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in

Solid and Structural Mechanics

Physically based constitutive models for crash of composites

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Physically based fibre kinking model for crash of composites
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Cover:
Experiments on the left side of the “road” (courtesy of Thomas Bru) and simulations on the right side.

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Abstract

The transportation industry and passenger cars in particular are strong emitters of gases that contribute to the climate crisis. For this reason, the automotive industry investigates opportunities to reduce emissions, such as reducing the weight of the car. Composite materials, due to their high strength, stiffness and energy absorption to weight ratio, are a suitable material choice to reduce weight. The challenge here is that composites do not satisfy the fast development times and low costs required by the car industry. An efficient design phase, using more simulation and less physical testing, allows for time and cost-savings. However, there is a lack of efficient computational models to help the design with composite materials, which is fundamental for a widespread usage of composites in the automotive industry.

This thesis presents the development, improvement and validation of constitutive models for composites in crash, focusing on compressive damage modes, matrix compression and fibre compression. The material being modelled is a carbon fibre/epoxy uni-weave Non-Crimp Fabric (NCF) composite. The properties of the composite constituents are homogenized to the ply level for a more efficient modelling.

The matrix behaviour is modelled by combining damage and friction on the microcrack surfaces. The transverse mechanisms are modelled efficiently using a criterion for final failure, interaction of damage modes and a continuous response between compression and tension. The model is validated against 45- and 90-degree specimens. The fibre compression mode is fibre kinking growth, a very complex mechanism, responsible for high energy absorption. A homogenized 3D model based on Fibre Kinking Theory (FKT) is developed. It includes initial fibre misalignments and further rotations are governed by equilibrium with shear nonlinearity. The model is implemented in a commercial Finite Element (FE) software together with a mesh objective methodology. Furthermore, another formulation with similar physical principles but more suitable, efficient and robust for crash simulations is developed, implemented in an FE software and validated against experiments. The results show good qualitative and quantitative agreement. The proposed models allow for a reduction of physical testing required to develop crashworthy structures.

Keywords: Crushing, kinking, friction, damage mechanics, FEA

Preface

My motivation for working with research in material modelling started during my internship at *Simulia* in California, back in 2011. I was working with stents when a constitutive model of Nitinol, roughly 5000 lines of code, was briefly presented to me. The following two years, I worked with numerical simulation as a Consultant Engineer for Airbus, in Toulouse, France. Throughout this experience, I was fascinated by the replacement of metals with composites in a newly designed A350 aircraft. This experience motivated me further to pursue a PhD with the aim of modelling composite materials in crash. In the end of 2013, I moved to Gothenburg to start my PhD position at Swerea SICOMP, now RISE, the Research Institutes of Sweden.

This work was only possible due to the funding of *Fordonsstrategisk Forskning och Innovation* (FFI) via VINNOVA and the Swedish Energy Agency *Energimyndigheten*. The financing of both funding agencies is gratefully acknowledged as well as all the project partners involved.

The unwearied efforts, guidance and support from my supervisors Robin Olsson, Renaud Gutkin and Martin Fagerström are highly appreciated. I also would like to acknowledge my colleagues at RISE SICOMP, Chalmers and Volvo for their support and the great time we have spent together. Special thanks go to Thomas Bru and Dennis Wilhelmsson for the countless discussions that we have had about our research; Gaurav Vyas for his many advices and support.

Finally, I would like to express my sincere gratitude to my parents, my girlfriend Imelda and my friends for their support and encouragement.

Sérgio Costa,

Gothenburg, August 2019

Thesis

This PhD thesis includes a brief description of motivation and challenges of crash modelling of composites, as well as the following appended papers:

Paper A Renaud Gutkin; **Sérgio Costa**, Robin Olsson**.** A physically based model for kink-band growth and longitudinal crushing of composites under 3D stress states accounting for friction. *Composite Science and Technology*, (2016)

Paper B **Sérgio Costa**; Renaud Gutkin; Robin Olsson**.** Mesh objective implementation of a fibre kinking model for damage growth with friction. *Composite Structures*, (2017)

Paper C **Sérgio Costa**; Thomas Bru; Robin Olsson**;** André Portugal. Improvement and validation of a physically based model for the shear and transverse crushing of orthotropic composites. *Journal of Composite Materials*, (2018)

Paper D **Sérgio Costa**; Martin Fagerström; Robin Olsson**.** Development and numerical validation of a 3D fibre kinking model for crushing of composite. S*ubmitted for journal publication*, (2019)

The full list of publications from the project is included in the references.

Division of the work between authors

Paper A: Renaud Gutkin developed the model. Sérgio Costa implemented the model in Matlab and participated actively in the writing and structuring of the paper with suggestions from Robin Olsson.

Paper B: Sérgio Costa implemented the model in a Fortran subroutine and performed the studies on mesh objectivity with the guidance of Renaud Gutkin and Robin Olsson. Sérgio Costa wrote the paper with suggestions and comments from the co-authors.

Paper C: Sérgio Costa developed and implemented the material model. Sérgio Costa and Thomas Bru assisted André Portugal with the numerical simulations of the compression and crush tests. Sérgio Costa wrote the paper with the help of Thomas Bru. Robin Olsson contributed with suggestions and comments.

Paper D: Sérgio Costa developed and validated the model. Martin Fagerström brought up the need to develop a new framework for fibre-kinking. Sérgio Costa wrote the paper with guidance from Martin Fagerström and Robin Olsson.

Contents

1. Introduction

1.1. Background

Over the past fifty years, the use of Fibre Reinforced Plastics (FRP) increased substantially. Carbon Fibre Reinforced Plastics (CFRP) are particularly attractive due to their high stiffness to weight ratio. This trend is very clear in the aerospace industry, as shown Figure 1(a). Nowadays, CFRPs are mostly used in high performance applications that are not cost-driven and have small production volumes, such as in aerospace and sports. In the early days of composite materials, their ability to perform well in a crash situation was highly questionable. Many designers of repute expressed doubts regarding the suitability of such brittle materials in a crash scenario [1].

However, the image of composites was about to change. In 1981, the first Formula One car with carbon monocoque entirely made from composites, Figure 1(b), smashed violently into the barriers. To the surprise of most, the driver was able to walk away from the debris unscathed, proving the safety of carbon fibre composites under high strain rate loading. The energy absorbing properties of composites have subsequently made a great contribution to the safety record of the sport [1].

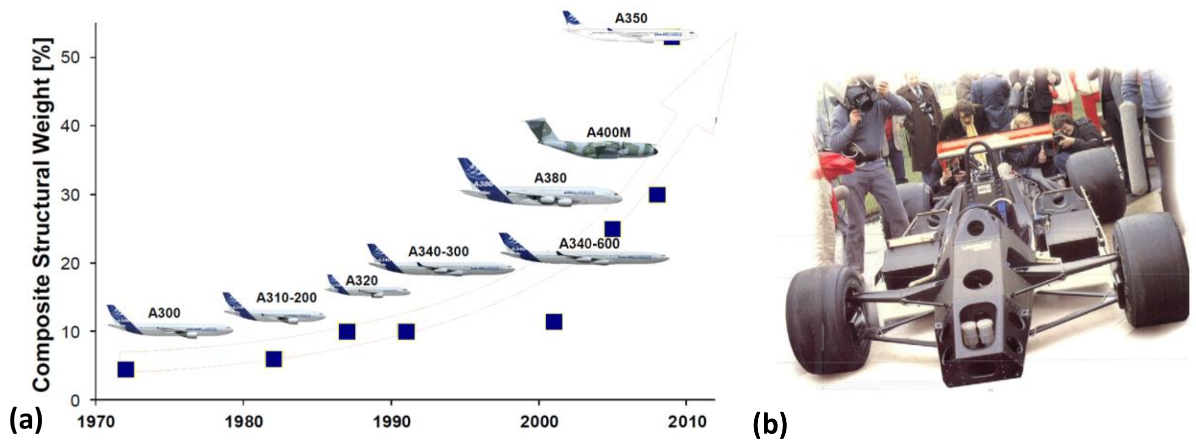

Figure 1. (a) Growth of composites usage in Airbus aircrafts; (b)The first carbon monocoque in Formula 1, the McLaren MP4/1 (1980)[1]*;*

Our current climate crisis results mainly from too high concentration of CO_2 in the atmosphere. The contribution of CO_2 to the greenhouse effect (and subsequent temperature rise) was first quantified by Arrhenius in 1896 [2]. More than a century after, the reaction of the regulatory authorities has been to impose stricter regulations on the automotive manufacturers. The proposed targets for 2020 and 2025 for an automakers fleet is to have a maximum average of 95 and 81g per kilometre respectively. Therefore, we need effective methods to reduce CO_2 emissions from Internal Combustion (IC) engines. Improving IC engines is becoming too expensive, forcing the car manufactures to search for other solutions, such as weight reduction. Since approximately three quarters of the energy consumption is related to vehicle weight [3], reducing weight is an efficient way to lower emissions.

Over the past decades, cars are becoming heavier due to new safety and comfort features introduced. Removing these features would be a backward step that is not attractive for automakers and their customers. More recently, composites have also been envisaged for mainstream cars as a possibility to reduce weight and thereby fuel consumption and its associated Carbon Dioxide (CO_2) emissions. Composites possess some of the necessary characteristics to outperform the current materials used in the automotive industry such as high stiffness, strength and energy absorption per weight. The main challenge is that the automotive industry aims at very high production volumes and is highly cost driven.

For the purpose of reducing the weight of the vehicle, it is necessary to replace the current metals, mainly steel and aluminium, by composite materials in the structural parts [3]. Even though producing 1 kg of steel causes less emission than 1 kg of CFRP, in the long run, due to the lower vehicle emissions, conventional composites outperform steel. Furthermore, according to Ref [4], there is great potential for improving the CFRP, as shown in Figure 2.

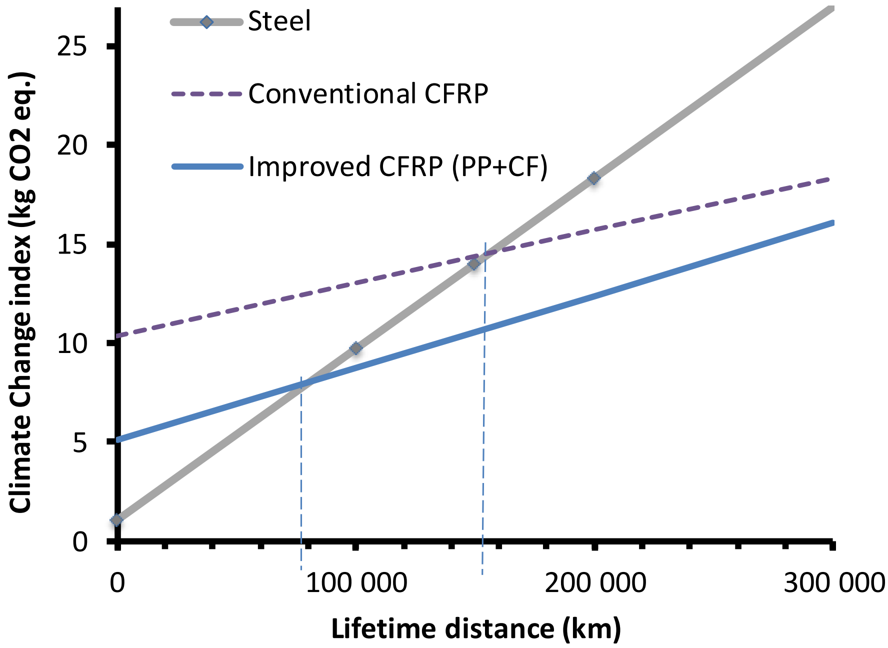

Figure 2. Lightweight potential of composites in the automotive industry, adapted from [4]

Composite materials, with their excellent corrosion resistance and good fatigue behaviour, can also play an important role when it comes to longer term usage of cars and thus reduce the CO_2 footprint even further. Another alternative to reduce emission is to use electric cars which do not have direct CO_2 emissions. However, range anxiety is a major concern for most of the costumers, making weight reduction equally important.

1.2. Potential of composites for energy absorption

The establishment of composite materials in the automotive market sector depends mainly on: (i) improving the manufacturing process; (ii) developing a material database with relevant parameters; (iii) increasing the understanding of composite components during vehicle crashes; (iv) and developing predictive (crash) models to avoid costly overdesign [3,5]. The focus of this thesis is on (iv): developing, enhancing and validating physically based crash models.

In order to protect the passengers in a potential car crash, the aim is to obtain a stable crushing with a low peak load and a high average crushing load, resulting in low initial impact force and high energy absorption. The car components should be designed to fail in a controlled manner. Designing components using Computer Aided Engineering (CAE) will allow significant cost savings and optimal design for crash. Using CAE and constitutive models capable of predicting the crushing behaviour for varying shapes and loading conditions, will help to create an optimal design of composite parts.

Nowadays, composites are already dominant in the luxury car segment, as shown in Figure 3(a). The first car to use CFRP on the car body and being produced in relatively high volumes is the BMW i3, shown in Figure 3(b).

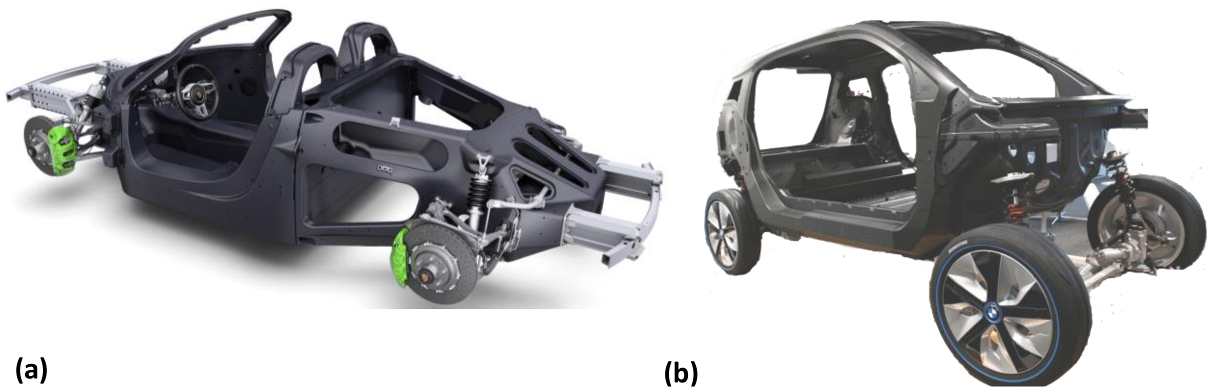

Figure 3.Composite body structure with front and rear steel subframes: (a) Porsche 918 [6]*; (b) BMW i3*

Note that, even though both cars use composites in the body, the parts designed specifically to deal with crash situations are not made from composites. However, composites can be designed to outperform metals in specific energy absorption, as shown in Figure 4.

Composite tubes with most of the fibres oriented in the loading direction, can outperform steel by a factor of six, as shown in Figure 4. Thus, the lack a reliable crash models is likely to be the main reason to justify the choice of metals over composites for the front and rear subframe.

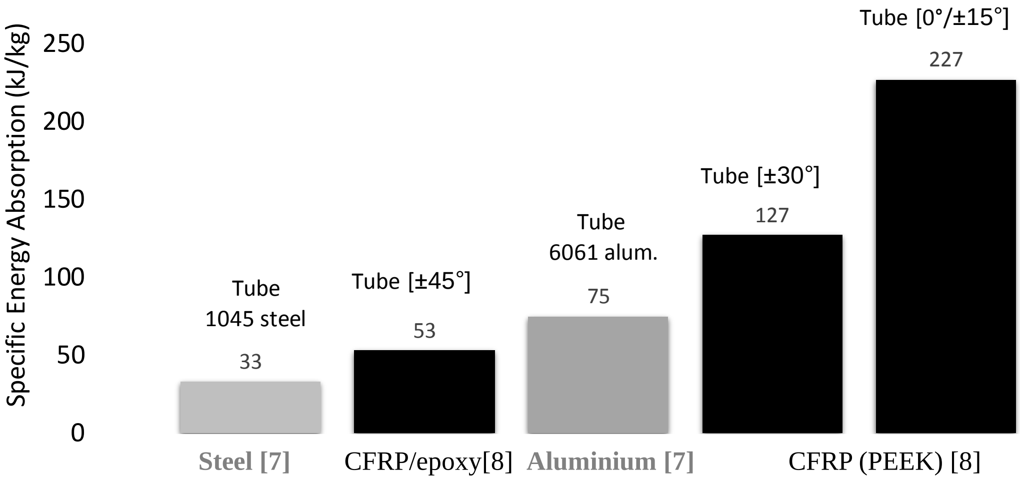

Figure 4. Examples of energy absorption for metal and composite tubes

Crushing describes the continued compressive loading of the *material* beyond its compressive strength limit. A *crash* is a dynamic event involving gross deformations of a *structure* under compressive loading beyond its elastic limit, and generally involves a combination of elastic deformations with crushing or yielding. Since a crash only takes a split of a second it is difficult to follow even using high speed cameras. Therefore, most of the structural cr*a*sh modelling is based on static cr*u*sh tests of the material. By compressing a coupon in a quasi-static manner, it becomes easier to follow and register the failure mechanisms. The drawback of a quasi-static approach is that some materials are strain-rate dependent, as in the case of thermoplastic polymer reinforced composites, [9,10]. Strain rate effects were not investigated in the current work but are being addressed in a parallel project.

1.3. Current challenges for the automotive industry

Modelling crash is essential to improve the design and ensure the crashworthiness of the automotive composite structures in a short time frame and low budget. Current crash simulations are not predictive enough and therefore, more accurate damage models are necessary [11]. Feraboli and colleagues [12], created a protocol for crashworthiness certification using the foundations of (*i*) the Building Block Approach (BBA) adapted to crashworthiness and (*ii*) based on analysis supported by test evidence. The more the development relies on analysis, the less expensive it becomes [13]. A material model available in LS-Dyna, *MAT 54*, was used extensively by Feraboli and colleagues but many difficulties were encountered. Those difficulties were mainly due to the lack of predictable capabilities of the MAT 54 constitutive model causing extensive coupon testing to build up a material database as well as necessary model calibration when climbing the stairs of the BBA.

Another obstacle for the crash simulation of composites, besides the lack of predictive crash models, is to identify and obtain relevant properties for crash models. There are ASTM standards for the elastic and strength properties, as well as for some toughness properties.

However, there are properties necessary for crash that still lack standard test methods. The extraction of relevant material properties has been the focus of a parallel PhD thesis [14].

Another difficulty to overcome is the lack of expertise necessary to perform crash simulations of composite materials. The currently available models need many material parameters, some of them are unphysical and need to be calibrated, in accordance with the type of simulation. Furthermore, when building the CAE model, extra care is necessary with meshing in order to create a mesh as regular as possible, i.e. with good element ratios. The minimum time step required for convergence is not always well estimated by the software. It is up to the CAE analysist to define an appropriate step time. The small scale at which the failure occurs requires very detailed modelling, which together with small time steps, will slow down the simulation. This leads to another challenge. Crash simulations with reasonably sophisticated models, are very computationally expensive and not affordable in a full-scale model. This challenge is also being addressed in a parallel PhD project.

1.4. Material system considerations: UD tape vs Woven vs NCF

Unidirectional (UD), pre-impregnated (prepreg) tape composites have excellent mechanical properties per unit weight. However, their costly manufacturing and poor drapability does not make them an attractive candidate material to use in low to medium end cars. On the other hand, textile laminates, can be manufactured with an infusion process, leading to cheaper components but with lower mechanical properties. Several types of textile reinforcements have been proposed, e.g. woven, braided, knitted, uni-weave NCF, biaxial NCF, etc.

UD prepreg plies are transversely isotropic, Figure 5(a), while Non-Crimp Fabrics (NCFs) are orthotropic and heterogeneous on different scales: microscale, mesoscale and macroscale, [15]. Observing the geometry of an NCF, one can notice: agglomerates of fibres in a fibre bundle, stitching yarns interlaced in the fibre bundles and a small waviness (crimp) of the fibres, Figure 5(b).

The fact that NCF composites have lower crimp or waviness than other textiles gives NCF better mechanical properties. Furthermore, NCF composites have good impregnation which eases manufacturing and helps to ensure lower void content of the matrix. The stitching reinforcement (yarns) keep the fibre tows together, so they help handling during manufacturing and improve the out-of-plane compressive strength.

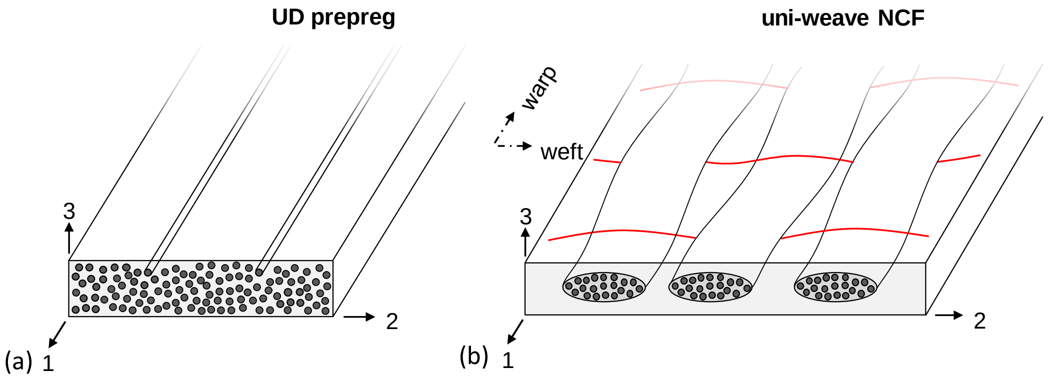

Figure 5. Representation of a composite ply: (a) UD pre-impregnated; (b) Textile uni-weave NCF, [14]

Even though NCF have lower waviness than most textiles, they still have more waviness than UD prepreg composites. The waviness affects the (in-plane) fibre compressive strength and is a key characteristic for compressive failure. Overall, NCF composites are good candidates for the automotive industry due to their relatively high mechanical properties, low manufacturing times as well as their suitability for large scale production. NCFs also have good drapability which fulfils the needs of the automotive industry to manufacture complex shapes [16].

From a crash modelling perspective, all the failure mechanisms observed in conventional UD prepreg tape composites are also present in NCF. The fibre misalignment in prepreg tape composites should be present inside the fibre tows of NCF, plus fibre tow waviness. Consequently, the compressive strength of NCF is about half of the tensile strength. However, the influence of the stitching yarn, for example, should be included in a mesoscale modelling. The elastic properties of the layers of fibre tows should also be homogenised [15].

1.5. Energy absorption during crash

The legislation for automobiles requires that vehicles are designed according to several safety requirements. For example, in the event of an impact at speeds up to 15.5 m/s (35 mph) with a solid, immovable object, the occupants in the passenger compartment should not experience a resulting force that produces a net deceleration greater than 20 g, [17]. To fulfil the requirements, the initial peak load must be avoided, and large deformations must be obtained in a controlled way. To do so, a trigger is necessary to initiate the crushing, either by a geometric feature or by taking advantage of a fibre lay-up with a local off-axis angle.

For a given fibre lay-up, different tube geometries will have different energy absorption [18]. Energy absorption is dependent on many parameters, such as: fibre and matrix type, fibre architecture, lay-up, specimen geometry, processing conditions, fibre volume fraction and testing speed. The Specific Energy Absorption (SEA) during crash, according to Grauers et al. [19], can be estimated as:

$$SEA = \frac{\int_{\delta}^{\delta + \Delta\delta} F dx}{m} = \frac{\int_{\delta}^{\delta + \Delta\delta} F dx}{\rho A \Delta\delta} \approx \frac{\overline{F} \Delta\delta}{\rho A \Delta\delta} = \frac{\overline{\sigma}}{\rho} \qquad (1)$$

where F is the applied force between δ and $\delta + \Delta\delta$, the initial and final crushing positions respectively, x is the displacement and m is the mass of the crushed material. This expression was approximated and simplified by taking advantage of the average crush load $\overline{F}$ over the studied interval.

The SEA is an apparent material parameter influenced by the cross-section geometry and the interaction of various failure mechanisms in the plies and at the structural level. The SEA of a component can be used as an indicator of crash performance. However, to predict the complex behaviour that occurs at the material microstructure, the mechanisms that occur during crash of composites need to be represented by the model. In the next chapters, the focus is on these mechanisms, their characteristics and finally, how to model them.

2. Crushing mechanisms

2.1. Ply and inter-ply damage modes

Due to the complexity involved in crushing of composites, it is fundamental to identify and classify the different damage mechanisms. This will guide the development of predictive, physically based models. The damage mechanisms can be distinguished based on the location of the damage: *intra*laminar for the damage inside of the ply and *inter*laminar in the interface between plies. The last one is often referred to as delamination. Interface failure may also refer to the separation between fibres and matrix, mostly known as debonding. If the damage grows transversely to the fibres, it is classified as *trans*laminar. These mechanisms, depicted in Figure 6(a), depend on the loading, geometry and the fibre orientation.

The ply-level damage mechanisms under compressive loads are the most important for energy absorption during crash, particularly when the crushing of the fibres is in the loading direction. The phenomenon in which a layer of fibres buckles locally in compression until its sudden break, is known as fibre kinking. Generally, when a compressive load is applied in the axial direction of the fibres, kinking takes place, as seen in Figure 6(b). The focus of this work is on the ply level mechanisms, fibre compression and matrix compression.

(a) (b)

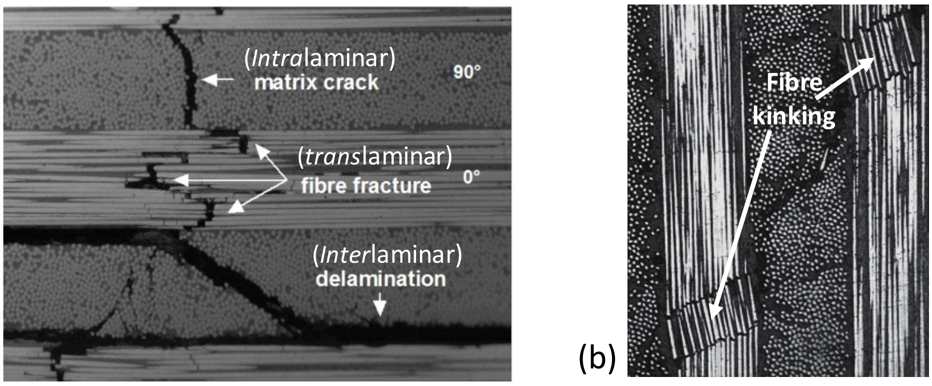

Figure 6. Micrograph of ply-level damage mechanisms exhibited by CFRP; (a) tension dominated, [20]*; (b) Compression dominated* [21]

In fibre compression, damage is introduced via kinking, which causes the surrounding matrix to yield and soften while the fibres rotate. In matrix compression, damage is introduced via microcracks that increase in size and number during loading. These microcracks are under normal compressive load which leads to their closure and involves friction. This makes it possible for the laminate to sustain a significant level of compressive deformations. Under compression, unlike tension, load can be transferred between the two sides of the damage through friction. This leads to the formation of slip surfaces and to a constant plateau stress under compression [22].

A failure envelope, i.e. the curve which joins points of failure at progressive stress configurations, is continuous between tension and compression, implying a smooth transition of damage mechanisms. However, these underlying mechanisms are quite different. In tension along the fibres, the damage is introduced via fibre breakage, often leading to catastrophic failures. In tension transverse to the fibres, micro-cracks open and coalesce into larger cracks between the fibres that often develop into delaminations. Accounting for these damage mechanisms in a constitutive model is fundamental to design crashworthy parts.

Accounting correctly for initiation and growth of delaminations is also fundamental for crash. Delamination failure modes can be classified in an opening mode (Mode I), in-plane shear mode (Mode II), out-of-plane shear mode (Mode III) and mixed mode. As with the ply-level modes, the occurrence of interlaminar modes depends on the geometry, load and fibre direction.

Reducing delaminations is a key aspect for a more crashworthy performance. Interlaminar stresses, causing delamination cracks to initiate, are related to the angle between neighbouring plies. Thus, a smooth variation of angle is preferable between plies in composite design. Particularly, in the case of NCF, the stitching of the bundles improves the delamination toughness, i.e. delamination growth is more contained. However, the stitching seems to have little influence on delamination initiation, i.e. interlaminar strength [23]. The fracture toughness of both ply and interface are key material properties for crash simulations. How these properties are used in crash is described further in this thesis.

2.2. Crushing mechanisms and their interactions

The crash of composite structures is a combination of complex phenomena that can be triggered by one failure mechanism but evolve into another and continuously interact. During damage evolution, matrix cracking can evolve into delamination, Figure 6 (a) and/or fibre kinking, Figure 6 (b). These interactions depend on the properties of the constituents, which complicates both the analysis and the modelling.

Grauers et al. [19] performed compression tests in order to study the energy absorbing mechanisms. The specimens tested were corrugated NCF laminates with a $[0/90]_{3S}$ stacking sequence made of uni-weave carbon fabric and epoxy resin. Corrugated panels are often used in the literature for crash tests mainly due to the low risk of global buckling and also, because they are self-standing [24]. The specimens tested fail partially in splaying, i.e. by delamination and subsequent buckling and bending of entire plies, and partially in pure compression (by crushing) with a Mode I delamination, separating these two regions, Figure 7(a). The parts failing by splaying have lower energy absorption and thus, the aim is to mitigate splaying failure and/or delaminations in compression. As shown in Ref. [25], materials with low Mode-I and Mode-II interlaminar fracture toughness cause low mean crush stress. The part failing by compression absorbs more energy through kink band formation, Figure 7(b). Looking at a single bundle, Figure 7(c), the kink bands induce interlaminar cracks at the interface.

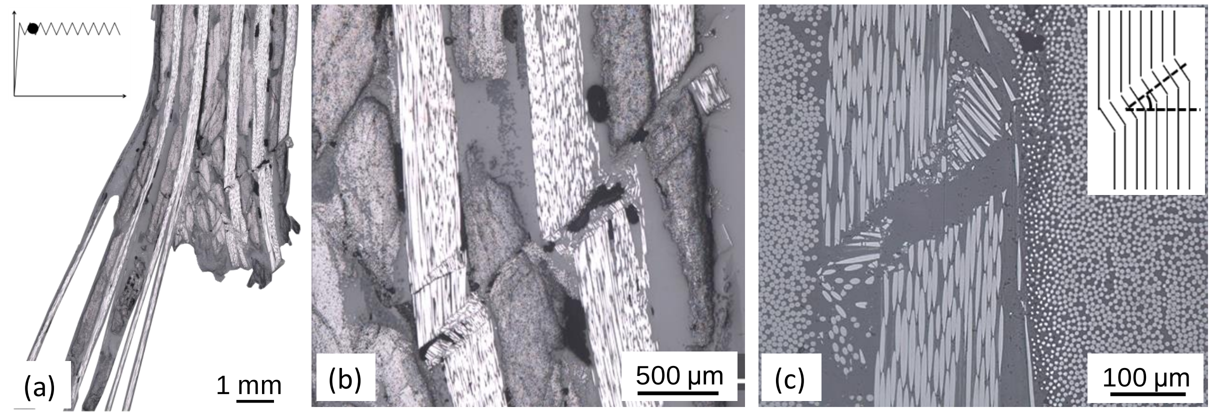

Figure 7. Micrographs through the thickness with different amplifications: (a) Bending failure (left) and compressive failure (right); (b) Kink bands in several bundles with intermediate matrix cracking; (c) Kink bands through a single bundle, adapted from [19]

2.2.1. *The role of testing on crash mechanisms identification*

Experimental methods with in-situ tracking of damage modes and/or followed by fractography are an excellent tool to further investigate the mechanisms present during crash. Testing methods that isolate the damage mechanism are thus envisaged. For example, flat specimens reduce the influence of the structure on the crash response. In that context Bru et al. studied the influence of several crash triggers on the crash response of flat specimens [26]. Like the self-standing specimens, such as the corrugated panel, this setup does not have intrinsic bending problems. The use of UD plies and tulip triggers (with the shape of triangular prism) reduces the splaying and therefore makes it easier to identify the crash mechanisms, as shown in Figure 9.

From observing Figure 8, it becomes evident that the crush stress varies with fibre orientation. However, this variation is not linear, reflecting the strong dependency on the damage modes prevailing in each orientation. The lower crush stress for 20 and 25 degrees is likely to be related to a change in dominating failure mode. For 45 and 90 degrees, matrix cracking dominates the response.

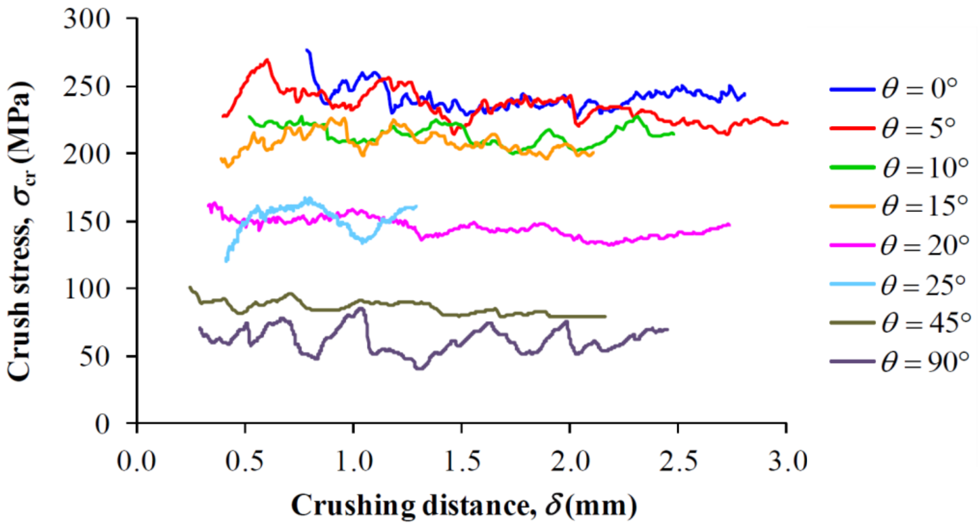

Figure 8. Crush stress obtained from the load displacement curves of flat coupons, [27]

Using the same experimental setup, but with a ±45° layup instead, reveals some of the complexity involved in crush simulations, Figure 9. Matrix cracking evolves into delaminations. Fragmentation is visible in the central region in contact with the crushing plate. The fact that fibre kinking occurs in this specimen is unexpected. Typically, kinking occurs when the fibres are aligned or with small off-axis angles with the load. Observing fibre kinking at 45 degrees highlights the need to include this failure mode even for large off-axis angles.

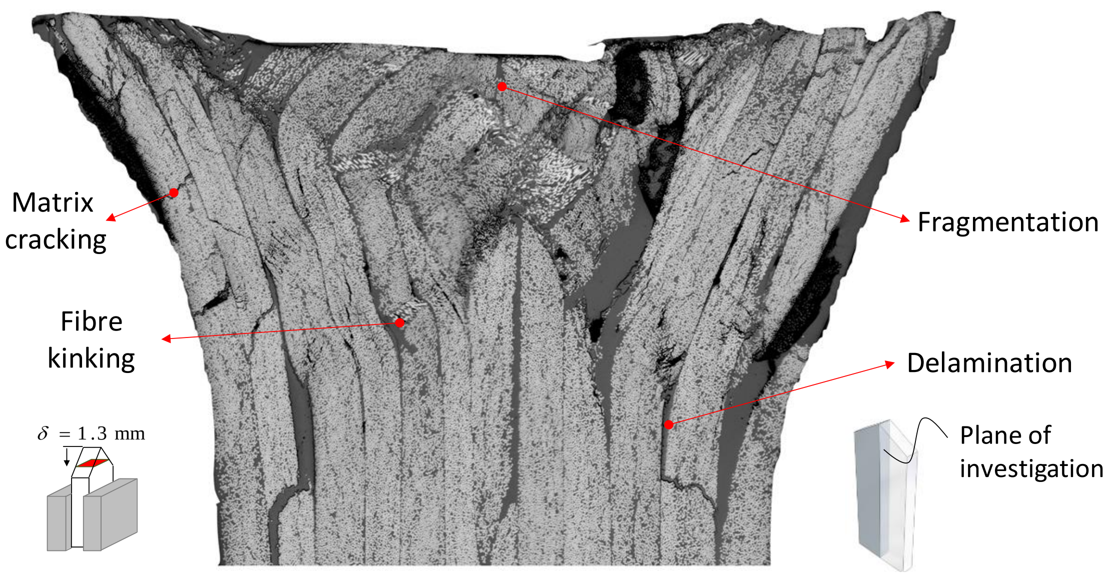

Figure 9. Micrograph of the cross section of a partially crushed flat coupon with fibre lay-up of [±45] showing several crash mechanisms including kink band formation, courtesy of Thomas Bru

2.2.2. *The role of micromechanical models on crash mechanisms identification*

Despite the aforementioned advantages and the knowledge obtained with experiments, there are also limitations on what can be achieved with experimental work. Micromechanical analyses along with homogenisation techniques can provide detailed information for any loading condition, allowing for further confidence in the mesoscale models [28]. In fact, there has been micromechanical models used to validate the assumptions of mesoscale models [42]. The models at the lower scales will provide the understanding and will improve the predictive capabilities of the models developed at the higher scales. However, experimental testing is still necessary to obtain the properties of the reinforcement, matrix materials and their interfaces, as well as appropriate material models for each constituent and the interfaces.

Developing predictive damage models for composite structures is complex due to the small scale at which damage occurs. Thus, micromechanics provides the means to analyse the constitutive behaviour of fibres, matrix and the interaction between them. Although computationally more expensive, micromechanical models would provide more information on the influence of each constituent in the mechanical behaviour of the composite in crash. One possible strategy would include to model a small section of the specimen with as much realistic and computationally inexpensive models as possible. Damage should be included to the constituent properties and study the interaction between fibre kinking and matrix cracking for example.

Micromechanical FE models can also be useful to understand the kink-band growth [29,30], and validate mesoscale models. Since kink-band formation is a 3D phenomenon in which multi-axial stress states should be considered, it is difficult and time consuming to develop test methods that account for the whole range of multiaxial stress state. For example, transverse compression is beneficial in raising the longitudinal strength of the composite while transverse tension lowers it, [31]. The final aim though, is to develop efficient and predictive models that account for the referred mechanisms without modelling fibres individually, i.e. micromechanical models could be used as a support to the development of mesoscale models.

2.3. Interaction between scales

Another challenge with developing predictive models is to correctly account for the interaction between damage mechanisms that occur in a scale orders of magnitude smaller than the engineering scale required. Thus, it is important to develop a modelling framework across the different scales. It is impossible to manufacture a composite without any imperfections, e.g. residual stresses generated by manufacturing, misaligned fibres and voids during impregnation. Those imperfections degrade the mechanical properties and often trigger damage initiation due to stress concentrations. Mapping the sequence of failure is very time consuming and requires high expertise in the fractography of composites. A proper definition of a modelling scale has particular importance in the case of composite laminates, because typically the in-plane dimensions exceed the length scale at which delamination, matrix cracking, and fibre-matrix debonding take place by one to several orders of magnitude. The different scales typically considered in composite materials are shown in Figure 10.

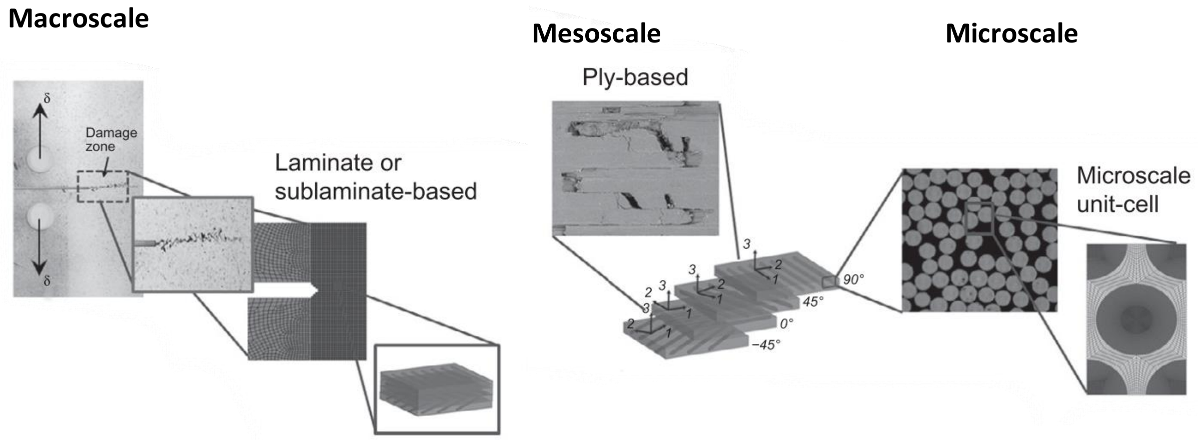

Figure 10. A schematic representation of the various scales involved in modelling the damage [32]

In the current work, the material is homogenised, i.e. the properties of the fibres and the matrix are not considered separately. Without homogenisation, the models would be prohibitively expensive for engineering crash simulations. The mesoscale (ply-level) is a good choice because, at this level, it is still possible to capture the most important mechanisms at the microscale and at acceptable computational speeds. Some of those mechanisms captured by the mesoscale modes are the orientation of the fracture plane and the fibre rotation. Both will dictate the interaction with other damage mechanisms such as delaminations.

A full-scale validation of material models also requires simulation of different scales of structures. The typical approach is the building block approach pyramid, first suggested by Rouchon [33]. Rouchon's pyramid starts with simple small coupons used in material characterization, then moves to more complex structural parts, ending with full-scale components. The long-term aim is to replace the costly physical testing by simulation throughout the different levels, as shown in Figure 11. The current short-term aim is to reduce physical testing at the intermediate levels by gradually replacing it with simulation.

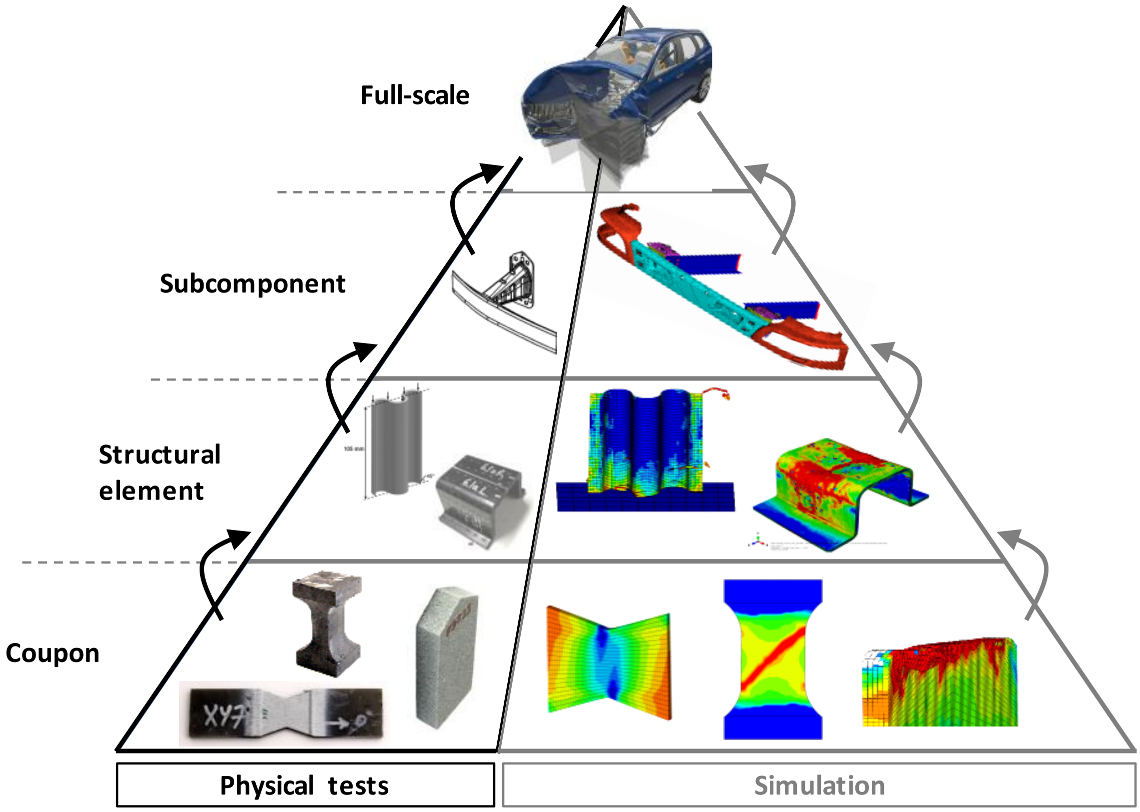

Figure 11. Rouchoun's Pyramid applied to crash of automotive structures, courtesy of Thomas Bru

3. Modelling approaches used for crash

The approaches for failure prediction presented in the literature can be divided into: failure initiation criteria, fracture mechanics, plasticity and Continuum Damage Mechanics (CDM). This section is based on CDM approach, although the author recognises that the extended finite element method, XFEM, has gained some attention recently in the research community. However, due to the large amount of matrix cracks formed during crash, many new degrees of freedom must be added to the model, making XFEM (or similar) techniques prohibitively expensive.

3.1. Failure initiation

The effective use of composite materials in load-carrying structures depends on the ability to obtain reliable predictions of the onset and propagation of the different failure mechanisms. Many years of research resulted in reasonable predictions for failure initiation in composite materials [34]. Indeed, this has been the subject of many research studies in the literature for several years, e.g. refs. [35–38].

Physically based failure criteria can predict the failure mode and also provide details about the failure process. The first physically based failure criteria were introduced by Hashin [37]. Puck et al. [39] modified the Mohr-Coulomb approach for the application to UD composites. More recently, the LaRC (Langley Research Centre) was further developed to LaRC05 [40].

Given the vast number of failure criteria available, a world-wide failure exercise was organized in an attempt to assess predictability of several failure modes. From all the models tested, the LaRC05 failure criteria had top performance [41]. This model innovates by being a set of 3D failure criteria with emphasis on onset of fibre kinking. For longitudinal compression these failure criteria added two notions for failure initiation that guided our presented papers for damage growth. One idea is the evaluation of a matrix failure criterion in the misaligned fibre direction [42] and the other is consideration of the competition between matrix cracking and instability due to shear nonlinearity for the prediction of the compressive strength [38]. These notions will be further explained in this thesis. The in-situ effects were later included by Camanho et. al [38], although they were not considered in the current research.

Due to the complexity of crash and its modelling, the typical approach is to distinguish between damage modes. The separation of damage modes is based on the loading direction and fibre orientation, as shown in Figure 12. In the current work, matrix compression and in-plane shear have the same modelling strategy. Matrix compression is shear failure with additional pressure in the fracture plane. Fibre compression will be detailed in the next section. Fibre tension is particularly simple compared to the other failure modes due to the lack of interaction between the different stress components a maximum stress criterion is commonly used. Matrix tension is similar to matrix compression except that there is a tensile component in the fracture plane and therefore, friction is not included. Note that out-of-plane shear also belongs to the matrix tension failure mode.

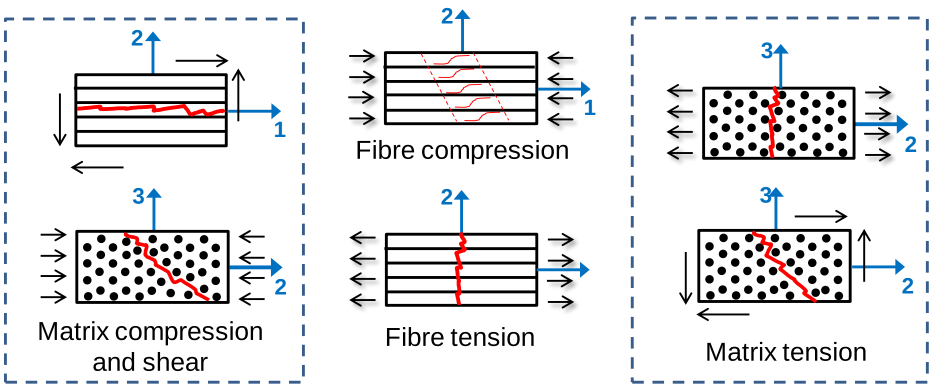

Figure 12. Separation of intralaminar failure modes

Transverse failure modes occur when the load is normal to the fibre direction and are dominated by matrix properties [39]. The microcracks usually coalesce in a visibly fracture plane as represented in Figure 13(a). In case of fibre compression, fibres often rotate in a well-defined band, forming a kink-band plane, Figure 13(b). The typical approach to compute the fracture plane (and the kink-band plane) is to check if the respective failure criterion has reached the unity for a set of tested angles. For a pure compressive load, the fracture plane typically occurs at an angle α of 53º ±3º. The deviation of this angle from a pure shear case with a $\alpha = 45^{\circ}$ is due to the friction stress occurring on the fracture plane [39]. Friction results from the stresses created in the fracture plane, thus, increasing the compressive stress.

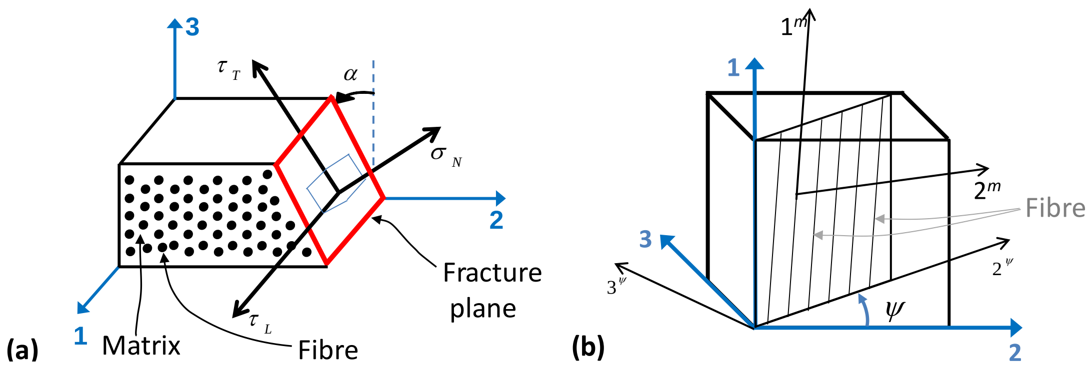

Figure 13. (a) Fracture plane NLT for matrix compression; (b) kink-band plane for fibre compression

3.2. Damage growth

A total reduction of elastic properties at damage initiation it is still common practice in industry and research, e.g. MAT 54, [5]. Also, modelling approaches using a linear softening law to represent the damage growth, as shown in Figure 14, are common in the literature. The whole response may be simply called a bilinear law. For both tension and compression, it was shown that a bilinear strain-softening response is applicable only to the cases where the damage zone is narrow and the surface strains represent the though-thickness strains [22]. Even though bilinear models lack physical foundations, they are still commonly used for crash simulations [43–45].

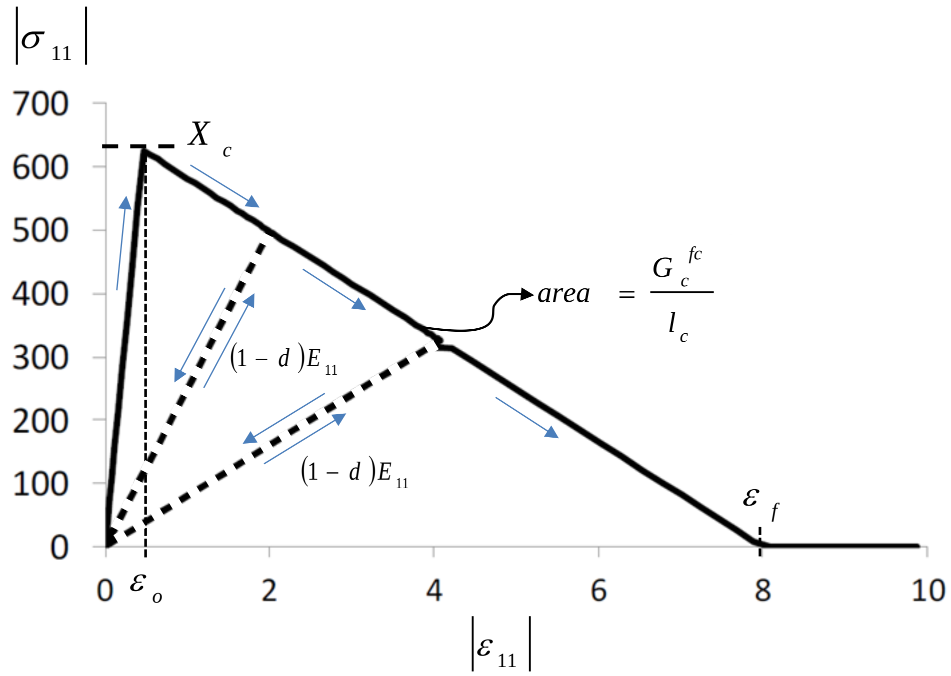

Figure 14. Example of a typical bilinear law with loading and unloading

The damage mechanics approach is the most investigated in the recent years, being applied efficiently to damage modelling. A reference damage model, based on CDM was proposed by Ladeveze and Le Dantec in 1992, ref [46]. It was an in-plane damage model for the elementary ply, which was able to represent matrix micro-cracking and fibre/matrix debonding by two damage variables.

The damage variables are used to represent the reduction of area resisting the load, i.e. to degrade the material mechanical properties. Once a failure criterion is met, the damage variable is activated and acts on its respective failure mode by degrading the respective stress component(s). The damage variables increase monotonically from 0, at failure onset ($\varepsilon = \varepsilon_o$, representing the intact material) to 1 representing the fully damaged state ($\varepsilon = \varepsilon_f$), as shown in Figure 14. Thus, based on CDM models, the applied stress is the result of the effective stress, σ^{ef} degraded by a damage variable as below:

$$\sigma = (1 - d)\sigma^{ef} \tag{2}$$

The toughness of composite materials will depend on the crack growth mode and the failure mode. For example, for pure fibre compressive failure (negative σ_{11} acting alone), the fracture toughness is the mode I translaminar fracture mode, G_c^{fc} . For a (bi-)linear material model with linear softening, the final strain is calculated using the expression below:

$$\varepsilon_f = \frac{2G_c^{fc}}{\sigma_o l_c} \tag{3}$$

The characteristic element length (l_c) is necessary to avoid mesh dependency and represents the characteristic width of damage process zone, and σ_o is the material strength. The fracture toughness is obtained from physical experiments for each failure mode; it defines final strain and drives damage growth. Once the final strain is known, it is possible to derive the evolution of the damage variable. Once again, for a (bi-)linear model with linear softening, the total strain ε must be in accordance with the respective failure mode.

$$d = 1 - \varepsilon_f \frac{\varepsilon - \varepsilon_o}{\varepsilon(\varepsilon_f - \varepsilon_o)} \tag{4}$$

Each failure mode has a damage variable associated. The three failure modes in LaRC, i.e. matrix fracture, fibre-kinking and fibre tension require a respective damage variable. Depending on the model definitions, several damage variables can be defined, being activated when the respective failure index reaches the unity.

3.3. Matrix damage – compression and shear

Possible voids created during manufacturing and/or new microcracks developed during loading, will propagate during matrix compression. This leads to formation of bigger crack surfaces, as the one shown in Figure 15(a). These cracks are under substantial pressure and shear. The compressive stress can be decomposed into a shear component and a normal component in the newly formed crack (fracture) plane, as represented in Figure 15(b).

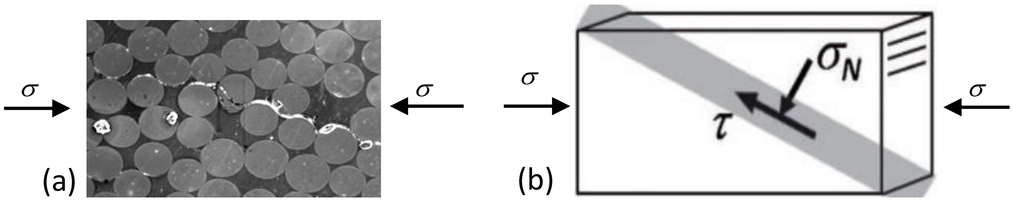

Figure 15. Transverse compression: (a) Matrix failure; (b) Representation with projection of the stresses in the fracture plane, adapted from [47]

The nonlinear behaviour of composites, either resulting from plastic deformations or damage, has been an ongoing challenge to model. The stress-strain constitutive laws could be modelled by an exponential shear curve [48] or by plasticity combined with damage [49]. An efficient and physically based approach to model damage growth is by combining damage and friction [47]. The physical mechanisms are captured by coupling damage with contact friction on the microcracks. These mechanisms accounts for some of the nonlinear behaviour in the shear response. This approach for modelling the shear response is very efficient computationally, since it only requires a few mathematical operations due to the few equations involved. Taking advantage of the sticking/slipping behaviour it is possible to model the typical hysteresis loops observed in Figure 16.

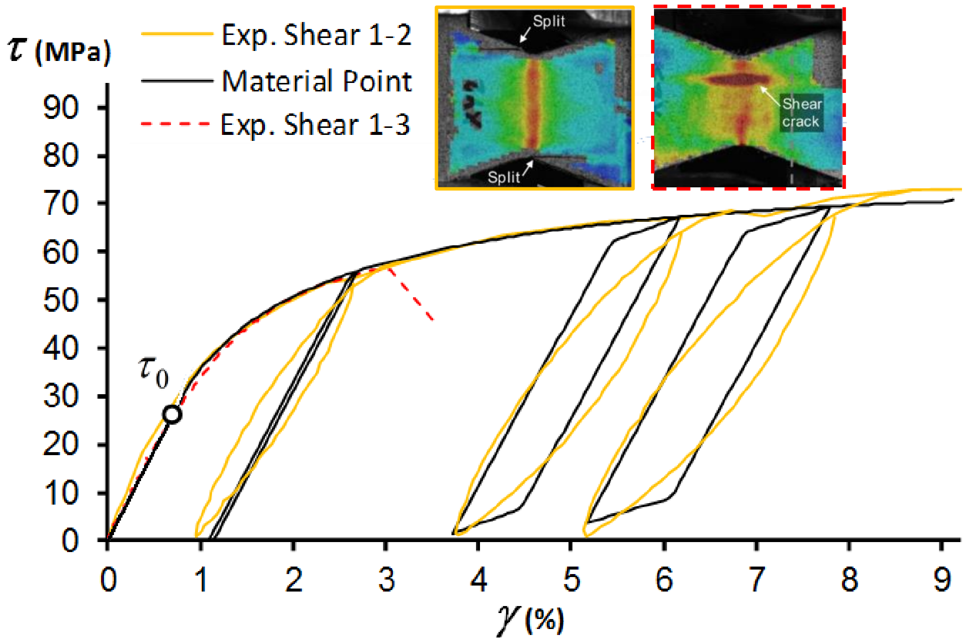

Figure 16. Shear response experiments and simulation, adapted from Paper D

The damaged area cannot carry stresses in tension, but in compression the contact between the microcracks creates friction directly proportional to the state of damage. In one dimension this influence can be represented by the following equation:

$$\tau = (1 - d)G\gamma + d\tau^{friction} \quad (5)$$

where the friction term follows Coulomb's law.

The influence of pressure on the matrix response has been accounted for initially by Puck, [39] and also included in LaRC failure criteria, [40,50]. A friction and normal stresses in the fracture plane increase the shear strength. However, both models have linear behaviour before final failure. Including friction with damage can account for the pressure dependency of the matrix behaviour in composite materials and the shear nonlinearity.

There are only a few models in the literature that are capable of simulating the mechanical behaviour of composite materials during compressive and tensile loading [43,51–53]. Most of the existing models are based on linear softening laws for both tensile and compressive behaviour. In paper C, compression and tension are included in the constitutive model, but differently to previous research, the model also includes nonlinear behaviour and inelastic deformations. Using this approach, it is possible to capture the nonlinear shear behaviour as shown in Figure 16, but also, the correct influence of pressure and the smooth transition between tension and compression, as shown in the failure envelope in Figure 17.

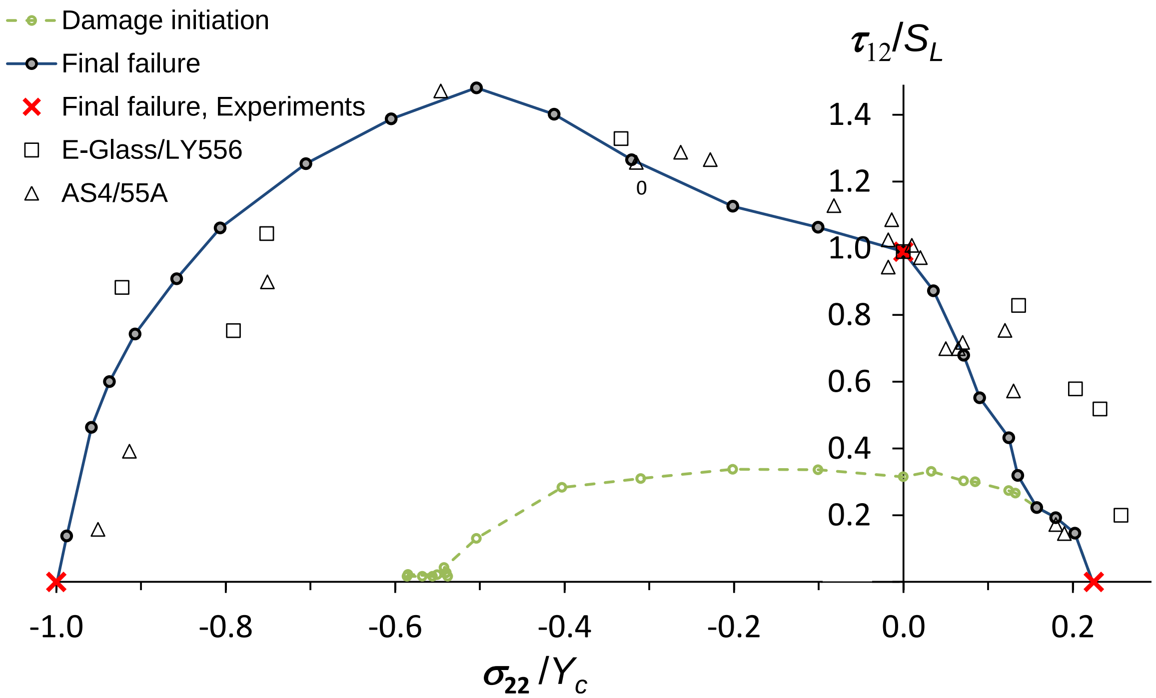

Figure 17. Model predictions for combined in-plane shear and transverse compression of HTS45/LY556 NCF composite vs. the strength values in the literature, (Paper C) Ref. [54]

An additional failure criterion is introduced in Paper C to define the final failure of the material. Since the shear behaviour after rupture of the Iosipescu specimen in unknown, an additional damage variable is created to represent a sudden propagation of cracks, leading to the rupture of the specimen. Capturing these mechanisms correctly plays an important role in predicting the correct energy absorption.

3.3.1. *Large deformations for damage growth of composite materials*

Large deformation approach for modelling damage growth in composites is gaining some attention in the literature, as for example in refs. [55,56]. Accounting for large deformations for fibre kinking seems to be important for accurate predictions, due to the large deformations experienced by the fibres. Large rotations were already included by Schapery in 1995 [57]. In this thesis, the influence of large deformations for matrix damage was not investigated. However, large deformations are included for fibre kinking in Paper D.

4. Fibre kinking

Fibre kinking has been extensively studied. There are more than a thousand papers published in the fields of materials science, mechanics, and engineering in the last decade [58]. However, models that deal with the behaviour after the peak stress has been reached, critical for crash modelling and the mechanism of fibre kinking growth, are still lacking. Therefore, Paper A, B and D are dedicated to this topic. This last chapter is dedicated entirely to fibre kinking, due to its complexity and relevance for crash of composites.

According to microbuckling theory [59], the lowest buckling stress associated with a shear mode of buckling of a fibre with a long wavelength, and supported by an elastic matrix, is given according to:

$$\sigma_c = \frac{G_m}{1 - \nu_f} \tag{6}$$

where G_m is the elastic shear modulus of the matrix and ν_f is the fibre volume fraction of the composite. This equation results in a compressive strength significantly higher than the compressive strength measured experimentally.

Another line of thought to the compression of composites distanced from the global buckling was suggested by Argon in 1972, [60]. Argon pointed out that engineering composites have regions of fibre misalignment and compression leads to the development of shear stresses in those regions, forming a band of kinked fibres. Thus, the peak stress is given according to:

$$\sigma_c = \frac{S_L}{\theta_i} \tag{7}$$

where θ_i is the local fibre misalignment angle and S_L is the shear strength. Nearly a decade later, Budiansky (1983), [61] reaffirmed the sensitivity of the critical stress to imperfection and included the rotation of the fibres. The compressive response with an elastic-plastic shear response, assuming that the fibres are inextensional is given by the following relationship:

$$\sigma = \frac{\tau_{12}^m}{\theta_i + \gamma_{12}^m} \tag{8}$$

where τ_{12}^m is the response of the composite to simple shear in the misaligned (material) coordinate system. In summary, initial fibre misalignment introduces shear stresses, which rotate fibres, thus, increasing shear stresses in a progressive loop, until failure is reached.

A thorough description on the stages of kink-band formation is given in the work of Kyriakides et al. [62]. They used confined rod experiments to avoid the sudden and catastrophic failure by kinking. They observed that, as the confining pressure increased, the deformation in the kink planes, i.e. the rotation of the broken fibres, was reduced. The model presented in Paper D is able to capture this phenomenon.

4.1. Mechanisms of kink-band growth

Fibre kinking takes place in a well-defined area – the kink-band. The kink-band develops at an inclined angle to the direction of fibre, as shown in Figure 6(b). The kink-band growth often activates other failure mechanisms such as matrix cracking and/or delaminations. Furthermore, the matrix has a very important role during kink-band formation as it supports the fibres and controls their rotation.

Carbon fibre composites typically fail in compression by kink-band formation throughout the range 10-60% of fibre volume fraction [63]. Microbuckling of the fibre is the origin of fibre failure according to the first studies on the area, [61]. Existing imperfections such as initial fibre misalignment, waviness and voids greatly affect the compressive strength. Thus, fibre kinking failure is assumed to be a shear-dominated failure mode in the material frame, under significant longitudinal compression.

Kink-band development and growth is a sequence of several stages, starting with initiation of fibre kinking, propagation and finally broadening, [64]. The mechanisms of kink band formation are difficult to investigate due to the unstable nature of the failure process [55] and the difficulties to observe the kink-band growth at the microscale, while compressing the specimen. Gutkin et al. [65] developed a test jig to test UD and cross-ply carbon/epoxy specimens in an SEM chamber under loading. From both UD and cross-ply specimens, it appears that failure initiates by compressive shear failure of the fibres at the notch tip, Figure 18. In this region, shear-driven fibre compressive failure is promoted by the large compressive stresses with small rotation of the fibres. After fibre failure at the crack-tip, the failure mechanism changes to kink-band formation.

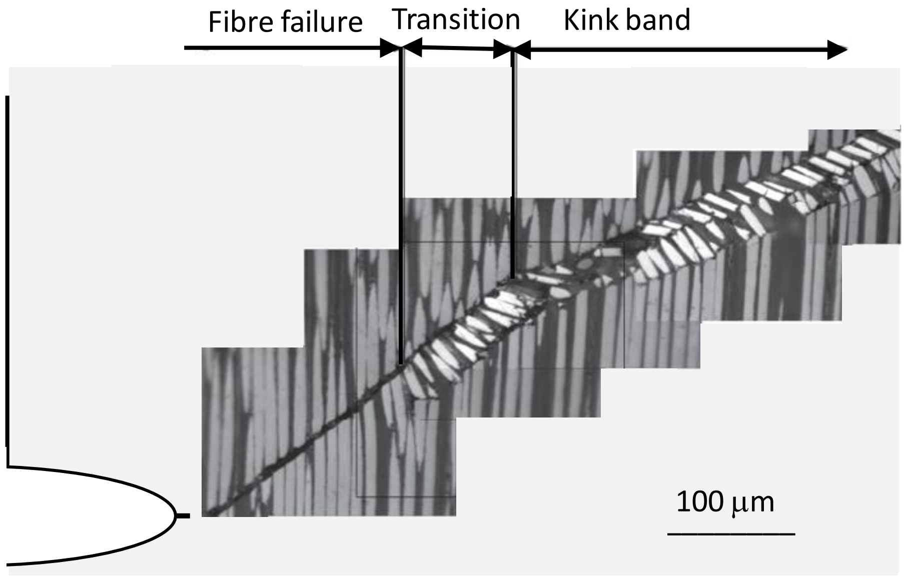

Figure 18. Kink-band progression including three different failure patterns, adapted from [65]

The kink-band is usually a well-defined band not perpendicular with the fibres, Figure 19(a). In this plane, all the stresses and strains should be projected. The matrix supporting the fibres inside the kink-band is more degraded than outside the band, thus cracks start to appear, Figure 19(b). These shear cracks are partially in compression and therefore friction develops. Eventually the fibres break in a combination of shear and bending, Figure 19(c).

The stages of kink-band formation can be summarized as follows:

Elastic domain: fibres and matrix deform elastically [66]. The imperfection induces slight bending of the fibres, initially with large wavelength, which creates shear stresses in the matrix. The end of this region may be represented by micrograph “a” in Figure 19

Immediately before peak load: The rotating fibres are about to lose support from the matrix. In this phase, the matrix starts to behave nonlinearly, and an inclined band of fibres starts to develop. This phase may be represented by micrograph “b” in Figure 19, where splitting is observed at the interface of the fibres, represented by “1”. The first fibre failure, represented by “2”, starts to develop. Despite the large cracks observed in the matrix, the fibres remain reasonably straight. At the end of this stage the fibres break in bending (combined with shear).

Immediately after the peak load: The support of the matrix is no longer sufficient and sudden fibre rotations occur. A clearly defined kink band is suddenly fully developed. This could be represented by micrograph “c” in Figure 19.

Softening domain: The broken fibres continue to rotate, this time at a nearly constant rate in relation to the compressive strain. Matrix cracks/delaminations will continue to grow. This is clearly represented by micrograph “c” in Figure 19, where a kink-band is perfectly defined.

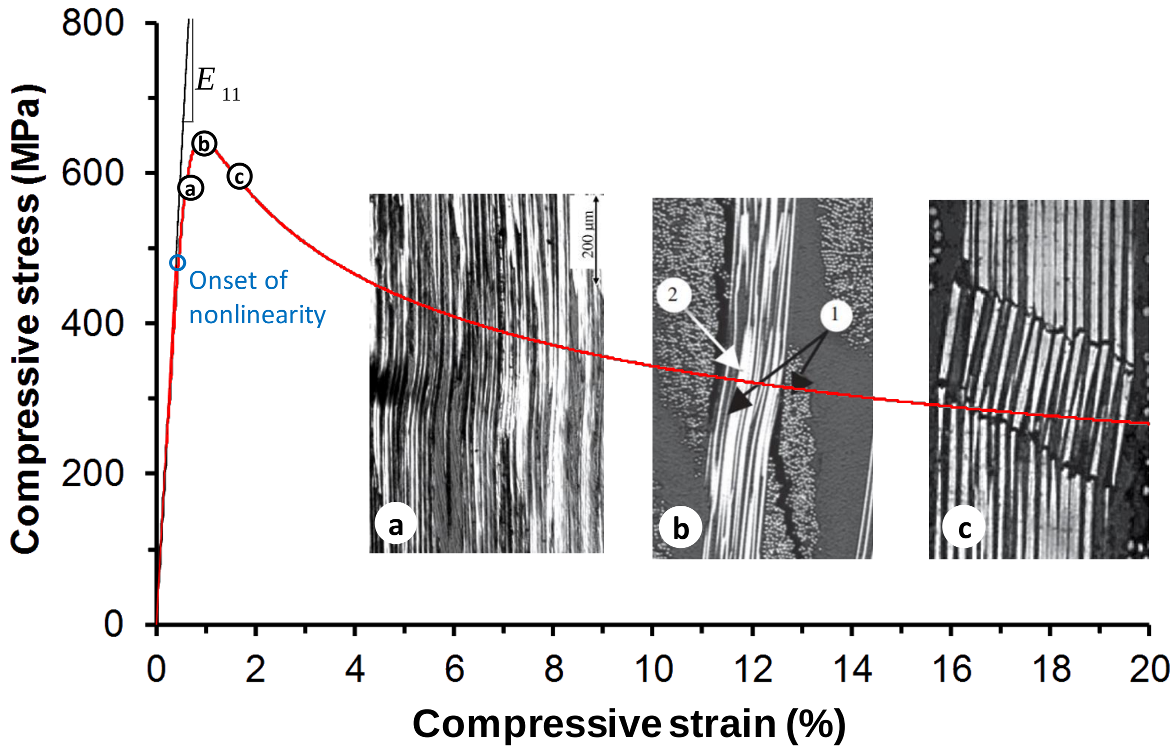

Figure 19. Load response predicted by the proposed model and illustrative micrographs of the sequence of events during kink band formation. a and c from ref. [21] *and b from ref.* [67]

The shear stresses develop at the flanks of the kink-band and form shear cusps that may open and coalesce into a split, [68]. Splitting may also compete with kink-band formation, although, especially for carbon fibres, kink-band formation is the dominant mechanism in compression, [63].

The behaviour and response after a kink-band is fully formed has received limited attention in the literature. However, the general agreement is that at some point, due to geometrical constraints, the fibres stop rotating, i.e. they lock-up. The fibre lock-up angle can be found when the volumetric strain in the matrix material becomes zero, [69]. There is no consensus in the literature for the values of fibre lock-up, maybe due to its strong dependency on the fibre volume fraction. Recently the value of 41° has been reported [70] and this was the fibre lock-up angle used in Paper D, although lock-up angles up to 52 degrees have been reported [71]. Once the fibre rotation is locked-up, kink band broadening occurs, i.e. the kink-band spreads in the fibre direction into the unkinked material, [63,64].

4.2. Fibre kinking due to shear instability

In order to maximize the energy absorption of composite materials, a significant amount of fibres must be oriented longitudinally with the loading directions. In this orientation fibres fail mainly by kinking [63], which provides high energy absorption but causes difficulties in predicting the response. Fibre kinking formation is an instability phenomenon governed by fibre misalignment and nonlinear shear behaviour [72–74]. It is known that transverse loads and shear also affect kink-band formation [31]. In fact, Pinho et al. [40] proposed to use the stress transformation around the 3-axis between the global and material frame, in combination with nonlinear shear. The shear response in the material frame is given by:

$$\tau_{12}^{m} = -\frac{\sigma_{11} - \sigma_{22}}{2}\sin(2\theta) + |\tau_{12}|\cos(2\theta) \qquad \text{where } \theta = \theta_i + \gamma_{12}^{m} \tag{9}$$

Notice that the initial misalignment and the transverse and shear stresses are included in this equation. The nonlinear shear behaviour of the material may be approximated by combining friction and damage, as Gutkin and Pinho [47] suggested. The complete equation becomes:

$$G_{12}\gamma_{12}^{m}(1-d) + d\,\tau^{fric} = -\frac{\sigma_{11} - \sigma_{22}}{2}\sin\left[2\left(\theta_i + \gamma_{12}^{m}\right)\right] + |\tau_{12}|\cos\left[2\left(\theta_i + \gamma_{12}^{m}\right)\right] \tag{10}$$

where d is the damage accounting for the amount of microcracks in the material and τ^{fric} is the frictional stress on the microcracks. Equation (10) is a key equation for fibre kinking theory. However, as Pinho et al. [40] wrote "there might be no easy way of solving Eq. (10) without iterating." Thus, a research gap was pointed out, i.e. the need to solve Eq. (10) in order to obtain the kinking response due to shear instability. However, since this is a nonlinear equation and has two unknowns, σ_{11} and γ_{12}^{m}, another set of equations is necessary. The new set of equations that allows to solve Equation (10) was developed in Paper A.

Before introducing the contents of Paper A, a deeper understanding of what the equilibrium in Eq. (10) means (and its consequences) can be achieved graphically, by plotting both the Left-hand side (LHS) and Right-hand side (RHS), of Eq. (10). In order to simplify further, one can assume a uniaxial stress state in compression. Then, in order to verify the role of the different initial misalignments in fibre kinking, one can replace θ_i by 3 arbitrary values of initial misalignments. For each θ_i one can easily obtain the respective peak stress and insert it in Eq. (10). Finally, this will result in 3 lines for the RHS, as shown in Figure 20. Note that the lines are not perfectly straight but reflect the nonlinearity of the trigonometric expressions for small angles.

Any intersection point occurs when the equality in Eq. (10) is fulfilled. For $|\sigma_{11}|$ greater than the strength, there will be no intersection. For lower values intersection will occur. In other words, the intersection of these two curves represents the kinking stress for a given shear angle. Note that when the intersection between the RHS and LHS is tangential, the value of σ_{11} must correspond to the strength value. If there is no interception at all that means that kinking by shear instability does not occur.

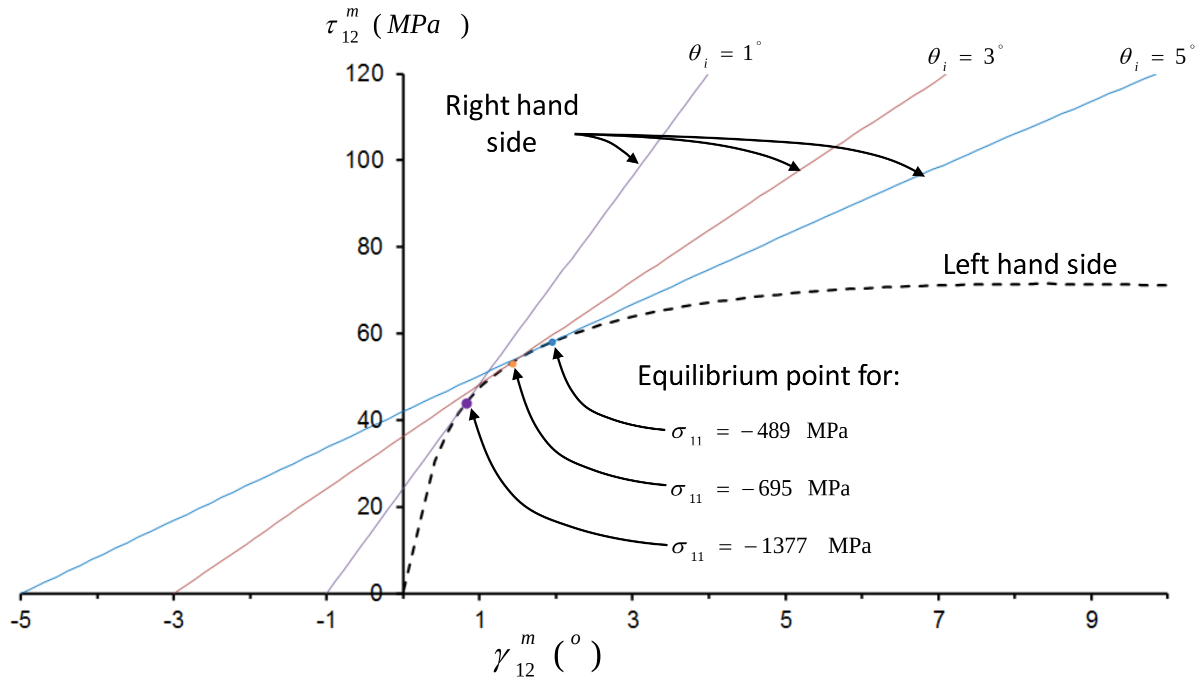

Figure 20. Equilibrium for three different initial fibre misalignments: $\theta_i \rightarrow 1^\circ, 2^\circ$ *and* 3° *for nonlinear shear behaviour*

The geometric interpretation of the figure helps to understand kinking formation due to shear nonlinearity and the influence of fibre misalignment in interaction with the nonlinear shear response. An important observation is that the peak load occurs at lower strains for smaller fibre misalignments.

The strong dependence of misalignment is known since the work of Argon [60] and Budiansky. The role of the shear response was studied by Hsu et al. [75]. However, before the work presented in paper A, there was no solution for Eq. (10), but an alternative was suggested.

Equation (8) has been used by Hsu and colleagues [75] to predict the complete kinking response [75] for uniaxial loading. They also recognised the strong influence of the shear behaviour and recommended to measure shear response (instead of using approximations), in order to accurately predict the kinking response. This statement is backed up explicitly by Figure 20, i.e. one can deduce the influence that small variations in the shear curve can have on the kinking response. The compressive strength given by Eq. (8) correlates well with micromechanical models and experiments. If both the shear strain in the material frame, γ_{12}^m, and the respective shear stress, τ_{12}^m, are known, the fibre kinking response for uniaxial loading could be easily obtained. However, there are two main drawbacks of this approach, (i) the shear response is pressure dependent [76] and thus, it does not have a unique curve and (ii) the interest is to relate the kinking stress to the compressive strain $\sigma_{11} - \varepsilon_{11}$. The latter was approximated by Hsu et al. [75] with the following expression

$$\varepsilon_{11} = \theta_i \gamma_{12}^m + (\gamma_{12}^m)^2 + \sigma_{11}/E_{11} \quad (11)$$

where θ_i is the initial misalignment. However, their model does not solve the high-pressure dependence in the shear response, neither the influence of multiaxial loading.

Notice that for smaller misalignments failure occurs at higher compressive normal strains than higher misalignment, *Figure 21*.

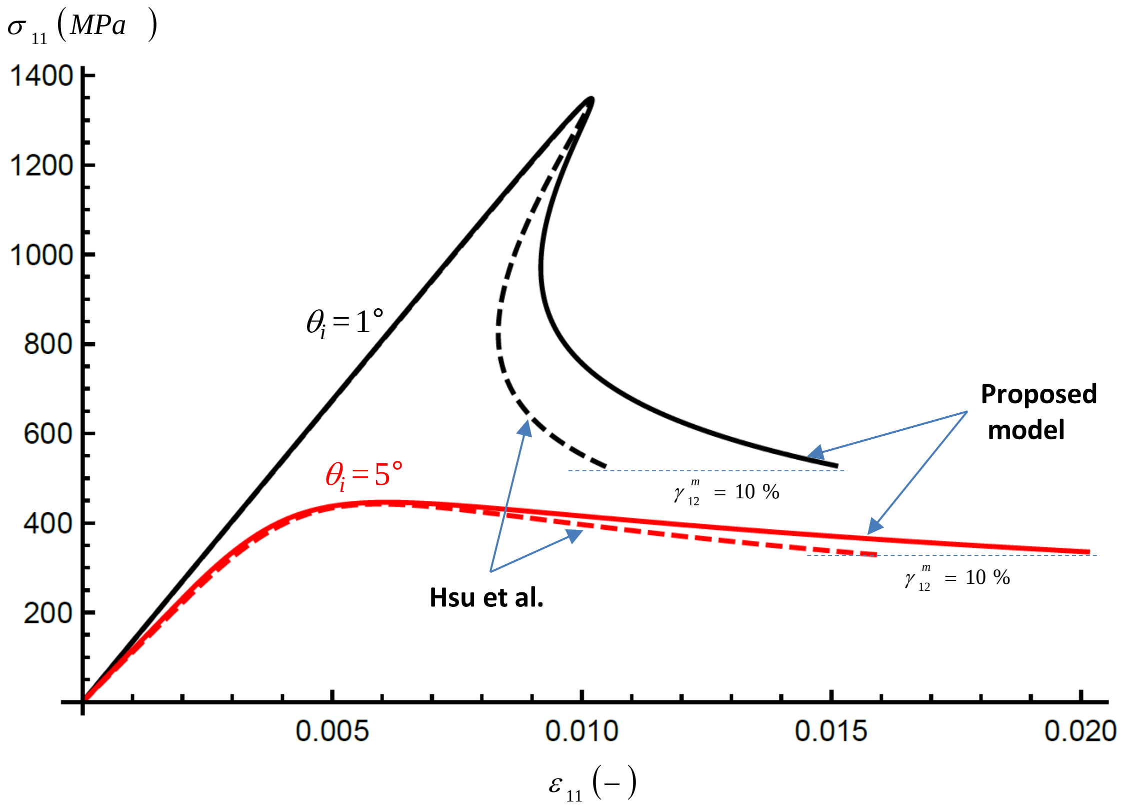

Figure 21. Comparison between the proposed model (Papers A,B and D) and the model by Hsu et al.[75] *for two different misalignments, image courtesy of Rafael Machado*

5. Summary of the appended papers

5.1. Fibre kinking model with progressive damage and friction – Paper A

In this paper, an analytical material model for kink-band growth under a 3D stress state is developed. The model uses Fibre Kinking Theory (FKT) combined with a physically based constitutive law for the nonlinear shear response. The whole collapse response is governed by nonlinear shear instability. In this way, the model predicts advanced fibre kinking mechanisms that would be simplified otherwise. Furthermore, a major advantage of this methodology is that it removes the need to measure the translaminar compressive toughness, simplifying thereby the material characterization. The model response is compared with a micromechanical FE analysis, an analytical model and the experimental mean crush stress. The results show that the model is able to capture the different stages of kink-band formation and crushing.

5.2. FE implementation and mesh objectivity – Paper B

In this paper, the analytical model developed in paper A is implemented into a VUMAT subroutine in the commercial FE code ABAQUS. An issue with damage models is the mesh size dependency due to the softening response. Previous mesh regularization strategies take advantage of fracture toughness and element characteristic length. However, a similar strategy cannot be used here, since the kinking response is obtained from equilibrium with shear nonlinearity. Therefore, two methods to handle the mesh objectivity are developed and compared. Furthermore, the kinking equilibrium equations are re-written with only one unknown, in contrast to solving simultaneously for two unknowns, σ_{11} and γ_{12}^{m}. This reduces convergence difficulties and the need to try two different initial guesses, thus increasing efficiency. The fibre kinking model was successfully implemented and validated in uniaxial compression for a regular and a severely distorted mesh, showing mesh independency in both cases.

5.3. Shear and transverse model for NCF composites – Paper C

In this paper, a ply-based material model for crushing of composites is developed and validated against experiments. The model includes all the intralaminar failure modes, as identified in Figure 12, however the fibre kinking is a simplified bilinear law. The focus is on the improvements of the matrix compression/shear mode and on its interaction with other modes. The model is based on the fixed crack plane approach, i.e. the critical angle obtained by the model is kept throughout damage growth. This angle defines the fracture plane, as shown in Figure 13(a), where the constitutive response is defined. The shear/transverse behaviour is modelled by combining damage with friction in a physically based way. The response of the model in shear and transverse compression is validated with experiments showing that it accounts correctly for the influence of pressure on the shear response. The shear calibration, together with the criterion for final failure, allows to avoid the measurement of fracture toughness.

A criterion for final failure is developed and its resulting failure envelope, σ_{22}-τ_{12}, is validated against values in the literature. This criterion for final failure depends on the loading direction in order to include orthotropic effects as observed in NCF composites. The typical mesh convergence issues of this type of models are avoided by the introduction of an artificial sudden softening response.

5.4. Development and validation of a full 3D kinking model – Paper D

The model developed in Paper A and implemented in Paper B with a mesh objective formulation, has difficulties handling multiaxial situations, as is the case during crash. For example, the model is not valid for situations that result in fibre rotations with the opposite value of the initial misalignment, i.e. $\gamma_{12}^{m} = -\theta_i$. Furthermore, "for a general 3D stress state, a convergence criterion between the damage variable calculated for matrix only and for the one calculated during kinking should be achieved." This downside aspect pointed out in Paper A, will add computational costs to the model. However, the ability of the model to capture the physical principles is not called into question. Therefore, this paper presents a new formulation that is valid for the whole range of fibre rotations, stable, efficient in FE simulations and it is still physically based.

The rotation of the fibres is computed from the strains in the in the kinking plane. Then, once the fibre rotation is known, the shear nonlinear response is computed using the physically based constitutive law presented in Paper A. This allows all the stress components to be computed in the material frame, which are then rotated back to the global frame.

The response at the material point for two loading conditions is compared with the model in Paper A and discussed. The model is validated against compression tests of specimens with a known misalignment and against crushing of a flat coupon with the fibres oriented to the load direction. The results show remarkable correlation with both experiments, showing the model ability to predict the stiffness, strength and crash response.

6. Conclusions and outlook

Composite materials have great potential for crash applications due to their high specific energy absorption. The crash performance is strongly dependent on the design therefore tailoring the material is fundamental for an efficient material usage. In order to implement composites in structural components of mainstream cars, it is necessary to reduce costs. Despite the high material costs, most of the costs result from the lengthy development times due to extensive testing campaigns. A predictive simulation is the solution for an optimized design and lower costs. Thus, modelling crash of composites is of crucial importance for introducing composite materials in mainstream vehicles. The previous sections approach the crash of composites towards the development of more reliable, physically based crash models. Predictive models allows for reliable crash simulations, thus reducing expensive testing and shortening development times.

The material system used to validate the models was Non-Crimp Fabric (NCF) composites. NCFs have a good compromise between crash performance and cost, which makes them good candidates for the fast cycle times required by the automotive industry. However, there is less knowledge in the literature of failure mechanisms in NCFs than for UD prepregs composites. Some of the orthotropic effects of NCFs were already included in Paper C, however more research is needed to include all NCF characteristics into the kinking model.

Due to the complexity of crash and its modelling, we separate the damage mechanisms into six different damage modes. The modelling approach taken for the compressive modes, matrix compression and fibre compression is developed and validated in this thesis. The appended papers A, B and D focus on a new model for kink-band growth. Paper C details a crash model with all damage modes and their interactions, although the fibre compression model has a simplified kinking behaviour.

Currently, there are no numerical models able to capture all the mechanisms involved in the whole kinking response of fibre composite materials. Therefore, we propose a model, which is able to capture the physical mechanisms involved during kink-band growth, such as friction, fibre rotation and influence transverse stresses. We have also shown that characterizing and modelling the shear response is fundamental for reliable modelling of the compressive damage modes. Accounting for friction on the microcracks and in combination with damage allows for an efficient modelling of the nonlinear response that composites exhibit. This approach can also be used to model the shear nonlinearity caused by initially misaligned fibres during longitudinal compression. This reduces experimental characterization.

Fragmentation is an important mechanism in crash. The behaviour of the fragments of composites being compressed is very complex due to an amalgamation of relatively unknown mechanisms and interactions between them. In the current model, fully damaged materials under compression are represented by friction. During fibre compression, fibre lock-up is also an important mechanism that likely evolves into fragmentation. Further research is needed to better represent both mechanisms. The constitutive behaviour after fibre lock-up has not been modelled yet.

Further experimental and modelling work is needed to investigate the interaction of fibre kinking with other failure models, as well as further model validation of kink-band growth under multiaxial stress state scenarios.

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