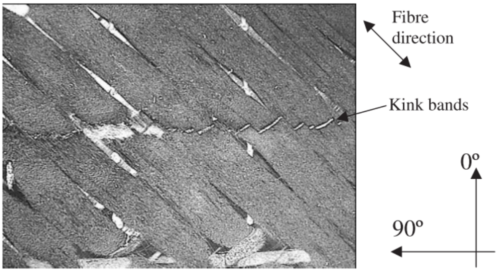


Figure 2.5: Fibre kinking failure of a sandwich, NCF facesheet from [11] loaded in the zero direction.

an elastic microbuckling phenomenon [12]. He established equation (2.1) to predict the compressive strength, where G_{12} and E_{11} are the in plane shear and elastic moduli of the composite, d is the fibre diameter and λ is the buckling wavelength. The compressive strength is equal to the shear moduli of the composite for large λ but as it decreases the second term adds strength in the form of bending resistance. An experiment was conducted by Jelf and Fleck in 1992 to prove the concept of elastic micro-buckling by compressing spaghetti embedded in a silicon matrix [13]. Different lengths were tested and the results agreed well with equation (2.1).

$$X_c = G_{12} + \frac{\pi^2}{3} + \left(\frac{d}{\lambda}\right)^2 E_{11} \tag{2.1}$$

The compressive strength was however overestimated with equation (2.1) of polymer based composites [6]. In 1972, Argon formed the basis for current kinking models when he derived equation (2.2) based on plastic work [14].

$$X_c = \frac{\tau_y}{\phi_0} \tag{2.2}$$

The Argon formula states that the compressive strength X_c is equal to the shear yield limit τ_y divided by the initial fibre misalignment angle ϕ_0. It assumes a kink band inclination angle β of 0° and can be seen as rigid perfectly plastic since there is no consideration of the increased angle during loading.

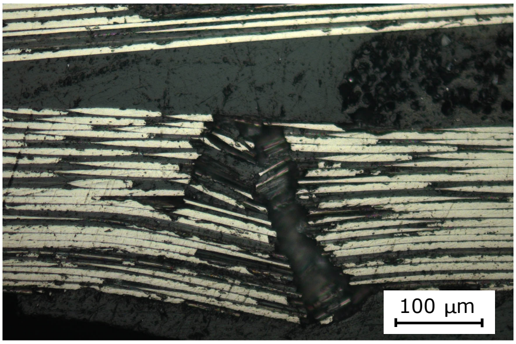


Figure 2.6: A micrograph from the experimental study in Paper C, which shows a kink-band out-of-plane for a fibre tow. A resin rich region can be seen above this kinked fibre tow.

The Argon formula was extended by Budiansky in 1983 to account for an elastic-perfectly plastic composite [15]. The yield strain γ_y in equation (2.3) is introduced to predict the compressive strength, still for β equal to zero.

$$X_c = \frac{\tau_y}{\gamma_y + \phi_0} \tag{2.3}$$

The extended expression by Budiansky was later modified by Budiansky and Fleck in 1990 for the progression of a kink-band formation as

$$\sigma_{11} = \frac{\alpha\tau_y - \tau_{12}}{\phi_0 - \phi}, \tag{2.4}$$

where $\alpha = \sqrt{1 + R^2 tan^2 \beta}$ and $R = \frac{Y_T}{\tau_y}$. The additional angle of the kink-band, which comes from loading is defined as ϕ.

The *Maximum-work theory* by Tsai [16] is commonly referred to as the *Tsai-Hill criterion*. He derived the failure criterion (2.5) based on a yield criterion for anisotropic metals proposed by Hill. The strengths of each ply should be tensile or compressive corresponding to the applied stress. The Tsai-Hill criterion is still used because it is an "easy to use" multi-axial model.

$$\left(\frac{\sigma_{11}}{X_{c/t}}\right)^2 - \left(\frac{\sigma_{11}}{X_{c/t}}\right) - \left(\frac{\sigma_{22}}{X_{c/t}}\right) + \left(\frac{\sigma_{22}}{Y_{c/t}}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 < 1 \tag{2.5}$$

The Hashin failure criteria [17] provide a first step towards phenomenological models and consider four different failure modes, i) Compressive fibre failure, ii) Tensile fibre failure, iii) Compressive matrix failure and iv) Tensile matrix failure.

Physically based models may come from micro-mechanical derivations or phenomenological investigations. They are meant to describe the mechanisms involved with failure to give accurate predictions of strength. Their definition is typically separated for matrix and fibre failure, denoted Inter Fibre Failure (IFF) and Fibre Failure (FF). These criteria have to be used in a model which couples the interaction between matrix and fibre to achieve any practical use. Various constitutive models may be used such as elastic or elasto-plastic for the matrix.

The failure criterion proposed by Puck [18] for matrix failure was the first to use Mohr-Coulomb theory for brittle materials. The criterion was later adopted in the LaRC failure criteria [19], which is a set of physically based criteria for FF and IFF and was originally developed by NASA[1], USA, and Imperial Collage London in the UK. It is based on Puck's criterion for matrix failure and fibre kinking and the maximum stress criterion for fibre failure. The LaRC criteria has undergone minor modifications and are currently at version 5. The LaRC05, which is considered state-of-the art for failure prediction is used in Papers A and B.

Matrix cracking without fibre kinking will occur mainly for loading in the transverse 2-3-plane. This type of failure is predicted with equation 2.6 in LaRC05, where failure occurs for a value greater than one. A compressive failure from load in the 2-direction is shown in Fig. 2.7 (a). The first two terms, basically compare the shear stresses in Fig. 2.7 (d) to the measured strengths in the corresponding planes. The last term with a Macauley bracket is only acting when the normal stress to the fracture plane is positive, where it compares this stress to the allowed transverse tensile stress Y_T. The strength values have a superscript "is", meaning the in-situ strength in a specific laminate configuration. The strength is increased when compressive normal stresses on the fracture plane σ_N are multiplied with the frictional constants η. The physical motivation is that a compressive stress close micro cracks in the brittle matrix and generate frictional forces. Closing the micro cracks is obviously good for the strength of the composite and opening the cracks have a negative effect which is modelled with the third term in equation 2.6. The fracture plane is found in a numerical implementation by trying a number of tentative angles until the highest failure index is found.

$$FI_M = \sqrt{\left(\frac{\tau_T}{S_T^{is} - \eta_T \sigma_N}\right)^2 + \left(\frac{\tau_L}{S_L^{is} - \eta_L \sigma_N}\right)^2 + \left(\frac{\langle \sigma_N \rangle_+}{Y_T^{is}}\right)^2} \tag{2.6}$$

$$FI_K = \sqrt{\left(\frac{\tau_T^m}{S_T^{is} - \eta_T \sigma_N^m}\right)^2 + \left(\frac{\tau_L^m}{S_L^{is} - \eta_L \sigma_N^m}\right)^2 + \left(\frac{\langle \sigma_N^m \rangle_+}{Y_T^{is}}\right)^2} \tag{2.7}$$

As discussed in section 2.1, fibre kinking is also governed by the behaviour of the matrix. Thus, fibre kinking can be predicted using equation 2.7, which is a similar expression to equation 2.6. The main difference is that applied stresses have a superscript m, which indicates a transformation to a misaligned coordinate system. First, a potential kink-plane is found, similar to the illustration in Fig. 2.7 (d) but typically denoted ψ as in [19]. The misaligned reference frame used to predict failure by kinking then rotates with the angle $\phi_0 + \phi$ in Fig. 2.1. Thus, it considers both the initial misalignment angle ϕ_0 which is characterized in Paper C and the additional angle ϕ from loading. Note that the first term will be negligible in the case of longitudinal compressive loading since shear stresses in the transverse plane τ_T will be small. Fibre kinking has a transition to *matrix*

[1]National Aeronautics and Space Administration

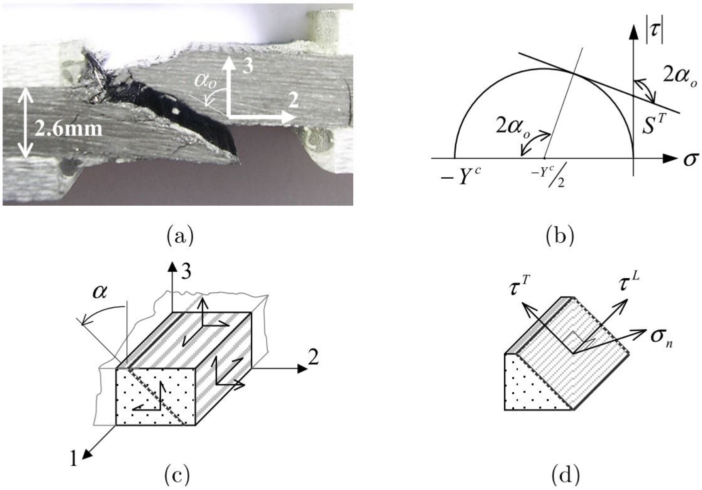


Figure 2.7: Puck's failure criteria essentials from [20]. a) Transverse compression failure for a CFRP composite. b) Fracture plane for a 3D state. c) Definition of stresses acting on the fracture plane. d) Geometrical representation of the Mohr-Coulomb criterion.

splitting for large ϕ_0. The LaRC criteria states that fibre kinking occurs if $\sigma_{11} < -X_c/2$ and *matrix splitting* if $-X_c/2 < \sigma_{11} < 0$.

The failure criteria in equation 2.6 was used in paper A and B to predict the onset of matrix failure from transverse loading. As seen, there is a great similarity between this failure criterion and that in equation 2.7, which is used to predict failure initiation by kinking. Thus, the work in Paper A and B is directly linked to the main goal of the project, which is to predict compressive failure.

2.3 Finite elements models

The Finite Element Method (FEM) is a numerical method with wide use in industry and academia for solving various type of field problems. Pioneering work using computers started in the middle of the 20th century and is today common practise for solving mechanical problems. It is a powerful tool since it allows one to represent virtually any type of geometry. This is also one of the main concerns, dealing with the compromise between modelling resolution and computational cost. It has been noted early in this research project that the model should not be too complex. It should only include features which are important for the compressive strength of an NCF composite.

The first attempts to model continuous fibre composites was focused on the constituents, fibre and matrix on a micro-mechanical scale. Whereas nowadays (2016) it is very much focus on modelling complex 3D-textiles. Fabrics such as NCF and different types of weave require sophisticated models to represent the meso-level architecture of the composite. Innovative representative volume elements (RVE), which utilize symmetry are common in this application.

A composite consists of thousands or millions of individual fibres embedded in a matrix material. To model each of these fibres in the analysis of a component is not feasible for at least two reasons, i) The number of finite elements needed to discretise the geometry would exceed the limit of the current computational limit. ii) The actual position and orientation of each individual fibre is not known. Even if all the fibres with their exact position and geometry could be simulated it is not sure how one should treat the stresses from such a model in strength prediction. The concept of treating the composite on three scales, micro, meso and macro with different models which can share information has therefore become very used.

By homogenization it is meant that the response of several phases (constituents) such as fibres and matrix is made homogeneous and replaced with only one phase such as the ply properties in a composite. This homogenized response is valid for a material on a larger length-scale than which the individual phases are modelled. The most correct RVE of a meso-scale domain has the same size as the macroscopic one but that is not really efficient. The whole idea when choosing an appropriate RVE domain is to have the correct homogenized response. One benefit with CFRP composites is that they are more or less repetitive and in this case we can talk about a repetitive unit cell (RUC) acting as an RVE. One such example is from [9] where the compressive behaviour of a "ply" was modelled with one fibre, given boundary conditions such that it behaved as an infinite amount of fibres in the plane. We are then talking about Periodic Boundary Conditions (PBC). These boundary conditions are written in a general format as

$$\vec{\boldsymbol{x}}^{+}\vec{\boldsymbol{x}}^{-} = \boldsymbol{F_M} \cdot \left(\vec{\boldsymbol{X}}^{+}\vec{\boldsymbol{X}}^{-}\right) \tag{2.8}$$

The actual position vector is denoted $\vec{x}$, the initial position vector $\vec{X}$ and the deformation gradient tensor F_M. The plus and minus signs refers to opposite edges of the RVE. Other types of boundary conditions applicable to an RVE are Dirichlet and Neumann. The PBC is acting in between these two extreme choices and considered to give better estimation of the overall properties.

As mentioned above, homogenized properties are supposed to be used at a higher length scale. The step from micro to meso level where bundles obtain homogenized properties may be seen as less problematic than the step from tow to laminate. The diameter of a carbon fibre is typically 7 μm and the smallest dimension of a bundle (out of plane) is around 300 μm. This homogenization step becomes questionable however if local imperfections are considered as in Paper A and B. The homogenization performed from ply (meso) to laminate (meso) level is tricky. On the macro level, classical laminate theory (CLT) is typically used where each ply is considered to be homogeneous, but the thickness of a ply is very close to the thickness of a bundle.

If the lower end of the micro length scale is considered, then individual fibres are represented with surrounding matrix for a model of stiffness and strength. This may be done in a deterministic manner with an RUC [21], as in Fig. 2.8 or as randomly distributed fibres in an RVE [22]. The main purpose is to calculate properites of a UD ply or to use its homogenized properties in conjunction with CLT in laminate consisting of UD plies.

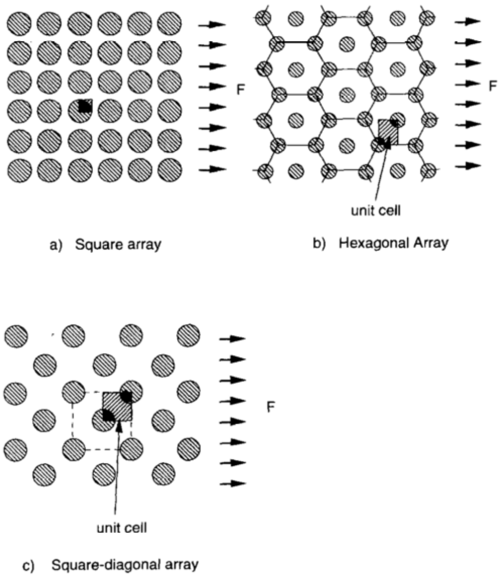


Figure 2.8: Different types of RUC:s for micro-mechanical modelling from [21].

Most of the modelling in future work is expected to be at the meso-scale and it is thus the most important one. It is at this level where the architecture of the textile is considered with homogenized input from a micro-mechanical FE model or experiments such as stiffness and strength. The bundles may then be seen as an "extra composite level" when compared to the UD prepreg composite which impose additional complexity.

A widely cited article by Stephan Lomov "Meso-FE modelling of textile composites: Road map, data flow and algorithms" [23] explains the main steps for FE modelling of a textile composite on the meso-scale. Nine steps are defined for modelling on the meso-scale (1) Building a model of internal geometry of the reinforcement; (2) Transferring the geometry into a volume description ("solid" CAD-model); (3) Preparation for meshing: correction of the interpenetration of volumes of yarns in the solid model and providing space for the thin matrix layers between the yarns; (4) Meshing; (5) Assigning local material properties of the impregnated yarns and the matrix; (6) Definition of the minimum possible unit cell using symmetry of the reinforcement and assigning periodic boundary conditions; (7) Homogenization procedure; (8) Damage initiation criteria; (9) Damage propagation modelling.

It is very interesting from an industrial perspective to use homogenized plies with CLT in a multi-layered shell model or as discrete layers in a solid model. It is not feasible to model fibre tows in strength assessments of larger aero-engine components. The big question is how much of the stiffness and strength input on a ply level that will be obtained with numerical predictions and with experimental work respectively. An experimental approach typically adds complexity and costs but has the special benefit of including phenomena which we cannot model or even do not know of. This is a research question which will be given special attention in the next part of the project. It is of great importance that the chosen approach complies with a feasible, industrial route.

3 Summary of appended papers

3.1 Paper A: Orthotropic criteria for transverse failure of non-crimp fabric-reinforced composites

In this paper, a set of failure criteria for transverse failure in non-crimp fabric-reinforced composites is presented. The proposed failure criteria are physically based and take into account the orthotropic character of non-crimp fabric composites addressing the observed lack of transverse isotropy. Experimental data for transverse loading out-of-plane in combination with in-plane loads are scarce. Therefore, to validate the developed criteria, experimental data are complemented with numerical data from a representative volume element model using a meso-micromechanical approach. The representative volume element model also provides a deeper understanding of how failure occurs in non-crimp fabric composites. Strength predictions from the developed set of failure criteria show good agreement with the experimental and numerical data.

3.2 Paper B: Numerical analysis of the orthotropic transverse strength of NCF reinforced composites

This paper describes the numerical model developed for Paper A, where a finite element model has been developed for strength predictions in the transverse plane of Non-crimp fabric (NCF) reinforced composites. The numerical model considers a simplified representative volume element (RVE) description of the composite. The RVE consists of two material phases – the impregnated fibre bundle and the surrounding matrix material. The model considers competing failure modes initiating either in the fibre bundle or the surrounding matrix material. Intrabundle failure initiation in the homogenized fibre bundle is predicted with the Mohr-Coulomb criterion (LaRC), whereas failure initiation in the surrounding matrix material is predicted with the Raghava yield criterion. The aim of this study is to analyse the influence of fibre bundle geometry imperfections and the competing failure modes on the orthotropic performance in the transverse plane for NCF composites. Failure envelopes for multi-axial loading are generated by a superposition, post-processing technique, which is very fast but limited to a linear response. Consideration of bundle geometry imperfections allows for prediction of the low out-of-plane tensile strength of the NCF composite observed in experiments.

3.3 Paper C: Compressive strength and waviness characterisation of unidirectional NCF composites

A comprehensive test series have been made of non-crimp fibre composites to gain fundamental understanding of how different parameters control the compressive strength. A total of 140 specimens have been tested from 13 different laminates. A method to characterize the out-of-plane waviness have also been developed in conjunction to the compressive testing. It is a direct method based on optical microscopy and a Matlab script where the angle of individual fibres is measured. In this study, we shown that the compressive strength is reduced to half when the out-of-plane waviness increases by a factor of two. A group of laminates with a mean misalignment angle of 1.3° demonstrated a compressive strength of approximately 750 MPa, while another group of laminates with a mean misalignment angle of 2.6° resulted in a compressive strength of approximately 400 MPa. There is also a correlation between the out-of-plane waviness and stiffness reduction. The knock-down factor of stiffness in the longitudinal direction is approximately 7 % / degree mean misalignment angle.

4 Conclusions and outlook

The contribution of paper A and B refers to the fundamental understanding of the meso structure with tows, specific for NCF composites. A new failure criterion has been developed to take into account the orthotropic properties in the transverse plane (2-3), especially the demonstrated lower tensile strength out-of-plane compared to the in-plane. It is debatable how much difference it is on these properties in real laminates but there is now a criteria for dealing with this. It should be noted that transverse isotropy for composites is an approximation where not even tape-based laminates are 100 % transversely isotropic. The criterion is a modification of an available and widely accepted state-of-the art criterion for UD, namely LaRC. These orthotropic strength properties in the transverse plane (2-3) were also studied with a finite element model, based on a representative volume element on the meso-scale. We have with this model been able to find at least one possible explanation to the difference in tensile strength between the 2- and 3-directions. The local interaction between two bundles simply result in a stress concentration which lowers the strength.

The experimental work in the paper C is very extensive, given that all tests focused on compression testing of unidirectional NCF composites. A total of 13 different configurations of unidirectional NCF composites have been considered in this work, which makes it unique and valuable for future work in the project. In conjunction with the compression test campaign, a method to measure fibre misalignment angles has been developed. Fibre misalignment angle measurements obtained were used to study how the waviness out-of-plane influence the longitudinal stiffness and strength of the composite. As expected, fibre waviness is found to have a strong adverse effect on the compressive mechanical properties of the composite. The measured compressive strength was found to be reduced to half as the mean fibre misalignment angle was doubled. We were also able to demonstrate a correlation between the out-of-plane waviness and stiffness reduction. A knock-down of the stiffness in the longitudinal direction of approximately 7 % per degree mean misalignment angle has been identified.

Paper A-C all aimed at basic understanding of matrix controlled failure mechanisms, specific to NCF composites. They are contributions to research in this area but also to be used directly for the second part of the project. In the end, a method will be delivered to GKN aerospace, which means that our research should now become more applied and oriented towards their needs. From the author's point of view, there is a gap to fill. Strength calculations of real composite structures are missing, where the level of technology in all parts is state-of-the art. This is generally not the case for works aiming at strength predictions of real components. The probabilistic thinking is also lacking in these works. The probabilist thinking is otherwise something that the entire aviation industry is based on. One interesting way forward is an holistic approach where the best failure criteria are combined with tailored testing in an efficient FE model to structurally design an actual component with statistically secured margins.

References

[1] B. D. Agarwal, L. J. Broutman, and K. Chandrashekhara. *Analysis and Performance of Fiber Composites*. 3rd ed. Hoboken, New Jersey: John Wiley and Sons, 2006.

[2] T. Carlson, D. Ordéus, M. Wysocki, and L. E. Asp. "Structural capacitor materials made from carbon fibre epoxy composites". In: *Composites Science and Technology* 70 (2010), pp. 1135–1140.

[3] M. Whiteside, S. T. Pinho, and P. Robinson. "Stochastic failure modelling of unidirectional composite ply failure". In: *Reliability Engineering & System Safety* 108 (2012), pp. 1–9.

[4] F. Edgren. "Physically Based Engineering Models for NCF Composites, PhD thesis". PhD Thesis. Royal Institute of Technology, KTH, 2006.

[5] GKN Aerospace webpage. *Boost for GKN Aerospace and the Swedish National Green Aero-engine demonstrator programme*. 2014. URL: `http://www.gkn.com/aerospace/media/news/Pages/...`.

[6] N. A. Fleck. "Compressive failure of fibre composites". In: *Advances in Applied Mechanics* 33 (1997), pp. 43–117.

[7] S. Pimenta, R. Gutkin, S. T. Pinho, and P. Robinson. "A micromechanical model for kink-band formation: Part I — Experimental study and numerical modelling". In: *Composites Science and Technology* 69 (2009), pp. 948–955.

[8] E. S. Greenhalgh. *Failure Analysis and Fractography of Polymer Composites*. 1st ed. Cambridge, UK: Woodhead Publishing, 2009.

[9] R. Gutkin, S. T. Pinho, P. Robinson, and P. Curtis. "Micro-mechanical modelling of shear-driven fibre compressive failure and of fibre kinking for failure envelope generation in CFRP laminates". In: *Composites Science and Technology* 70 (2010), pp. 1214–1222.

[10] P. Jelf and N. A. Fleck. "The failure of composite tubes due to combined compression and torsion". In: *Journal of materials science* 29 (1994), pp. 3080–3084.

[11] F. Edgren, L. E. Asp, and P. H. Bull. "Compressive Failure of Impacted NCF Composite Sandwich Panels - Characterisation of the Failure Process". In: *Journal of Composite Materials* 38 (2004), pp. 495–514.

[12] B. Rosen. "Mechanics of composites strengthening". In: *American Society of Metals* (1965), pp. 37–75.

[13] P. Jelf and N. A. Fleck. "Compression Failure Mechanisms in Unidirectional Composites". In: *Journal of Composite Materials* 26 (1992), pp. 2706–2726.

[14] A. S. Argon. "Fracture of composites". In: *Treatise on materials science and technology* 1 (1972), pp. 79–114.

[15] B. Budiansky. "Micromechanics". In: *Computers & Structures* 16 (1983), pp. 3–12.

[16] S. W. Tsai. "Strength Theories of Filamentary Structures, Fundamental Aspects of Fiber Reinforced Plastic Composites". In: *Interscience* (1968).

[17] Z. Hashin. "Failure Criteria for Unidirectional Fiber Composites". In: *Journal of Applied Mechanics* 47 (1980), pp. 329–334.

[18] A Puck and H Schürmann. "Failure analysis of FRP laminates by means of physically based phenomenological models". In: *Composites Science and Technology* 62 (1998), pp. 1633–1662.

[19] S. T. Pinho, C. Dávila, P. P. Camanho, L. Iannucci, and P. Robinson. "Failure models and criteria for FRP under in-plane or three-dimensional stress states including shear non-linearity". In: *NASA/TM-2005-213530* (2005).

[20] S. T. Pinho, L. Iannucci, and P. Robinson. "Physically-based failure models and criteria for laminated fibre-reinforced composites with emphasis on fibre kinking: Part I: Development". In: *Composites Part A: Applied Science and Manufacturing* 37 (2006), pp. 63–73.

[21] L. E. Asp, L. Berglund, and R. Talreja. "Prediction of matrix-initiated transverese failure in polymer composites". In: *Composites Science and Technology* 3538 (1996), pp. 1089–1097.

[22] A. Melro, P. Camanho, and S. T. Pinho. "Influence of geometrical parameters on the elastic response of unidirectional composite materials". In: *Composite Structures* 94 (2012), pp. 3223–3231.

[23] S. Lomov et al. "Meso-FE modelling of textile composites: Road map, data flow and algorithms". In: *Composites Science and Technology* 67 (2007), pp. 1870–1891.