THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN SOLID AND STRUCTURAL MECHANICS

Compressive failure of unidirectional NCF composites

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Cover:
Analysis of compressive failure: (a) A micrograph aligned with the kink-plane, (b) fibre misalignment measurements, (c) local material orientations in FEM, (d) finite element simulation to obtain failure initiation location and failure stress (the color bar shows matrix damage where 1 is equal to full damage), (e) defect severity analysis in Matlab.

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Abstract

With more people flying every year, new technologies are needed to reduce our impact on the environment. One option is to reduce the energy used in flight by introducing lighter materials such as carbon fibre reinforced polymers (CFRP). This type of material can be used in cold to moderately high temperature regions of the aero-engine and the current trend is to maximize its use. The current use of CFRP in aerospace is dominated by tape-based composites (pre-pregs), which are processed in an autoclave. This offers optimum performance but at high cost. 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. Composites based on dry textile reinforcements such non-crimp fabric (NCF) offers potential cost savings over tape-based pre-preg materials, with good mechanical properties in general. One problem with the textile composites is their relatively low strength in longitudinal compression. This is due to the higher degree of fibre waviness generated by the textile architecture. The aim with this research projects is to develop failure criteria and computational methods needed for reliable and efficient design of aero-engine components from textile composites.

When longitudinally arranged fibres in a composite are wavy, local misalignments are generated with respect to the load axis. These induce shear stresses, critical to compressive failure. The sensitivity to fibre misalignments is generally well known. Yet, no systematic measurements have previously been conducted of its spatial distribution. Existing models for strength prediction consider fibre misalignment representations as either, a scalar value, periodic or random. Our approach is instead based on measurements of fibre misalignment with high accuracy and high spatial resolution in a large number of samples. Misalignment data has been used for statistically based direct assessments of compressive strength. The misalignment data has also been used to calibrate models for strength prediction and for numerical studies to increase understanding. The diversity in studied fibre misalignments are not generated by artificial means, but instead reflect upon the relevant material architecture and processing principles.

Many studies on compressive failure seek to model or understand details on kink-band formation. We have instead maintained a clear focus on failure initiation, relevant to aero-engine components. We have addressed the extreme sensitivity of kink-band initiation to fibre misalignment angle that subsequently lead to compressive failure within a ply. We conclude that kink-band initiation in practical fibre composites is a coordinated kinematic event. It requires studies of regions with real (measured) spatial distributions of fibre misalignment angles. These studies are preferably conducted on 2D micrographs parallel to the kink-plane.

Keywords: Aerospace, NCF composite, Compressive failure, Fibre misalignment

To Hanna and my children, Leonora and Frank ♡

Preface

This work has been performed at Chalmers University of Technology in Gothenburg, Sweden, during the period of December 2013 to March 2019. Major parts of the research has been done at the Division of Material and Computational Mechanics, Department of Industrial and Materials Science. Experimental work for Paper B, C and D were performed in the laboratory at Rise Sicomp, Mölndal.

Dr. Fredrik Edgren initiated the project KOMPRESS "Compressive failure of complex NCF composite structures" at GKN Aerospace in Trollhättan, Sweden and later assisted in an extension. Mr. Dennis Rikemanson at GKN Aerospace continued on GKN:s behaf from May 2018 and has since then involved KOMPRESS in the test program at GKN. Rise Sicomp (former Swerea Sicomp) has been involved in KOMPRESS and their contributions are also acknowledged. 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 Academy. GKN Aerospace Sweden is gratefully acknowledged for funding 50 % of this project. The computations in Paper C, D and E were performed on resources provided by Chalmers Centre for Computational Science and Engineering (C3SE).

In this thesis, I have tried to avoid direct content from the appended papers in the extended summary. The extended summary in this thesis is meant to reflect upon the papers in a larger context and to discuss certain matters a bit more freely. Based on the research and my experience as a CAE engineer, I give recomendations for GKN aerospace on how to proceed with the challange of compressive strength assessments.

The time as a PhD student has been both challening and rewarding. My children Leonora and Frank were born in 2014 and 2016 and I am so proud to be their father. They have kept me busy but also given me energy and joy to take up work again on Monday morning. The love and support from my wife Hanna has been important during these years. I also want to thank my parents for their love and support.

I have very much enjoyed working with Prof. Leif Asp and the many discussions over the years. Leif is a person that I respect very much and he has put much effort into my PhD project and guided me as mentor, not only in research but also on how to manage various aspects of the PhD project. Leif's energy and leadership has never sieced to amaze me and I am truly greatful that I have had the fortune to work together with him. I have also enjoyed many discussions on compressive faliure with Dr. Renaud Gutkin and learnt many things. I am thankful for supervision in the first years and also for the involvment in the last Paper. I want to acknowledge Dr. Søren Fæster and Prof. Lars Mikkelsen from DTU in Denmark for the nice collaboration in Paper D. I am honored that Prof. Ramesh Talreja from Texas A&M in the USA found interest in our research and I am thankful for his contribution to Paper E. I have shared the office with my friend Dr. Siavash Shoja at Chalmers for four years and I am grateful for the support in research and the very nice time in the office.

Gothenburg, February 2018
Dennis Wilhelmsson

Thesis

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

Paper A	Dennis Wilhelmsson, Leif E. Asp. A high resolution method for characterisation of fibre misalignment angles in composites, *Composites Science and Technology*, **165** (2018), 214-221.
Paper B	Dennis Wilhelmsson, Renaud Gutkin, Fredrik Edgren, Leif E. Asp. An experimental study of fibre waviness and its effects on compressive properties of unidirectional NCF composites, *Composites Part A: Applied Science and Manufacturing*, **107** (2018), 665–674.
Paper C	Dennis Wilhelmsson, Leif E. Asp, Renaud Gutkin, Fredrik Edgren. Fibre waviness induced bending in compression tests of unidirectional NCF composites, *in: Proceedings of the 21st European conference on composite materials ICCM21, Xi'an, China, 2017.*
Paper D	Dennis Wilhelmsson, Søren Fæster, Lars Mikkelsen, Leif E. Asp. Influence of in-plane shear on kink-plane orientation in a unidirectional fibre composite, *Composites Part A: Applied Science and Manufacturing*, **119** (2019), 283–290.
Paper E	Dennis Wilhelmsson, Ramesh Talreja, Renaud Gutkin, Leif E. Asp. Compressive strength assessment of fibre composites based on a defect severity model, *Submitted for publication 2019.*

Paper A: Dennis Wilhelmsson proposed the work. Dennis Wilhelmsson developed the methodology and wrote the paper with supervision from Leif Asp.

Paper B: Leif Asp and Fredrik Edgren suggested the experimental variations. Dennis Wilhelmsson suggested the approach. Dennis Wilhelmsson performed experimental tests together with engineers at Rise Sicomp with supervision from Renaud Gutkin and Leif Asp. Dennis Wilhelmsson wrote the paper with supervision from Leif Asp. Renaud Gutkin and Fredrik Edgren proof-read the paper and contributed with suggestions and comments

Paper C: Dennis Wilhelmsson suggested the approach. Dennis Wilhelmsson performed DIC measurements together with engineers at Rise Sicomp. Dennis Wilhelmsson performed numerical work and wrote the paper with supervision from Leif Asp. Renaud Gutkin and Fredrik Edgren proof-read the paper and contributed with suggestions and comments.

Paper D: Dennis Wilhelmsson suggested the approach. Sören Fæster and Lars Mikkelsen at DTU Wind Energy, Denmark, performed the CT scans. Dennis Wilhelmsson performed experimental tests together with engineers at Rise Sicomp. Dennis Wilhelmsson performed numerical work and wrote the paper with supervision from Leif Asp. Sören Fæster and Lars Mikkelsen proof-read the paper and contributed with suggestions and comments.

Paper E: Dennis Wilhelmsson suggested the approach. Dennis Wilhelmsson performed numerical work with supervision from Leif Asp and input from Renaud Gutkin and Ramesh Talreja. Renaud Gutkin developed the Material model. Dennis Wilhelmsson wrote the paper with contributions from the co-authors.

Contents

Part I
Extended Summary

1 Introduction

1.1 Background and motivation

With increasing traffic levels, the civil aircraft industry is in constant need of new technologies to make air travel sustainable. One such technology is light materials to reduce the energy consumption in flight. Carbon fibre reinforced polymer (CFRP) materials have been successfully introduced to primary load-carrying parts such as the central wing box, fuselage sections, rear fuselage, floor beams, wing ribs, etc. There are other areas in the aircraft where components traditionally made from metals can be replaced by composite materials, for instance parts of the engines. CFRP fan-blades were successively introduced in a civil aircraft engine (GE90) in 1994 and the current trend is to maximize the use of CFRP in the cold regions of the engine and explore the possibility for use also in regions with moderately high temperatures. A hybrid, composite/metal fan frame demonstrator by GKN Aerospace can be seen in Fig. 1.1 with outlet guide vanes from a NCF reinforced composite material.

Figure 1.1: *A hybrid composite/metal fan frame for a commercial aircraft engine that was development by GKN Aerospace as demonstrator.*

Historically, high performance composites were first used in 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 semi-cured 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 but it comes at a high cost.

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 project was initiated by GKN aerospace (former Volvo Aero) and links to earlier work by Edgren [1]. Edgren

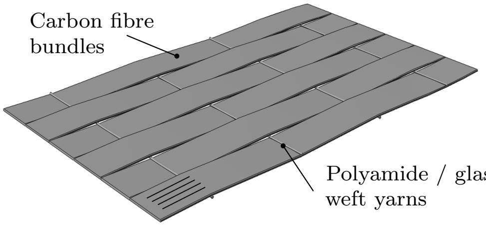


Figure 1.2: *Illustration of a unidirectional NCF used in the current research project.*

focused on engineering models for NCF composites and approached this with studies on formation of damage in tension [2], compressive failure of impacted NCF sandwich panels [3], analytical constitutive models [4], compressive failure [5] and failure from combined compression and shear [6]. All studies were performed on NCF composite laminates. Whereas Edgren considered different mechanical aspects of the NCF composite material, the current project focus solely on the mechanical behaviour in longitudinal compression.

The preferred route is an automated, out-of-autoclave manufacturing method using resin transfer moulding (RTM) with a non crimp fabric (NCF) as reinforcement. RTM is a manufacturing technique where a dry textile preform of desired layup is placed in a closed metal tool and infused with resin under heat and pressure [7]. There are many variants but the main difference compared to tape based composites is that the resin is added to a dry textile preform such as the one in Fig. 1.2. 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. However, one limiting factor for their use in primary structures is their relatively low strength in longitudinal compression. The aim is to use NCF composites also in compression, but currently the utilization has been limited to tensile loaded structures. The rear pressure bulkhead for the Airbus A380 aircraft shown in Fig. 1.3 is an example of such structure. The bulkhead is manufactured using an NCF with resin film infusion (RFI) processing technique [8].

Longitudinal compressive failure is governed by shear instability, where longitudinal shear stresses are generated from misalignments of the fibres with respect to the loading axis. An example of fibre misalignment out-of-plane from the NCF in Fig. 1.2 can be seen in the micrograph in Fig. 1.4. Fibre misalignments associated with fibre waviness are generated by the textile architecture and processing parameters. Thus, more pronounced fibre waviness lead to higher shear stresses with lower strength in compression as a result. The need to accurately consider fibre misalignments from fibre waviness in strength assessment is highly relevant.

Figure 1.3: *NCF composite bulkhead for the Airbus A380 civil aircraft (Photograph from EADS).*

Figure 1.4: *Micrograph of an NCF composite with high fibre waviness out-of-plane. The section is 20 mm in the longitudinal direction and 2 mm in the thickness direction. The weft yarns coming out of the image can be seen as dark elliptical regions.*

1.2 Aim and scope of work

The aim of the current research project "Compressive failure in complex NCF composite structures" (KOMPRESS) is to develop failure criteria and computational methods needed for reliable and efficient design of aero-engine components from textile composites. The complex shapes require new layup strategies with a large number of ply-drops due to aerodynamic constraints. Based on the open literature, fibre waviness was initially identified as the main concern with respect to compressive strength. A new potential interaction of fibre misalignments on different length scales as a consequence of ply drops, draping and textile architecture was also identified. To reach the aims of the project we have during the project revised the scope of work. Below, I discuss how the first project plan has been considered.

Fibre waviness associated with ply drops was identified as important. More specifically, potential failure initiation in wavy continuous plies that are in close proximity of discontinuous plies. The micrograph in Fig. 1.5 is from a study within KOMPRESS on the effect of ply drops on compressive strength. In this figure, a continuous ply is artificially given a waviness from two neighbouring ply drops. The conclusion, based on our own study and a set of very thorough studies [9–11], is that isolated, continuous plies next to ply drops are not prone to fail due to their ply waviness. As shown in the studies by Wisnom and co-workers [10, 11], compressive failure initiation in these regions is prone to initiate by delaminations. Large and steep ply drops result in a critical normal stress with delamination as result. Even though inter-laminar failure initiation by delamination can cause compressive collapse, we chose to limit the scope of work to intra-laminar failure by fibre kinking as we identified this to be more critical. Furthermore, we discard the idea of an interaction effect of misaligned fibres in tows and misaligned tows from ply drops.

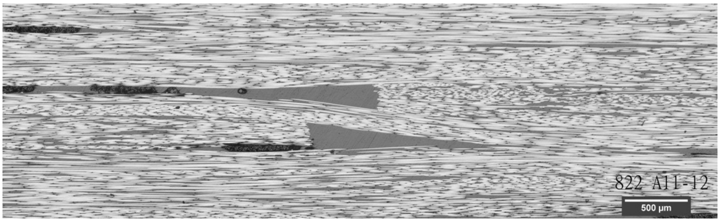


Figure 1.5: *Micrograph of a test specimen with a purposely inserted ply drop. Specimens were manufactured by Rise Sicomp according to the "Constant-thickness ply-drop method", developed by ACCIS, University of Bristol [9].*

We have studied the interaction of fibre misalignments on different length scales as a consequence of the textile architecture. In paper E, we give new insight to how misaligned fibre regions (defects) with different characteristics initiate failure. One such characteristic is their size that ranges from approximately 0.2 mm to 2 mm. Thus, we have studied regions with one order of magnitude difference in length. More importantly, we present a new defect severity concept to determine the critical region of fibre misalignment within a region of fibre waviness.

We have studied the interaction of fibre misalignments on different length scales as a consequence of the draping. When plies are draped on a double curved surface, large regions of entire plies may be misaligned with respect to a nominal (or preferred) orientation. As a consequence, local fibre misalignments on the micro-meso scale due to fibre waviness may have a uniform misalignment superimposed from the meso-macro scale. In Paper D, we therefore study the problem with unidirectional laminates that were produced with off-axis angles between 0-20°.

A reliable design methodology has to be statistically based. We have approached this with a large number samples in our studies, where we relate fibre waviness misalignment data to compressive properties. In fact, the study in Paper B is based on the largest characterisation of fibre waviness to date. Our philosophy has been to study authentic fibre waviness, generated by the NCF architecture and the RTM process parameters. We have avoided notched specimens to trigger failure and instead used normal-size test specimens, tested according to well established standards.

CFRP Laminates are in general multidirectional, with unidirectional plies stacked in different orientations. We have studied longitudinal compression on a ply-level with unidirectional laminates. Thus, we have studied the main load carrying plies (0°) of a multidirectional laminate ex-situ. Thereby, we have not considered any potential effects of different layup configurations.

Research has been conducted in the current project beyond the scope of longitudinal compression and thus not included in this thesis. In the first paper [12], 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. Also, a finite element model has been developed for strength predictions in the transverse plane of the NCF reinforced composites. This contribution has been described in more detail by a separate paper [13]. In that paper, a micro-meso-mechanical, finite element approach is used to complement scarce experimental data with numerical predictions. This research is relevant for KOMPRESS, considering the studied NCF material.

2 Longitudinal compression failure of unidirectional fibre composites

A vast amount of studies exist on failure and strength modelling of fibre composites in compression. Some 10,000 publications since the mid 1990's has been mentioned [14]. The extensive amount of studies on compressive behaviour are driven by a number of factors. Firstly, the compressive strength is typically 60 % of that in tension and is therefore critical in strength assessments. Secondly, the unstable behaviour during compression failure is difficult to observe, where the sequence of events are closely spaced in time. Post-mortem studies are also difficult to conduct due to the explosive nature of the compressive collapse. Moreover, compressive strength is difficult to model due to its extreme sensitivity on fibre misalignment angles.

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. Longitudinal tensile failure is example of a "pure" fibre failure mode, where the fibre tensile strength governs the strength of the composite. But most failure modes are initiated and controlled by the matrix material. In this section, I will discuss the relevant failure modes and mechanisms associated with compressive failure with focus on fibre kinking of CFRP at the micro-meso scales.

There are three uniquely different failure mechanisms in compression: i) fibre shear failure, ii) fibre kinking and iii) splitting, and these are a function of the fibre misalignment angle shown in Fig. 2.1. The most common failure mechanism relevant for the largest span of misalignment angles is fibre kinking.

At the largest length scale (macro/component/specimen), failure is stochastic and dependent on the specific order and modes by which failure occurs on the micro-meso scales. In Fig. 2.2, we can see two examples of quasi-isotropic NCF specimens tested by GKN aerospace. Failure is complex with many of the plies nested into each other.

Argon (1972) [15] was the first to consider a fibre misalignment angle in a model of compressive strength of fibre composites. Wisnom (1990) [16] continued on the effect of fibre misalignment due to fibre waviness (fibre curvature) on compressive strength. The first theoretical work by Wisnom was followed by a numerical study [17], where he

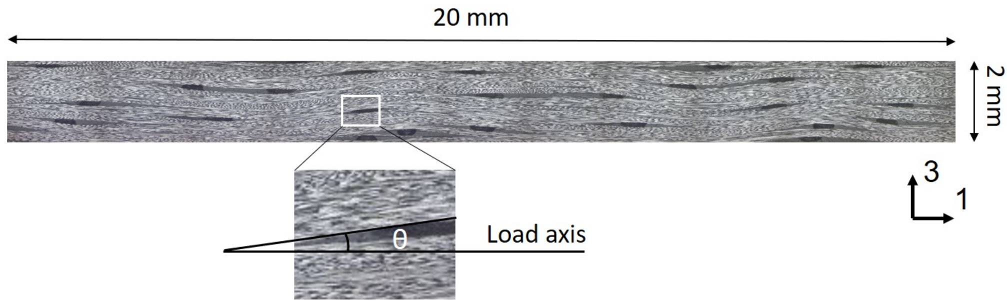


Figure 2.1: *Local fibre misalignment angle θ in a region of fibre waviness.*

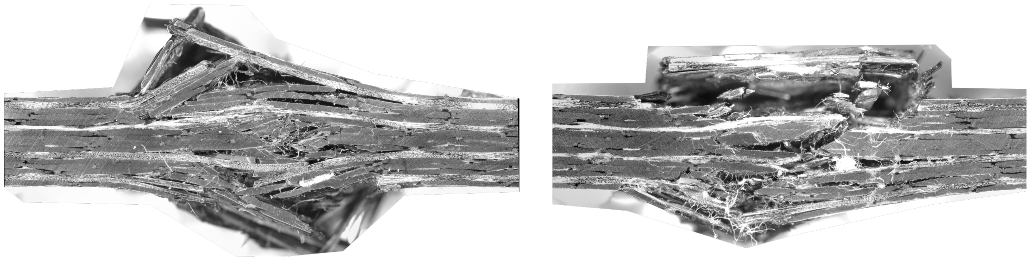


Figure 2.2: *Examples of compressive failure at the macro level. Both quasi-isotropic test samples come from the same batch.*

showed that the shear instability leading to failure is controlled by the maximum fibre misalignment angle in a region of waviness.

For very small misalignment angles ($< 2°$) and when the lateral support is high, a fibre can potentially fail in shear as shown in Fig. 2.3. This is referred to as fibre shear failure or fibre crushing. Gutkin et al. [18] performed in-situ observation with a scanning electron microscope (SEM) on unidirectional specimens with notches. It was observed that fibre shear failure occurred in proximity of the notch. This failure mechanism was promoted by very straight fibres and the lack of shear stresses at the notch. Also, Gutkin et al. [19] showed with FE models that an initial fibre misalignment angle less than 2° caused fibre shear failure. Fibre shear failure reflects upon the theoretical maximum compressive strength of a fibre composite. It was frequently encountered in the first generation polymer composite systems with large fibre diameters but is uncommon in today's composites with fibres of smaller diameter. As the fibre misalignment angle approach zero, i.e. as the fibre becomes perfectly straight, the strength of the composite increases exponentially. Instability also increases and the stored elastic strain, which is released upon fracture is large with explosive damage to the composite as a consequence. The sensitivity on compressive strength to misalignment angle is very high. Wisnom (1993) showed with an FE model that an increase from 0.75° misalignment to 3° misalignment reduced the maximum compressive stress from 1949 MPa to 940 MPa [17]. From the experimental study in Paper B, we show that an increase from 4.5° to 8.0° of maximum misalignment angle results in a reduction of the compressive strength from 750 MPa to 400 MPa.

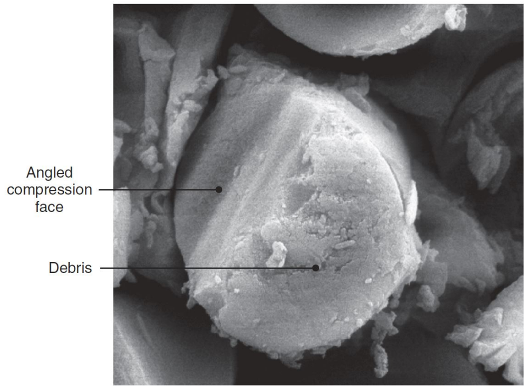


Figure 2.3: *Shear failure of a carbon fibre. SEM image by Greenhalgh [20].*

For very large misalignment angles or large in-plane shear, splitting occurs between the fibre and matrix as depicted in Fig. 2.4 [21]. Large misalignments of the fibres result in large shear stresses, which cause splitting along the fibres instead of shear instability. Gutkin et al. [19] showed with an FE model that there was no noticeable difference on the failure envelope in the transition between fibre kinking and longitudinal splitting. Jelf & Fleck[21] noted for tubes loaded in combined axial compression and torsion that splitting only occurred for the case of pure torsion. Sun [22] states that the transition in terms of off-axis angle (uniform misalignment angle) is 15° for a prepreg system. The transition between fibre kinking and splitting is also dependent on the architecture of the material system. For NCF systems, it has been experimentally observed that fibre kinking can occur at higher off-axis angles than for prepregs. Edgren et al. [6] and the tests in Paper D showed evidence of fibre kinking up to 20° off-axis angle. In another study by Edgren et al. [3] on impacted NCF face sheets, kinking was observed even in 45° plies. Shipsa et al. [23] tested biaxial NCF specimens at several off-axis angles. They observed fibre kinking at 30° off-axis angle but at 45° no evidence of fibre kinking was found. Instead splitting was observed at the interface of fibre bundles. Thus, the threshold between fibre kinking and splitting was between 30-45°.

The dominant failure mechanism in longitudinal compression for polymer based composites like carbon-fibre/epoxy is fibre kinking, referring to the shape of the failed fibres. It is also referred to as elastic or plastic micro-buckling. The kinking phenomenon is governed by the matrix inability to support the fibres and is largely affected by the shear yield limit of the matrix and the initial fibre misalignment angle. A kinking failure is depicted in Fig. 2.5 from the one of the tested specimens in Paper B alongside an schematic illustration with its key parameters in Fig. 2.5. The initial fibre misalignment angle is here denoted ϕ_0 with the additional fibre misalignment angle from loading ϕ. The kink-band angle is denoted β and the kink-band width w.

Kink-bands may appear at different length-scales, especially in NCF composites. A mesoscopic kink-band can be seen in Fig. 2.5, where the kink-band extends through the laminate with a thickness of 2 mm. An example of a microscopic kink-band can be seen

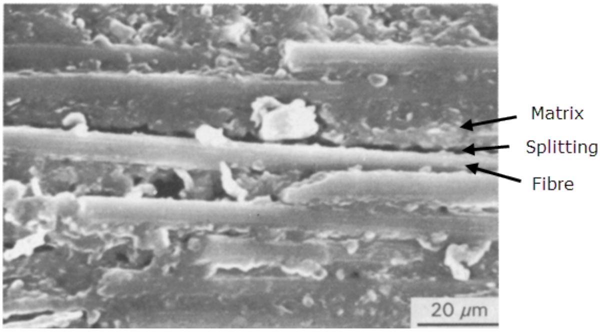


Figure 2.4: *SEM image that shows splitting along a fibre [21].*

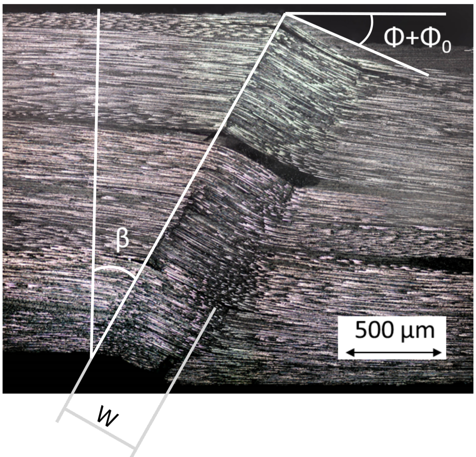


Figure 2.5: *Micrograph of a kink-band with typical definitions of the associated geometric parameters. The micrograph is from the experimental study in Paper B, which shows a partially developed kink-band out-of-plane in a laminate with 2 mm thickness.*

in Fig. 2.6, where a fibre tow with a thickness of 200 μm have kinked out-of-plane from one of the specimens also tested in Paper B.

It is a good approach to model fibre kinking on a 2D plane (kink-plane), as done in Paper A-E. A microscopy approach, which is also 2D, is however difficult to apply in studies of specimens tested in compression such as those in Fig. 2.2. SEM is a powerful tool for investigations of failure and the sequence of events. Tsampas et al. [24] used SEM in a dedicated fractographic study on compression failure. One type of fracture morphology typical of fibre kinking is fibre terraces as shown in Fig. 2.7(a) or clusters of broken fibres as in Fig. 2.7(b). Fibre terraces are generated from fibres in a kink-band that are fractured with equal lengths. Another fractographic evidence of fibre kinking is the cross-section fracture morphology on individual fibres as in Fig. 2.8. The failure mechanism of fibres that fail in a kink-band formation is from bending, where they first fail on the tension side. As seen in Fig. 2.8, a compression face and a tension face can be

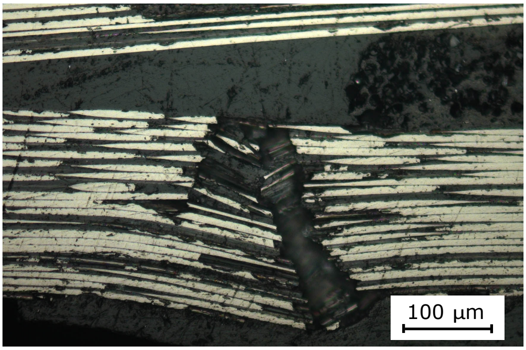
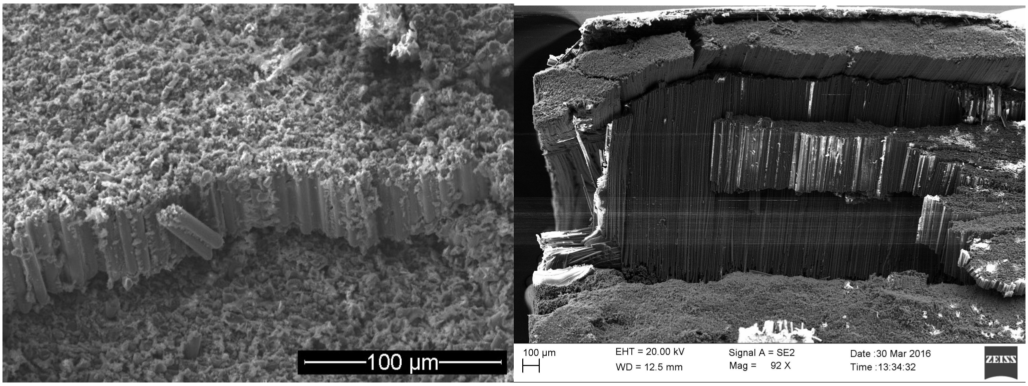


Figure 2.6: *A micrograph from the experimental study in Paper C, which shows a kink-band out-of-plane for a fibre tow. A resin rich region can be seen above this kinked fibre tow.*

identified. The orientation of the neutral axis may be used to deduct the orientation of the kink-band, i.e. the kink-plane orientation.



(a) (b)

Figure 2.7: *SEM evidence of fibre kinking: (a) Fibre terrace of broken fibres in a kink-band. SEM image by David Carlstedt (Paper B), (b) Clusters of broken fibres from a kink-band. SEM image by Spyros Tsampas.*

Advanced fractography and numerical models have in recent years contributed with more detailed knowledge of the fibre kinking mechanism and its sequence of events. Pimenta et al. [25] 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. 2.9 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 is fully yielded and micro-cracks start to form in the matrix, see the work by Gutkin et al. [18], (3) Shear-bands form on the compressive side of the fibres,

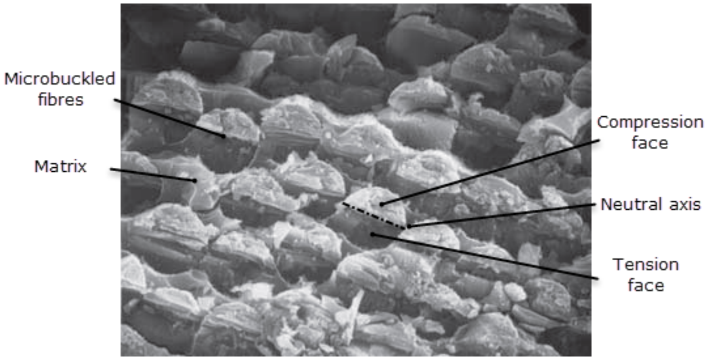


Figure 2.8: *Failed fibres due to kinking (x2.5k) [20].*

which then fail in *the fibre failure domain* due to bending or shear depending on the additional fibre angle ϕ, see Fig. 2.8. An FE model was used in Paper E to study the sequence of events close to peak load. The study clearly shows the strong dependence of failure on spatial distribution of fibre misalignment angles. This has not been previously studied.

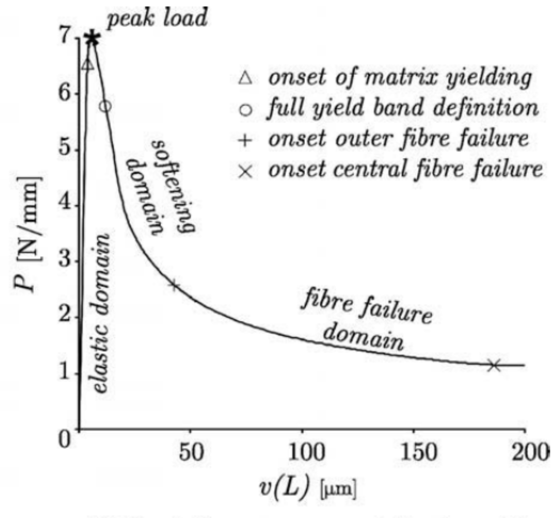


Figure 2.9: *Load-displacement curve showing the sequence of events for kinking [25].*

Previously unpublished results from the study in Paper D are presented in Fig. 2.10. These are tomographic reconstructions (CT-data) with planes aligned with the kink-band for (a) a 0° laminate and (b) a 15° off-axis specimen. Note that the fibres within the kink-band are in focus whereas the fibres beyond the kink-band are not, which is a consequence of the planes being aligned with the kink-plane. The images from CT-scans in Fig. 2.10 are obtained from tested specimens in compression, which means that peak load has been reached for these specimens (the test rig was displacement controlled with load monitoring such that the experiment is stopped when a sudden load drop is identified). Here, after peak load, we show that the *the fibre failure domain* is the current domain since fracture is ongoing. Interestingly, in (b) we can see that propagation of the kink-band takes place in three regions simultaneously, separated by weft yarns of the NCF. These results confirm the the sequence of events described above by Pimenta et al. [25].

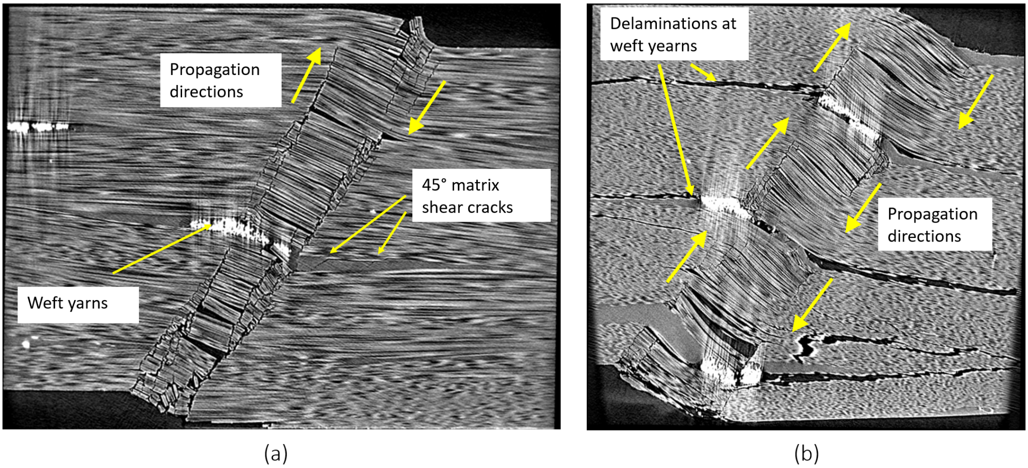


Figure 2.10: *Slices from tomographic reconstructions aligned with the kink-planes of tested specimens with (a) 0° off-axis angle and (b) 15° off-axis angle .*

The formation of damage in the matrix material reduces stiffness of the matrix material in conjunction with plastic deformations, subsequently removing the supporting foundation to the fibres in compression. From a recent study, evidence of micro-cracks and splitting has been shown in kink-bands under development with high resolution CT [26]. This is an important contribution to the understanding of compression failure, which supports the findings of Gutkin et al. [18].

NCF composites behave differently 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. Disparity appears at the tow level where homogenized tows can be viewed as large fibres that interacts with other large fibres, i.e. tows. 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. One example can be seen in Fig. 2.11 from the study by Edgren et al. [3], where the crack is propagating in the laminate transverse direction of a 45° ply. In addition, kink-bands are formed in the fibre tows. These form in plies with significantly higher off-axis orientation angles than for prepreg composites, even in 45° plies as shown in Fig. 2.11. In such cases the "kinking crack" extends normal to the compressive load, whereas the individual kink-bands form normal to the fibre tow orientation forming a saw tooth pattern. This behaviour is beneficial from a fracture toughness point of view but would not occur in a UD prepreg.

The heterogeneity on a meso scale also results in an increased damage tolerance of the composite. It should be noted that the studied NCF composite material in this thesis does not have a clear bundle structure as in the commented study by Edgren et al. [3] and Fig. 2.11.

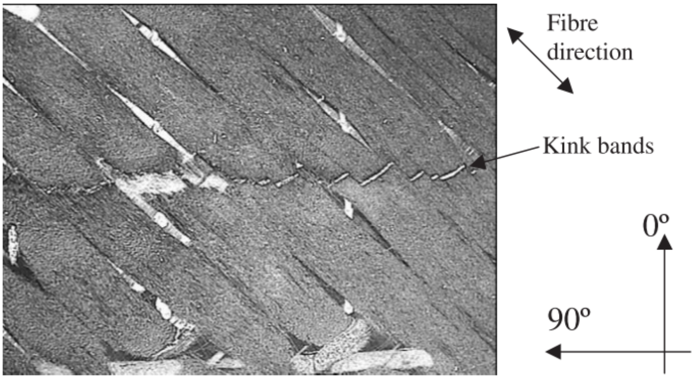
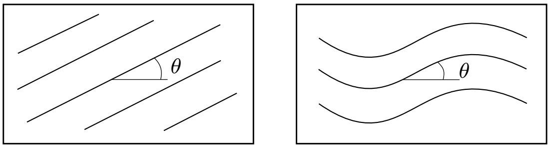


Figure 2.11: *Fibre kinking failure of a sandwich, NCF facesheet from [3] loaded in the zero direction.*

Fibre kinking is a mechanism. When the misaligned fibres are stochastically distributed as for fibre waviness, the wavy fibres will appear in clusters of different sizes. Within each cluster, there would be coordination among the fibres to generate kink-bands when longitudinal compression is imposed. Thus, the first, i.e. most critical, cluster to initiate a kink-band leading to failure is not obvious beforehand and the determination of this cluster is studied in Paper E.

Fundamentally, fibre misalignments originate either from a uniform distribution or a wavy (curved) distribution. The wavy distribution may have different degrees of periodicity or being close to random. Consider two composites with the same misalignment angle θ in Fig. 2.12, (a) has a uniform distribution representing either a local material point or an off-axis case and (b) has a wavy distribution typically found for fibres in processed composites. Case (a) and (b) will not have the same strength in compression. The critical case depends on the magnitude of θ and the orientation of the kink-plane in the composite material. As we show in Paper D, a uniform in-plane misalignment has a little effect on the compressive strength for values of θ below approximately 13°. The transition from out-of-plane to in-plane kinking depends on a number of factors further explained in Paper D.



(a) (b)

Figure 2.12: *Fibre misalignments fundamentally come from either (a) a uniform distribution or (b) fibre waviness (exemplified as periodic but is stochastic in composites).*

2.2 Failure models

Modelling of compressive strength is a large field and this section shall not be viewed as a literature review that covers all aspects. As discussed in the previous section, compressive failure is governed by the fibre misalignment angle. Therefore, it is a variable included in most models that aim at prediction of compressive strength. The fibre misalignment in models for strength prediction is the focus of this section.

The pioneering work by Rosen in 1965 treated compressive failure of a fibre composite as an elastic microbuckling phenomenon [27]. He established Eq. (2.1) to predict the compressive strength, where G_m is the matrix shear modulus, V_f and E_f are the fibre volume fraction and modulus respectively, d is the fibre diameter and λ is the buckling wavelength. The compressive strength is equal to the shear modulus of the lamina 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 [28]. Different lengths were tested and the results agreed well with Eq. (2.1).

$$\sigma_c = \frac{G_m}{1 - V_f} + \frac{\pi^2 E_f}{3}\left(\frac{d}{\lambda}\right)^2 V_f \tag{2.1}$$

The compressive strength of polymer based composites is however overestimated several times with Eq. 2.1. The reason is the fibre kinking cannot be viewed as an elastic buckling phenomenon. In 1972, Argon identified Rosen's model as an upper bound applicable to ideal composites where the fibres are perfectly parallel with the compression axis (zero fibre misalignment) [15]. But very importantly, he reasoned that, in reality the fibres will never be perfectly aligned with the compression axis. Argon introduced the initial fibre misalignment and by that the first fibre kinking criterion for compressive strength

$$\sigma_c = \frac{k}{\phi_0}. \tag{2.2}$$

Argon considered a region of fibre misalignment, like the close-up in Fig. 2.1. In such a region, the applied compressive stress σ produces a shear component of $\tau = \sigma\phi_0$ (assuming small angles). When this shear stress σ becomes equal to the shear strength k, the result is a local instability and shear collapse as

The Argon formula assumes a kink band inclination angle β of 0°, which is rigid-perfectly plastic. Furthermore, Argon realised that fibre kinking is independent of the fibre volume fraction as long it is not too low. The work in Paper B is an experimental validation of Argon's criterion and again proves Argon right as he developed the criterion in 1972.

Wisnom [16](1990) was also concerned with the extreme sensitivity of compressive strength on fibre misalignment angle. The theoretical model was specifically developed to study the sensitivity to misalignment angle and was not intended to directly predict compressive strength. It was shown that a fibre misalignment of only 0.25° was sufficient to reduce the compressive strength from 2720 MPa to 1850 MPa, which at 3° was reduced to 700 MPa. Interestingly, Wisnom states "Misalignments can easily arise during testing, cutting out specimens and laying up laminates, and may also exist within the prepreg tapes. This casts serious doubt on the possibility of measuring a true ultimate compressive strength of a unidirectional composite consisting of strong fibres in a flexible matrix". In contrast to this statement from pioneering research of composites, the current trend is to deal with material defects such as misalignment angles to obtain lower costs of the composites, but yet reliable strength predictions. Wisnom later followed up the important work on misalignment angle with numerical FE modelling in 1993 [17].

Several extensions of the Argon criterion has been developed that are more complex but it is debatable whether these has provided improvements in prediction. The most immediate was by Budiansky [29] in 1983 to account for an elastic-perfectly plastic composite. The yield strain γ_y in Eq. (2.3) is introduced to predict the compressive strength, still for β equal to zero

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

which was later modified by Budiansky and Fleck [30] in 1993 for the progression of a kink-band formation with a non-zero β angle.

In order to predict the strength of practical composites in industry, linear models are needed such that many load cases can be evaluated with a large number of finite elements in FE models. Most "engineering models" are too simplistic to describe the complexity of fibre reinforced composites and their strength due to different failure modes. The LaRC failure criteria has the potential to predict the onset of failure in complex problems at the homogenized ply level. The LaRC criterion is based on the failure criterion proposed by Puck [31] for matrix failure and was the first to use Mohr-Coulomb theory for brittle materials. The criterion was later adopted in the LaRC failure criteria [32], which is a set of physically based criteria for fibre failure (FF) and inter fibre failure (IFF). It was originally developed by NASA[1] in the USA and Imperial College London in the UK. 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 (IFF) and fibre (FF) failure. 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 behaviour for the matrix.

[1] National Aeronautics and Space Administration

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 [33]. Below, LaRC is explained for matrix failure in the transverse plane to show the similarities to the kinking criterion, which are both matrix driven.

Matrix cracking without fibre kinking will occur mainly for loading in the transverse 2-3-plane. This type of failure is predicted with Eq. 2.4 in LaRC05, where failure occurs for a value greater than one.

$$FI_M = \sqrt{\left(\frac{\tau_T}{S_T^{is} - \eta_T \sigma_N}\right)^2 + \left(\frac{\tau_L}{S_L^{is} - \eta_L \sigma_N}\right)^2 + \left(\frac{\langle \sigma_N \rangle_+}{Y_T^{is}}\right)^2}. \tag{2.4}$$

A compressive failure from load in the 2-direction is shown in Fig. 2.13(a). The first two terms, basically compare the shear stresses in Fig. 2.13(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 closes micro cracks in the brittle matrix and generate frictional forces. This concept was recently developed further by Pinho & Gutkin [34] and used in Paper E for high fidelity modelling. The fracture plane is found in a numerical implementation by trying a number of tentative angles α in Fig. 2.13(c) between 0-180°, where the calculation with the highest failure index determines both the angle of the fracture plane and the strength

Fibre kinking is governed by the behaviour of the matrix. Thus, fibre kinking can be predicted using Eq. 2.5, which is a similar expression to Eq. 2.4

$$FI_K = \sqrt{\left(\frac{\tau_T^m}{S_T^{is} - \eta_T \sigma_N^m}\right)^2 + \left(\frac{\tau_L^m}{S_L^{is} - \eta_L \sigma_N^m}\right)^2 + \left(\frac{\langle \sigma_N^m \rangle_+}{Y_T^{is}}\right)^2}. \tag{2.5}$$

The main difference is that the applied stress has a superscript m, which indicates a transformation to a misaligned coordinate system. Firstly, a potential kink-plane is found, illustrated in Fig. 2.14. The kink-plane orientation is denoted ψ and was studied in Paper D. The misaligned reference frame used to predict failure by kinking then rotates with the angle $\phi_0 + \phi$ in Fig. 2.5 on the kink-plane. Thus, it considers both the initial misalignment angle ϕ_0 and the additional angle ϕ from loading. Note that the first term in Eq. 2.5 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 splitting for large ϕ_0. The LaRC criteria states that fibre kinking occurs if $\sigma_{11} < -X_c/2$ and splitting if $-X_c/2 < \sigma_{11} < 0$. As the same equation is used both for fibre kinking and splitting, this statement is only an indication of the failure mode. As, discussed in Section 2.1, the transition between fibre kinking and splitting is diffuse and it is therefore difficult to define an exact threshold.

There are some different approaches to describe fibre misalignments in models. The most straightforward and simple way to describe a fibre misalignment is by a scalar value.

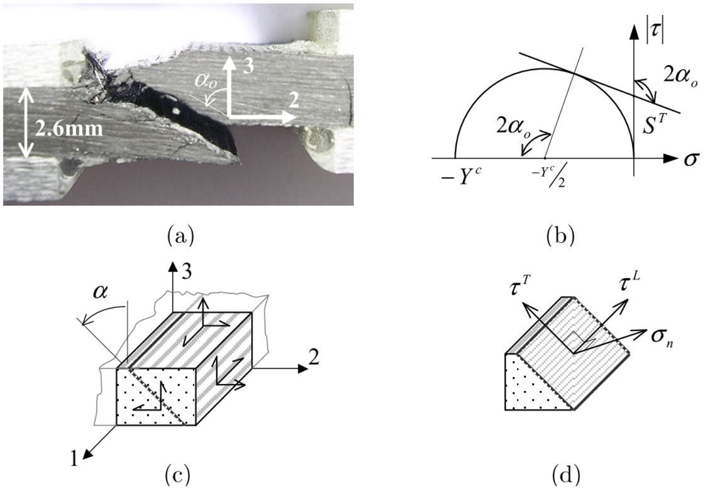


Figure 2.13: *Puck's failure criteria essentials from [35]. a) Transverse compression failure for a CFRP composite. b) Fracture plane for a 3D state. c) Definition of stresses acting on the fracture plane. d) Geometrical representation of the Mohr-Coulomb criterion.*

The first fibre kinking criterion by Argon [15] was defined by a single value of maximum fibre misalignment in a region of waviness. Similarly, many authors have developed theoretical models describing the misalignment as a scalar value, for example [16, 28–30, 36]. A scalar value is the most straightforward implementation of misalignment within a ply modelled by FEM [31, 32]. A uniform misalignment field has also been used in FE models to develop advanced material models for crash simulations of composites [37, 38]. It is important to consider for such models if the misalignment represents a small material volume or a meso-macroscopic representation of uniform misalignment.

The majority of models considers an analytical representation of the local fibre waviness. It is a simple and efficient approach that can be used for many purposes. It is based on the fact that fibre waviness in its most ideal shape is sinusoidal as in Fig. 2.12(b). For instance, Waas did theoretical validation work based on Rosen's model in 1990 with a sine shaped misalignment [39]. Edgren et al. used similar sine functions to analytically describe the knock-down on stiffness [4]. More recent contributions to strength modelling with analytical sine representations can be found in [40–42]. Analytical representations of fibre waviness in conjunction with FE modelling is a powerful tool for strength modelling and understanding the phenomenon. Pioneering work was done with FEM by Wisnom [43–45] to understand the phenomenon of waviness. Joffe et al. [46] and Drapier & Wisnom [47] FE modelled local regions of waviness caused by the NCF architecture. Even more detailed analyses can be performed with FEM by discrete modelling of individual fibres and matrix in conjunction with periodic boundary conditions [25, 48]. Pioneering work was done by Shu & Fleck in 1997 [49], where misaligned regions were considered as defects similarly to our work in Paper B and E.

As Slaughter & Fleck (1997) [50] very correctly states: "In engineering composites,

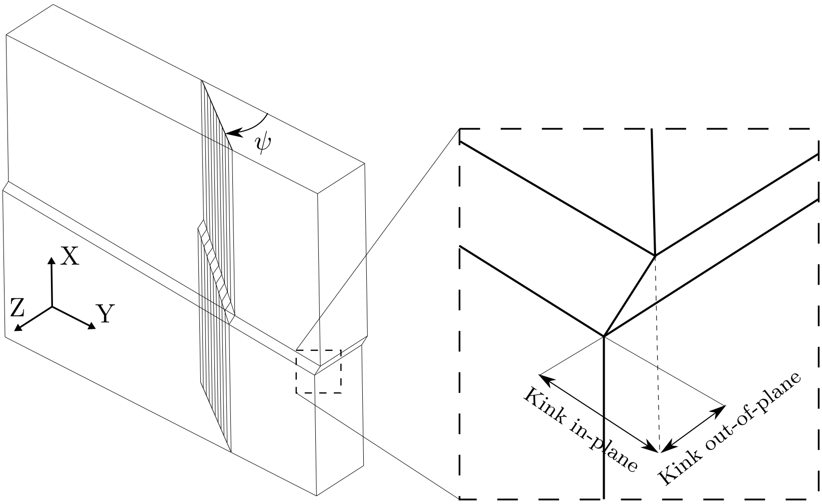


Figure 2.14: *Figure from Paper D. Schematic illustration of the kink-plane orientation angle ψ.*

fibre misalignment is stochastic rather than sinusoidal in nature". They attempted to model a random spatial variation of the fibre misalignment. They lacked measured data and instead assumed a simple shape for the spectral density of fibre slopes to generate ensembles of fibre waviness. Liu et al. [51] continued the work of Slaughter & Fleck [50] on the random misalignment description but also incorporated a development of the defect analysis performed earlier by Shu & Fleck [49]. The work we perform in Paper E is inspired by the work from Liu et al. [51], in particular their consideration of misaligned regions as elliptically shaped defects. Yushanov and Bogdanovich used stochastic theory to model the stiffness with a description of the fibres mean path and the standard deviation of the local tangent as a random variable [52]. Sutcliffe [53] was first to explore intricate details of the effects of random fibre misalignment on strength with FEM. Sutcliffe emphasised the importance of characterising and modelling fibre waviness in large structures. In a recent study, Safdar et al. [54] uses a similar approach but with Monte Carlo FE simulations to predict the strength response from generated random fibre misalignments.

Fibre misalignments for continuous fibre composites are stochastic but not random and I suggest that the random approach must be questioned in terms of its physicality. As we show in Paper B, distributions that appear to be random, in fact have a periodicity. We analysed the "random" waviness with Fourier analysis directly on the misalignment data and concluded that the wavelength was related to the weft yearns of the NCF. The stochastic distribution of misalignment angles is dependent on factors such as fibre architecture and processing. I believe that the most immediate research field for the advancement of compressive failure modelling is to measure and incorporate the spatial fibre misalignment variations for manufactured composites. Sutcliffe et al. [55] initiated this type of studies in 2012 with the characterisation of an industrial component with a size of 5×5 mm. The measured fibre misalignment data from that study was then used in an FE model describing the waviness [56]. Convincing results were obtained such as a failure initiation site that agreed with the critical defect. The postulated sensitivity on strength to transverse defect extension postulated in that paper was experimentally confirmed in Paper B.

3 Strength assessment of aero-engine components

Further work is required to transfer the knowledge from this thesis to an industrial implementation for strength assessment of aero-engine components. This section discusses possibilities and challenges associated with such implementation. Theoretically, the methods described in Paper A, B, D and E can be used to directly assess the compressive strength of a component. The basic steps for a direct assessment are outlined below.

Initially, the material shear strength has to be measured since compressive failure by fibre kinking is governed by the longitudinal shear strengths of the material. The longitudinal shear strengths are determined on a coupon level, both in-plane and out-of-plane. Preferably by a modified version of the Iosipescu fixture by Melin & Neumeister [57]. Bru et al. conclude that accurate values can be obtained with this method for a UD NCF material system [58].

Based on the work in Paper D, The orientation of the kink-plane must be established. It depends mainly on the stress state and fibre waviness. Fractographic evidence of fibre kinking is needed, e.g. by SEM results as in Fig. 2.7. The best approach to determine the kink-plane orientation in a tested component is yet to be determined. If the kink-plane orientation cannot be measured, the best assumption is that it is oriented out-of-plane of the composite laminate.

In the next step, the HRMA method (Paper A) can be employed to measure fibre misalignments with high resolution on micrograph sections parallel to the established kink-planes. These section are aligned with the longitudinal direction of the component and the applied compressive load.

One option is to predict the compressive strength as proposed in Paper B. We denote this method as "Argon99". The name refers to the Argon failure criterion [15] used in conjunction with the maximum fibre misalignment angle θ_{99} defined as the 99:th percentile of all measured fibre misalignments within a sample. Prediction with the Argon failure criterion is formulated as

$$X_{c,Argon99} = \frac{\tau_c}{\theta_{99}}, \tag{3.1}$$

where τ_c is the critical shear limit on the kink-plane based on the shear strength from coupon tests.

Alternatively, predictions of compressive strength can be based on the severity model described in (Paper E). The severity based model predicts with higher accuracy and sophistication. Work is ongoing to validate this method on aero-engine components and it is therefore difficult to state the need for model calibration. In the best case, the method has such level of physicality that model calibration performed in Paper E is sufficient to use the model in Eq. 3.2 directly.

$$X_{c,severity} = \tau_c S_D, \tag{3.2}$$

where the severity index S_D describes severity factors associated with regions of fibre misalignment (defects) as

$$S_D = D_1 D_2 D_s. \tag{3.3}$$

Sampling of fibre misalignment data can possibly be a part of the statistical approach to strength assessment. The degree to which fibre misalignments are characterised will determine the statistical confidence. Currently, variability in strength of test coupons reflects on the variability in fibre waviness of the corresponding laminate. The outcome is statistically based material parameters that considers this variability (a-basis and b-basis). Similarly, sampling of fibre waviness in manufactured components could be used for statistically based strength assessments in different regions.

The variability of processed fibre composites is complex with different types of fibre waviness defects [59]. Non destructive test methods (NDT) to obtain fibre misalignments is an attractive alternative. There are methods available for correct placement of preforms, such as laser projector systems [60]. Methods to measure fibre misalignment angles from fibre waviness are under development. Ultrasonic detection methods have the potential to measure fibre waviness. In a study by Pain & Drinkwater [61], variations in the fibre waviness were observed. In a recent study by Nelson & Smith [62], ultrasound was used to determine the orientation of individual plies in a multidirectional laminate. Measurements on the fibre level are however not currently available. Another potential NDT method is the usage of an Eddy current measurement probe. This probe does not need to be in contact with material and the authors of a recent study show that an accuracy of 1 ° on the misalignment measurement is possible to obtain [63]. No results on the spatial resolution have been given. Numerical simulations of the processing event can also be of interest for subsequent numerical analysis of compressive strength. For tape based composites, process simulations can predict where in the composite different kinds of wrinkles appear during the forming of the geometry [64]. Wrinkles may be viewed as large, distinct regions of fibre waviness out-of-plane with a significant effect on compression strength [65]. At this time, it does not seem possible to predict fibre orientations with high accuracy and resolution by the above mentioned methods. Currently, X-Ray CT is the only NDT method that can provide the necessary resolution and accuracy. With current laboratory size systems however, the sample size for such measurement is limited to approximately 6 mm [66]. To conclude, image processing on detailed micrographs [67–69] is still the best option at hand for measurement of fibre misalignments in the context of compressive strength modelling.

We have focused on unidirectional laminates and thus studied compression failure initiation on the ply-level. In this case, first-ply failure is similar to laminate failure. For a multidirectional laminate, where the zero-plies are assessed, first ply failure may not be associated with failure of the laminate. In this case, we obtain a conservative prediction of the compressive strength. The soundness of this approach depends on the level of conservatism, which needs further studies.

Practically, the failure initiation site in the component may be unknown. Furthermore, it may be cumbersome to verify fibre kinking and the associated kink-plane orientation experimentally. An FE implementation is most likely required to be successful in prediction of compressive strength of complex aero-engine components. The work has already begun within the KOMPRESS project to develop a layered finite element model with solid elements shown in Fig. 3.1. A solid model will be required in complex regions such as ply drops similarly to the work by Kawashita et al. [70]. A hybrid model with shell elements in regions with more constant thickness can however be a good approach. Next, the constitutive behaviour of such detailed representation has to be determined on the ply-level. Between plies, I recommend to use cohesive elements in proximity of ply drops, such that delamination can be predicted. In the homogenised representation of the plies, the LaRC05 criteria for failure initiation [33] can be used. The authors of this paper describes that: "The philosophy behind the approach is that failure models and resulting criteria ought to include as much as possible of the physics associated with the failure process at the micromechanical level, while still allowing for solutions to be computed for laminae and laminates". The criteria, which are further explained in Section 2.2 are physically based and consider all relevant failure modes for intra-laminar failure such as fibre tension failure, transverse failure, longitudinal compression failure and splitting. LaRC05 is formulated in a non-linear framework, which is consistent with the non-linear behaviour in compression on the material level of the polymer material. LaRC05 can however be used in a linear framework if only failure initiation is considered. Linear FE simulations are required when many load cases exist. In industrial applications, these are based on unitary load perturbations superimposed to construct representative stress states for all load cases. This is a very computationally efficient method and it was therefore utilized by Molker et al. [12] in conjunction with the LaRC criteria. The method is described in more detail in a separate paper [13]. Superposition in this study was made in the Fortran environment and this approach is recommended for aero-engine components subjected to a large number of load cases.

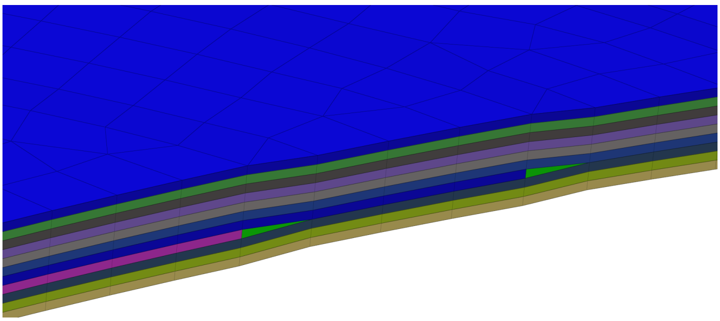


Figure 3.1: *A layered solid FE model under development. Modelling by Peter Hällström and Alann André, Rise Sicomp.*

In the LaRC criterion for longitudinal compression failure by fibre kinking, an initial fibre misalignment angle is given. It is common to include various reductions on the compressive strength by this parameter. Since the fibre misalignment is governing the compressive strength, I suggest that the input parameter is exclusively used to represent the fibre misalignment angle. On the topic of its spatial representation, I suggest a piecewise constant spatial variation. Local descriptions of the spatial variation of the misalignment angle as done in Paper C, D and E by the FE material orientation cannot be easily employed. Consider instead a case where a region of fibre waviness has been characterised with the HRMA method. Several local maxima of the misalignment angle θ_{max} can be transferred to the FE model as piecewise constant regions of fibre misalignment. By this approach, a local maxima of fibre misalignment determines the strength within a contained region and thus avoid unnecessary conservatism.

4 Novelty of appended papers

The main novelty of this thesis lies in the approach by which we consider fibre misalignments for compression failure and strength modelling. The approach is based on studies of fibre misalignment measurements with high accuracy and high spatial resolution in a large number of relevant and representative samples. Misalignment data has been used for statistically based direct assessments of compressive strength. The misalignment data has also been used to calibrate models for strength prediction and for numerical studies to increase understanding. Our contributions are presented more in detail below.

In Paper A, a method is proposed for measurement of fibre misalignment angles on detailed micrographs. Novelty lies mainly in the algorithm by which the misalignment angle is obtained. As opposed to the two existing (documented) methods [67, 68], individual fibres are traced, one by one, see Fig. 4.1. The method may thus be regarded as direct and not approximative. For that reason, the spatial resolution is only limited by the fibre diameter. A new type of software-generated images based on Gaussian wavelets and with known statistics are used to evaluate the method.

In Paper B, a comprehensive test campaign on specimen level was performed to study the effects of fibre misalignments on compressive properties. Novelty lies mainly in the size and detail of the study. It is the largest to date on the effect of measured fibre waviness on compressive properties. It is also the largest study to date on fibre waviness in manufactured composites. The produced laminates contained a unique diversity of fibre waviness. Fourier analysis is used directly on the fibre slopes to determine the spectral density distributions. A clear correlation on the wavelength was found to the weft yarn spacing of the NCF, both for periodic and random distributions. Good correlation was found between the mean misalignment angle and longitudinal stiffness reduction. We proposed to use the 99:th percentile of the fibre misalignment angles as the maximum misalignment angle. As we can see in Fig. 4.2, a striking correlation was found between the measured maximum fibre misalignment angle and measured compressive strength. When used with the Argon criterion, accurate predictions was made for all types of fibre waviness.

In Paper C, analysis of bending in compression tests was performed based on FE

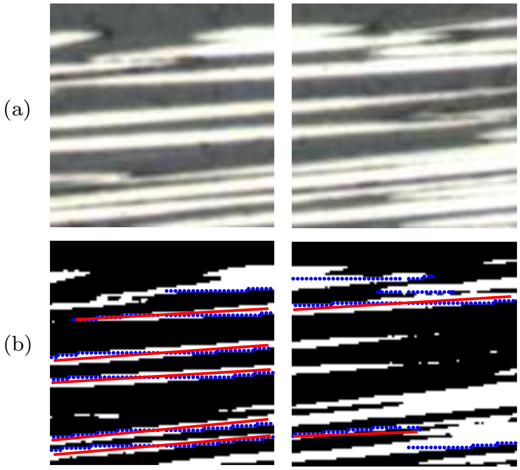


Figure 4.1: *Figure from Paper A. Two randomly chosen, horizontally neighbouring cells, each 100 × 100 pixels, with (a) the original micrographs and (b) the converted micrographs to black and white with measurements. The blue dotted lines represents traces of fibres. The red line-segments indicate that the traced fibres fulfils the quality criteria and that a measurement of the angle has been performed.*

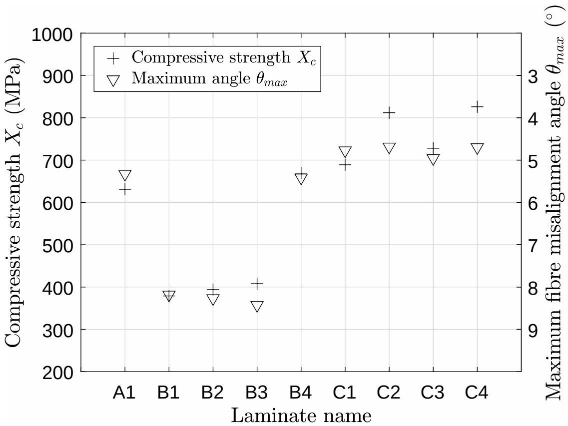


Figure 4.2: *Figure from Paper B. The compressive strength X_c and maximum misalignment angle θ_{max} for all 0° laminates. Note that the right y - axis is reversed with increasing angles downwards.*

modelling, virtual strain gauges, physical strain gauges and digital image correlation (DIC) measurements. It is a novel type of study. High resolution misalignment data was directly mapped on a finite element mesh in 2D for the first time. The effect of strain gauge size is shown in Fig. 4.3

In Paper D, we perform a study on the orientation of the kink-plane with X-ray

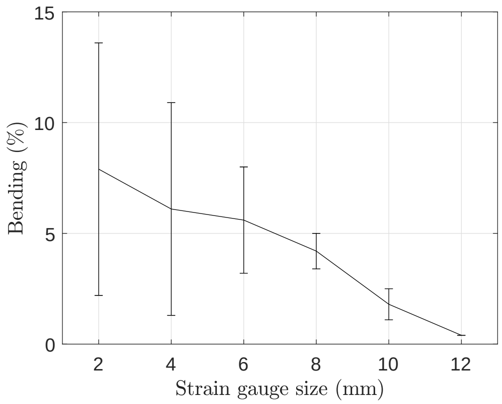
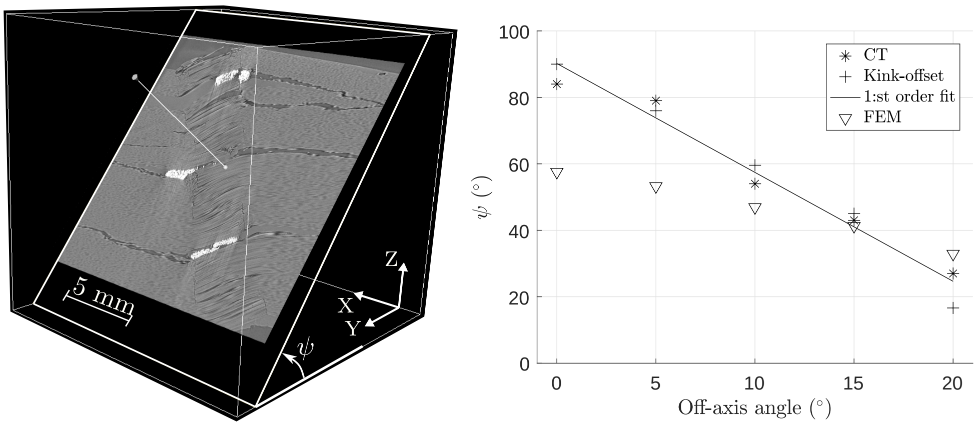


Figure 4.3: *Figure from Paper C. Bending defined according to ASTM standards D3410 and D6641 [71, 72] is plotted as a function of virtual strain-gauge length. The bending value is presented as the average from all possible placement combinations of the virtual strain gauges with the associated standard deviation.*

computed tomography (CT) of specimens with partially developed kink-bands. A kink-plane from CT is shown in Fig. 4.4(a). In this study details on the kink-plane orientation as function of stress state is revealed, see Fig. 4.4(b). The significance of this work is that for the first time results are reported that provide an explanation of the transition between in-plane and out-of-plane kinking. This makes it an important and unique contribution. High resolution misalignment data was directly mapped on a finite element mesh in 3D. These misalignment angles were a combination of misalignments from out-of-plane waviness, in-plane waviness and uniform off-axis angles. This resulted in a total of 237,620 unique fibre misalignment angles. Experimental results support the physicality of the LaRC05 kinking failure criterion [33] with respect to identification of the kink-plane orientation.

In paper E, a new defect severity concept is proposed that opens up new possibilities for accurate predictions of compressive strength in fibre composites. It was inspired by the work by Liu et al. [51] but analyses the criticality of the manufacturing induced defects (misaligned regions) considering physical (not simulated) data. An example is shown in Fig. 4.5 of individual predicted compressive strengths σ_d^c for different defects. The defect characteristics in the figure are normalized area A, extension ratio through the thickness Γ and mean misalignment angle $\bar{\theta}_d$. The defect severity analysis has provided further understanding of compressive failure in unidirectional fibre composites. We have demonstrated for the first time that FE modelling can be used to predict the compressive responses of a large number of samples of measured fibre misalignment angles (87 samples). The FE models used here revealed a diversity in the failure process between specimens, where e.g. kink-band angle β and failure locations were found to respond to variations in fibre waviness.



(a) (b)

Figure 4.4: *Figures from Paper D. (a) The kink-plane in a cross section through a tomographic reconstruction of tested specimen with 15° off-axis angle, (b) The kink-plane angle ψ is a linear function of off-axis angle, i.e. in-plane shear.*

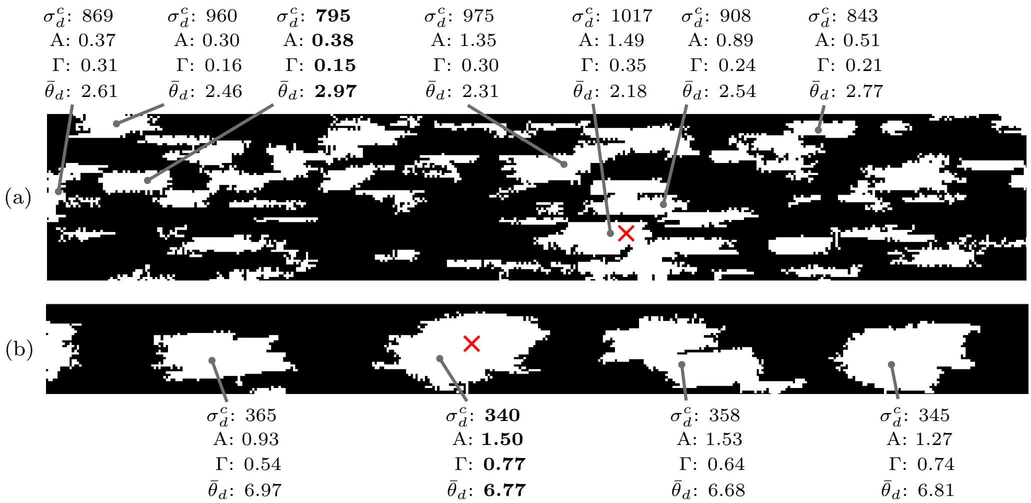


Figure 4.5: *Figure from Paper E. Examples of defects assessed with the defect severity model for (a) a sample with random fibre waviness and (b) a sample with periodic fibre waviness. The bold face values represent the critical values with lowest strength ($\sigma_d^c = \sigma_{cr}^c$). Strength values σ_d^c are reported in MPa and misalignment angles $\bar{\theta}_d$ in degrees. The cross indicates failure initiation region based on the FE model. Strength values that are not shown are higher than the presented ones.*

5 Summary of appended papers

Paper A: A high resolution method for characterisation of fibre misalignment angles in composites

In this paper a novel method for characterisation of fibre waviness in composites is presented and assessed. The proposed method referred to as "high resolution misalignment analysis" (HRMA) is suitable for measurements with high spatial resolution. The HRMA method measures the misalignment angles by tracing individual fibres in detailed micrographs. Here, the method is evaluated using software-generated images with known statistics to mimic real micrographs. Results reveal that the HRMA method provide very accurate measurements on composites with high fibre waviness, outperforming existing methods, whereas it performs on par with existing methods for materials featuring medium fibre waviness. The HRMA method sets a new standard by characterising a micrograph of size 2 cm^2 with a spatial resolution of 55 μm in approximately 1 minute on a standard laptop computer.

Paper B: An experimental study of fibre waviness and its effects on compressive properties of unidirectional NCF composites

In this paper a comprehensive experimental study on effects of different fibre waviness characteristics on the compressive properties of unidirectional non-crimp fabrics (NCF) composites is presented. The fibre waviness ranges from periodic to random with medium to large misalignment angles. As expected, fibre waviness is found to strongly impair the compressive mechanical properties of the composite. It is demonstrated that the maximum fibre misalignment alone can be used to accurately predict strength with analytical kinking criteria. Furthermore, there is a direct correlation between waviness and a knock-down factor on stiffness with approximately 5 %/degree mean fibre misalignment angle. Analysis of the extension of the misaligned regions (defects) provides additional evidence that defect extension in the transverse direction is more critical than in the longitudinal direction, supporting earlier theoretical predictions in the open literature.

Paper C: Fibre waviness induced bending in compression tests of unidirectional NCF composites

Compression testing of carbon fibre composites according to ASTM D6641/D3410 is limited by a maximum of 10 % bending for a valid test. This allowable was exceeded in a preceding study, where all the laminates had a large out-of-plane waviness. The aim of this study is to quantify the contribution from the out-of-plane fibre waviness to bending.

The fibre waviness was characterized on samples with high magnitudes of bending and the corresponding fibre misalignment angles were then mapped to a plane strain finite element model. This model represents the geometry through the thickness and in longitudinal direction. Virtual strain measurements and associated bending calculations could then be performed in Matlab from the strain field on the upper and lower surfaces, which resulted from compression loading. Virtual bending calculations have also been performed from strain measurements with an optical system (DIC).

The numerical model confirms that the out-of-plane waviness has an effect on bending. The magnitudes are however lower than expected, and lower than the experimental values. Bending was in the order of 5 % with a strain gauge of 5 mm, which constitutes half of the allowed amount of bending. It was also confirmed that the length of the strain gauge has a significant effect on the measured bending and on the experimental error.

Paper D: Influence of in-plane shear on kink-plane orientation in a unidirectional fibre composite
Kink-band formation is the governing failure mechanism for compressive failure of fibre reinforced composites. Here, kink-plane orientation, describing the direction of kink-band formation, is studied using X-ray computed tomography (CT). Unnotched unidirectional specimens with off-axis angles ranging from 0-20° are tested in compression. The required specimen width was first evaluated in a separate study [73]. The measured compressive strength is found practically constant for off-axis angles between 0-10°. For an off-axis angle of 15° the compressive strength drops dramatically. CT-results reveal this drop to be consistent with a transition from out-of-plane to in-plane dominated kinking. Furthermore, results show the kink-plane angle to be linearly dependant on off-axis angle, and hence in-plane shear stress. A three-dimensional finite element model considering measured fibre misalignment angles through its volume is generated for numerical analysis. Numerical predictions based on the LaRC05 kinking criterion are found to qualitatively capture the experimentally observed effects of off-axis angle on kink-plane orientation.

Paper E: Compressive strength assessment of fibre composites based on a defect severity model
This paper presents a defect severity concept for characterising fibre misalignments commonly found in practical composites. Drawing an analogy with brittle fracture from sharp defects, we show that compressive failure is governed by regions with clusters of misaligned fibres and that failure occurs from a critical region most favourable to initiating a kink-band. Based on a large database of measured fibre misalignments, a defect severity model is proposed. The initiation and progression of kink-bands are also analysed using a finite element model.

6 Concluding remarks and future work

The most influential parameter on compressive failure in UD composites is the misalignment of fibres. The effects on compressive behaviour have concerned researchers for decades. Until now, there has been no database of fibre misalignments measurements nor systematic studies of measured fibre misalignments on compressive strength.

We have studied fibre misalignments in unidirectional NCF composites with high spatial resolution and accuracy. The studies are based on a large number of unnotched test specimens with typical dimensions. The diversity in studied fibre misalignments are not generated by artificial means, but instead reflect upon the relevant material architecture and processing principles. I conclude that the chosen approach has been fruitful. A design approach is readily available for assessment of compressively loaded NCF composites. Furthermore, a new research approach to study and model compressive failure in fibre composites is presented.

Many studies on compressive failure seek to model or understand details on kink-band formation. We have instead maintained a clear focus on failure initiation, relevant to aero-engine components. We have addressed the extreme sensitivity of kink-band initiation to fibre misalignment angle that subsequently lead to compressive failure within a ply. We conclude that kink-band initiation in practical fibre composites is a coordinated kinematic event. It requires studies of regions with real (measured) spatial distributions of fibre misalignment angles. These studies are preferably conducted on 2D micrographs parallel to the kink-plane.

Work is ongoing to validate our method on recently tested outlet guide vanes (OGV). The tested OGV:s were loaded in radial (longitudinal) compression. A photograph is presented in Fig. 6.1 with the loading direction illustrated. Preliminary results from a fractographic investigation shows that failure initiated by fibre kinking. Thus, it has been shown that the fibre waviness is critical for compressive strength of this component. The ongoing work will be reported in a separate paper, naturally following the work in Paper B and Paper E. We have planned to evaluate both methods, referred to as the "Argon99" model and the "defect severity" model for assessment of strength. A layered FE model of the OGV based on solid elements is also under development. To assess future aero-engine components, our method has to be implemented in an industrial context and this requires further work.

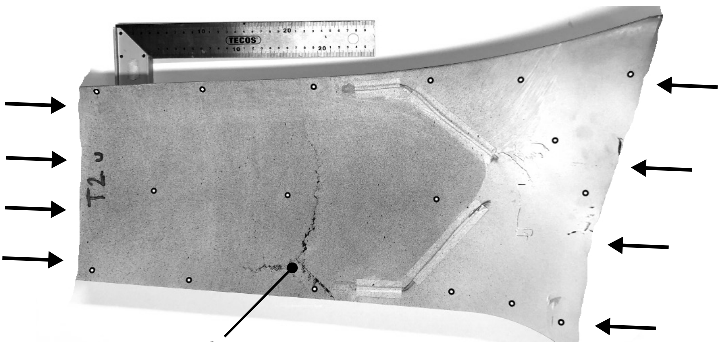


Figure 6.1: *Photograph of a tested CFRP OGV in compression. Photograph taken by Thomas Bru at Rise Sicomp. The component is tested at GKN Aerospace, Trollhättan, Sweden.*

References

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

[2] F. Edgren, D. Mattsson, L. E. Asp, and J. Varna. "Formation of damage and its effects on non-crimp fabric reinforced composites loaded in tension". *Composites Science and Technology* 64.5 (2004), pp. 675–692.

[3] F. Edgren, L. E. Asp, and P. H. Bull. "Compressive Failure of Impacted NCF Composite Sandwich Panels - Characterisation of the Failure Process". *Journal of Composite Materials* 38.6 (2004), pp. 495–514.

[4] F. Edgren and L. E. Asp. "Approximate analytical constitutive model for non-crimp fabric composites". *Composites Part A: Applied Science and Manufacturing* 36.2 (2005), pp. 173–181.

[5] F. Edgren. "Compressive Failure NCF Composites". *Proceedings of the American Society for Composites*. 2005.

[6] F. Edgren, L. E. Asp, and R. Joffe. "Failure of NCF composites subjected to combined compression and shear loading". *Composites Science and Technology* 66.15 (2006), pp. 2865–2877.

[7] P. K. Mallick. "Fiber-reinforced composites: Materials, manufacturing, and design, third edition". English. Fiber-Reinforced Composites: Materials, Manufacturing, and Design, Third Edition. 2007, pp. 1–621.

[8] J. Filsinger, R. Dittmann, and B. T. "Textile preforming technologies for fuselage applications". *Proceedings of the 25th jubilee international SAMPE Europe Conference*. 2004, pp. 450–455.

[9] J. Wang, K. D. Potter, K. Hazra, and M. R. Wisnom. "Experimental fabrication and characterization of out-of-plane fiber waviness in continuous fiber-reinforced composites". *Journal of Composite Materials* 46.17 (2012), pp. 2041–2053.

[10] S. Lemanski, J. Wang, M. P. F. Sutcliffe, K. Potter, and M. R. Wisnom. "Modelling failure of composite specimens with defects under compression loading". *Composites Part A: Applied Science and Manufacturing* 48 (2013), pp. 26–36.

[11] J Wang, K. D. Potter, M. R. Wisnom, and K Hazra. "Failure mechanisms under compression loading in composites with designed out-of-plane fibre waviness". *Plastics Rubber and Composites* 42.6 (2013), pp. 231–238.

[12] H. Molker, D. Wilhelmsson, R. Gutkin, and L. E. Asp. "Orthotropic criteria for transverse failure of non-crimp fabric-reinforced composites". *Journal of Composite Materials* 50.18 (2015), pp. 2445–2458.

[13] D. Wilhelmsson, R. Gutkin, F. Edgren, and L. E. Asp. "Numerical analysis of the orthotropic transverse strength of NCF reinforced composites". *Proceedings of the 12th International Conference on Textile Composites (Texcomp-12)*. May. 2015, pp. 26–29.

[14] O. Allix, N. Feld, E. Baranger, J. M. Guimard, and C. Ha-Minh. "The compressive behaviour of composites including fiber kinking: modelling across the scales". *Meccanica* 49.11 (2014), pp. 2571–2586.

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

[16] M. R. Wisnom. "The effect of fibre misalignment on the compressive strength of uniderectional carbon fibre/epoxy". *Composites* 21.5 (1990), pp. 403–407.

[17] M. R. Wisnom. "Analysis of Shear Instability in Compression Due to Fibre Waviness". *Journal of Reinforced Plastics and Composites* 12.November (1993), pp. 1171–1189.
[18] R. Gutkin, S. T. Pinho, P. Robinson, and P. T. Curtis. "On the transition from shear-driven fibre compressive failure to fibre kinking in notched CFRP laminates under longitudinal compression". *Composites Science and Technology* 70.8 (2010), pp. 1223–1231.
[19] 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". *Composites Science and Technology* 70 (2010), pp. 1214–1222.
[20] E. S. Greenhalgh. *Failure Analysis and Fractography of Polymer Composites*. 1st ed. Cambridge, UK: Woodhead Publishing, 2009.
[21] P. Jelf and N. A. Fleck. "The failure of composite tubes due to combined compression and torsion". *Journal of materials science* 29 (1994), pp. 3080–3084.
[22] C. Sun. "Novel methods for testing and modelling composite materials and laminates". *In: Presentation at the 2nd international conference on composites testing and model identification*. Bristol, UK, 2004.
[23] A. Shipsha, M. Burman, and J. Ekh. "Failure of cross-ply NCF composites under off-axis compressive loads - An experimental study and a new strength prediction model including fibre bundle waviness". *Composites Part B: Engineering* 153.December 2017 (2018), pp. 49–56.
[24] S. A. Tsampas, E. S. Greenhalgh, J. Ankersen, and P. T. Curtis. "On compressive failure of multidirectional fibre-reinforced composites: A fractographic study". *Composites Part A: Applied Science and Manufacturing* 43.3 (2012), pp. 454–468.
[25] S. Pimenta, R. Gutkin, S. T. Pinho, and P. Robinson. "A micromechanical model for kink-band formation: Part I — Experimental study and numerical modelling". *Composites Science and Technology* 69 (2009), pp. 948–955.
[26] Y. Wang, T. L. Burnett, Y. Chai, C. Soutis, P. J. Hogg, and P. J. Withers. "X-ray computed tomography study of kink bands in unidirectional composites". *Composite Structures* 160 (2017), pp. 917–924.
[27] B. Rosen. "Mechanics of composites strengthening". *American Society of Metals* (1965), pp. 37–75.
[28] P. Jelf and N. A. Fleck. "Compression Failure Mechanisms in Unidirectional Composites". *Journal of Composite Materials* 26 (1992), pp. 2706–2726.
[29] B. Budiansky. "Micromechanics". *Computers & Structures* 16 (1983), pp. 3–12.
[30] N. A. Fleck and B. Budiansky. "Compressive failure of fibre composites due to microbuckling". *Inelastic deformation of composite materials* (1991).
[31] A Puck and H Schürmann. "Failure analysis of FRP laminates by means of physically based phenomenological models". *Composites Science and Technology* 62 (1998), pp. 1633–1662.
[32] 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". *NASA/TM-2005-213530* (2005).

[33] S. T. Pinho, R. Darvizeh, P. Robinson, C. Schuecker, and P. Camanho. “Material and structural response of polymer-matrix fibre-reinforced composites”. *Journal of Composite Materials* 46.19-20 (2012), pp. 2313–2341.
[34] R. Gutkin and S. T. Pinho. “Combining damage and friction to model compressive damage growth in fibre reinforced composites”. *Journal of Composite Materials* 49.20 (2015), pp. 2183–2495.
[35] 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”. *Composites Part A: Applied Science and Manufacturing* 37 (2006), pp. 63–73.
[36] H. M. Jensen and J. Christoffersen. “Kink band formation in fiber reinforced materials”. *Journal of the Mechanics and Physics of Solids* 45.7 (1997), pp. 1121–1136.
[37] R. Gutkin, S. Costa, and R. Olsson. “A physically based model for kink-band growth and longitudinal crushing of composites under 3D stress states accounting for friction”. *Composites Science and Technology* 135 (2016), pp. 39–45.
[38] S. Costa, R. Gutkin, and R. Olsson. “Mesh objective implementation of a fibre kinking model for damage growth with friction”. *Composite Structures* 168 (2017), pp. 384–391.
[39] A. M. Waas, C. D. Babcock, and W. G. Knauss. “A Mechanical Model for Elastic Fiber Microbuckling”. *Journal of Applied Mechanics* 57.1 (1990), p. 138.
[40] S. Pimenta, R. Gutkin, S. T. Pinho, and P. Robinson. “A micromechanical model for kink-band formation: Part II—Analytical modelling”. *Composites Science and Technology* 69.7-8 (2009), pp. 956–964.
[41] A. Altmann, P. Gesell, and K. Drechsler. “Strength prediction of ply waviness in composite materials considering matrix dominated effects”. *Composite Structures* 127 (2015), pp. 51–59.
[42] P. Davidson and A. M. Waas. “Mechanics of kinking in fiber-reinforced composites under compressive loading”. *Mathematics and Mechanics of Solids* 21.6 (2016), pp. 667–684.
[43] M. R. Wisnom. “The effect of fibre waviness on the relationship between compressive and flexural strengths of unidirectional composites”. *Journal of Composite Materials* 28.1 (1994), pp. 66–76.
[44] M. R. Wisnom. “Finite Element Modeling of Shear Instability under Compression in Unidirectional Carbon-Fiber Composites”. *Journal of Thermoplastic Composite Materials* 7 (1994), pp. 352–363.
[45] M. R. Wisnom and J. W. Atkinson. “Compressive Failure due to shear Instability: Experimental investigation of waviness and correlation with analysis”. *Journal of Reinforced Plastics and Composites* 15 (1996), pp. 420–439.
[46] R. Joffe, D. Mattsson, J. Modniks, and J. Varna. “Compressive failure analysis of non-crimp fabric composites with large out-of-plane misalignment of fiber bundles”. *Composites Part A: Applied Science and Manufacturing* 36.8 (2005), pp. 1030–1046.
[47] S. Drapier and M. R. Wisnom. “Finite-element investigation of the compressive strength of non-crimp-fabric-based composites”. *Composites Science and Technology* 59.8 (1999), pp. 1287–1297.

[48] A. B. Jensen, J. Thesbjerg, J. L. Wind, and H. M. Jensen. “Kink band predictions in fiber composites using periodic boundary conditions”. *Composite Structures* 207.August 2018 (2019), pp. 331–339.
[49] J. Shu and N. A. Fleck. “Microbuckle Initiation in Fibre Composites under Multiaxial Loading”. *Proceedings:Mathematical and Physical Sciences* 453.1965 (1997), pp. 2063–2083.
[50] W. S. Slaughter and N. A. Fleck. “Microbuckling of fiber composites with random initial fiber waviness”. *Journal of the Mechanics and Physics of Solids* 42.11 (1994), pp. 1743–1766.
[51] D. Liu, N. A. Fleck, and M. P. F. Sutcliffe. “Compressive strength of fibre composites with random fibre waviness”. *Journal of the Mechanics and Physics of Solids* 52.7 (2004), pp. 1481–1505.
[52] S. P. Yushanov and A. E. Bogdanovich. “Stochastic theory of composite materials with random waviness of the reinforcements”. *International Journal of Solids and Structures* 35.22 (1998), pp. 2901–2930.
[53] M. P. F. Sutcliffe. “Modelling the effect of size on compressive strength of fibre composites with random waviness”. *Composites Science and Technology* 88 (2013), pp. 142–150.
[54] N. Safdar, B. Daum, and R Rolfes. “Stochastic compressive failure surface modelling for the unidirectional fibre reinforced composites under plainstress”. *6th European Conference on Computational Mechanics (ECCM 6)*. June. 2018.
[55] M. P. F. Sutcliffe, S. L. Lemanski, and A. E. Scott. “Measurement of fibre waviness in industrial composite components”. *Composites Science and Technology* 72.16 (2012), pp. 2016–2023.
[56] S. L. Lemanski and M. P. F. Sutcliffe. “Compressive failure of finite size unidirectional composite laminates with a region of fibre waviness”. *Composites Part A: Applied Science and Manufacturing* 43.3 (2012), pp. 435–444.
[57] L. N. Melin and J. M. Neumeister. “Measuring constitutive shear behavior of orthotropic composites and evaluation of the modified Iosipescu test”. *Composite Structures* 76.1-2 (2006), pp. 106–115.
[58] T. Bru, R. Olsson, R. Gutkin, and G. M. Vyas. “Use of the Iosipescu test for the identification of shear damage evolution laws of an orthotropic composite”. *Composite Structures* 174 (2017), pp. 319–328.
[59] K. D. Potter, B. Khan, M. R. Wisnom, T. Bell, and J. Stevens. “Variability, fibre waviness and misalignment in the determination of the properties of composite materials and structures”. *Composites Part A: Applied Science and Manufacturing* 39.9 (2008), pp. 1343–1354.
[60] K. Hazra, S. Blake, K. D. Potter, and M. R. Wisnom. “In-Process Fiber Orientation Measurement and Foreign Object Damage (FOD) Prevention for Complex Preform or Prepreg Lay-ups”. *Society for the Advancement of Material and Process Engineering Journal* 48.l (2012), pp. 6–11.
[61] D. Pain and B. W. Drinkwater. “Detection of fibre waviness using ultrasonic array scattering data”. *Journal of Nondestructive Evaluation* 32.3 (2013), pp. 215–227.

[62] L. J. Nelson and R. A. Smith. "Fibre direction and stacking sequence measurement in carbon fibre composites using Radon transforms of ultrasonic data". *Composites Part A: Applied Science and Manufacturing* 118 (2019), pp. 1–8.
[63] K. Mizukami and K. Ogi. "Non-contact visualization of fiber waviness distribution in carbon fiber composites using eddy current testing". *Advanced Composite Materials* 27.2 (2018), pp. 135–146.
[64] J. Sjölander, P. Hallander, and M. Åkermo. "Forming induced wrinkling of composite laminates: A numerical study on wrinkling mechanisms". *Composites Part A: Applied Science and Manufacturing* 81 (2016).
[65] N. Xie, R. A. Smith, S. Mukhopadhyay, and S. R. Hallett. "A numerical study on the influence of composite wrinkle defect geometry on compressive strength". *Materials and Design* 140 (2018), pp. 7–20.
[66] S. C. Garcea, Y. Wang, and P. J. Withers. "X-ray computed tomography of polymer composites". *Composites Science and Technology* 156 (2018), pp. 305–319.
[67] C. J. Creighton, M. P. F. Sutcliffe, and T. W. Clyne. "Multiple field image analysis procedure for characterization of fibre alignment in composites". *Composites Part A: Applied Science and Manufacturing* 32 (2001), pp. 221–229.
[68] K. K. Kratmann, M. P. F. Sutcliffe, L. T. Lilleheden, R. Pyrz, and O. T. Thomsen. "A novel image analysis procedure for measuring fibre misalignment in unidirectional fibre composites". *Composites Science and Technology* 69 (2009), pp. 228–238.
[69] D. Wilhelmsson and L. E. Asp. "A high resolution method for characterisation of fibre misalignment angles in composites". *Composites Science and Technology* 165.April (2018), pp. 214–221.
[70] L. Kawashita, M. Jones, S. Giannis, S. Hallett, and M. Wisnom. "Novel methods for testing and modelling composite materials and laminates". *In: ICCM International Conferences on Composite Materials.* Jeju Island, Korea, 2011.
[71] ASTM. *ASTM D3410 - Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear.* Tech. rep. Reapproved 2008. West Conshohocken, PA, 2008, pp. 1–16.
[72] ASTM. *ASTM D6641 - Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture.* Tech. rep. Clc. West Conshohocken, PA, 2014, pp. 1–11.
[73] D. Wilhelmsson, L. E. Asp, R. Gutkin, and F. Edgren. "Effect of specimen width on strength in off-axis compression tests". *Proceedings of the 17th European conference on composite materials (ECCM17).* Munich, 2016.