THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

in

Solid and Structural Mechanics

Physically based fibre kinking model for crash of composites

SÉRGIO COSTA

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

Physically based fibre kinking model for crash of composites
SÉRGIO COSTA

Licentiatavhandlingar vid Chalmers tekniska högskola
THESIS FOR LICENTIATE OF ENGINEERING no 2016:21
ISSN 1652-8565

Department of Applied Mechanics
Chalmers University of Technology
SE–412 96 Göteborg,
Sweden
Telephone: + 46 (0) 31 – 772 1000

Cover:
Left: Kink-bad formation courtesy of Renaud Gutkin. Arrow style was suggested by Siavash Shoja. Right: FE results of the proposed model with red colour representing the kink band

Chalmers Reproservice
Gothenburg, Sweden 2016

Physically based fibre kinking model for crash of composites
Thesis for the degree of Licentiate of Engineering in Solid and Structural Mechanics
SÉRGIO COSTA
Department of Applied Mechanics, Chalmers University of Technology

Abstract

Passenger cars are a major emitter of global warming gases which has led to tighter regulations being imposed on car manufacturers. An efficient way to reduce emissions is to reduce the weight of the cars. Composite materials, due to their high strength and energy absorption to weight ratio, are a suitable material choice to reduce the weight without affecting passenger safety. A major challenge today is the fast development times and low costs required by the automotive industry. An efficient design phase using more virtual tools and less physical testing allows time and cost-savings during the design phase.

Fibres oriented longitudinally with the load and subjected to compression fail mainly by kinking, which is the damage mode responsible for most of the energy absorption. In this thesis the focus is on developing a physically based fibre kinking model for crash of composites.

Fibre kinking is shear dominated, i.e. strongly influenced by the properties of the matrix as well as the alignment level of the fibres and the transverse loads. Modelling the complex physical mechanisms involved in crash at the microscale will result in prohibitively expensive simulations for the automotive industry. Therefore, in the present thesis, we homogenize the material while capturing the physical mechanisms involved, such as fibre rotation. The model parameters are physically meaningful and avoid cumbersome tests to obtain input for the model. Furthermore, the model is implemented in commercial Finite Element (FE) software together with a mesh objective methodology. The results show that the proposed model can be used to predict the whole kinking response in a 3D framework and thus account for the correct energy absorption.

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

Preface

The motivation to do research and material modelling started during my six month internship at *Simulia* in 2011 in San Francisco. The following two years I spent in Toulouse, as a CAE Engineer at Airbus. The exponential growth in composite usage in Airbus aircraft motivated me to further study Carbon Fibre Reinforced Polymers (CFRP).

In November 2013, I was accepted to a PhD position at Swerea SICOMP and moved to Sweden and so I adjusted to a new city, language and culture. The foundation for a new "home" has been laid.

The title of my project is: *Modelling crash behaviour in future lightweight composite vehicles*. The broader area of research in compression of composites has resulted in more than 10 000 papers in the last 10 years, making it a privilege to work on such a fascinating topic. This research is possible thanks to the funding from Fordonsstrategisk Forskning och Innovation (FFI) via VINNOVA and all the project partners. This thesis was achievable due to the unwearied efforts, guidance and support from supervisors Dr. Robin Olsson and Dr. Renaud Gutkin. High appreciation also goes to my colleagues at Swerea SICOMP, Chalmers and Volvo cars for the passionate discussions, the pleasant *fika* as well as the moments outside the office. I also would like to thank my family for their education and values and last but not least, I would like to thank Rūta for her companionship throughout the last two years.

Sérgio Costa,

Gothenburg, December 2016

Thesis

This licentiate 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*, (2016), submitted

The appended papers were prepared in collaboration with the co-authors.

Paper A: Gutkin developed the model. Costa implemented the model in Matlab, performed development tests and participated actively in the writing.

Paper B: Costa did the model implementation in FE software and studies on mesh objectivity with the supervision of the co-authors. Costa wrote the paper with the assistance of Gutkin and Olsson.

Contents

1. Introduction

1.1. Background

Over the past fifty years the use of Carbon Fibre Reinforced Plastics (CFRP), commonly called composites, has been increasing substantially in some industries, such as the aeronautic industry, Figure 1.

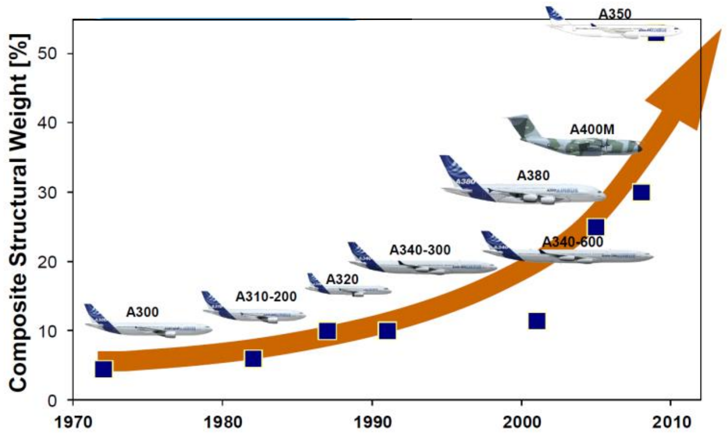

Figure 1. Growth of composites usage in Airbus aircrafts

The usage of composites was previously associated with high performance applications where their use is not principally cost-driven and have limited production volumes, such as aerospace and sports cars. Due to the tighter regulations on emissions imposed in the car industry composites have also been envisaged for mainstream cars as a means to reduce weight and thereby fuel consumption. In fact, composites possess some of the necessary characteristics to outperform the current materials used in the automotive industry: high specific stiffness, strength and energy absorption. The main challenge is that the automotive industry requires higher volumes and lower prices.

Combustion engine cars need to reduce their pollutants exhaust emissions, thus automakers seek effective methods for fuel reduction. Improving the engine is becoming too expensive, forcing the car manufactures to look for other solutions such as weight reduction. Approximately three-fourths of the energy consumption is related to vehicle weight [1]. Thus, reducing weight will result in lower emissions.

Another alternative to reduce emission is to use electric cars which do not have CO_2 emissions. However, range anxiety is a major concern for most of the costumers, making weight reduction equally important. Over the past decades cars are becoming heavier due to additional features. Removing these features will be a backward step in safety, comfort or handling, which is not a considered an option among the automakers. For the purpose of reducing the weight of the vehicle efficiently it is necessary to replace the steel by composite materials in structural parts [1]. Even though producing 1 kg of steel is causes less emission than 1 kg of CFRP, in the long run, due to the lower vehicle emissions, composites outperform steel, Figure 2.

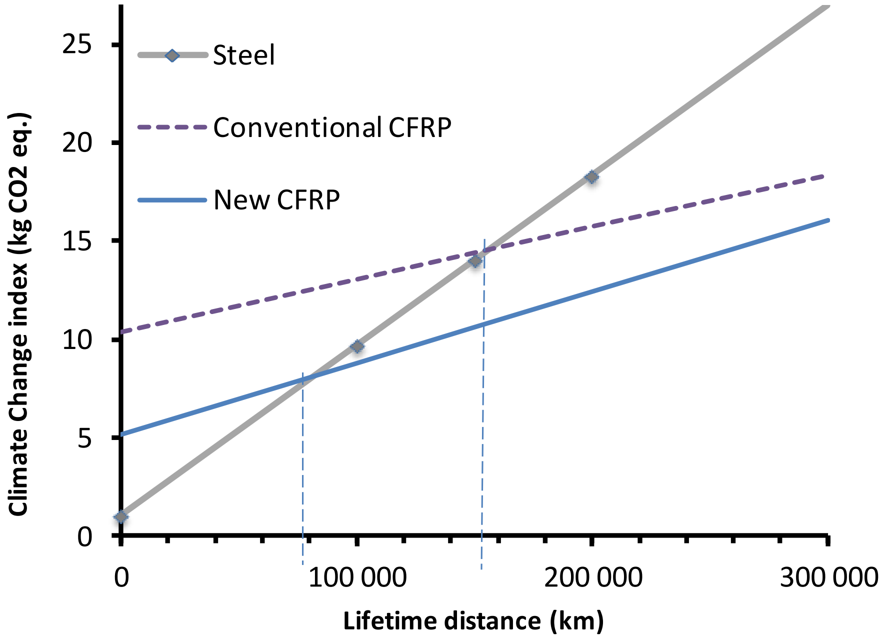

Figure 2. Lightweight potential of composites in the automotive industry, adapted from [2]

1.2. Composites materials towards crash

The establishment of composite materials in the automotive market sector depends mainly on (I) Improving the manufacturing process; (II) Increasing the understanding of composite components during vehicle crashes; (III) Develop a material database with relevant parameters; (IV) Enhance predictive (crash) models to avoid costly overdesign [1,3]. Designing components using Computer Aided Engineering (CAE) will allow significant cost savings and optimal design for crash. Thus, reliable CAE methods will also allow wider application in mid range cars and not as presently only in the luxury and sport cars segment, Figure 3.

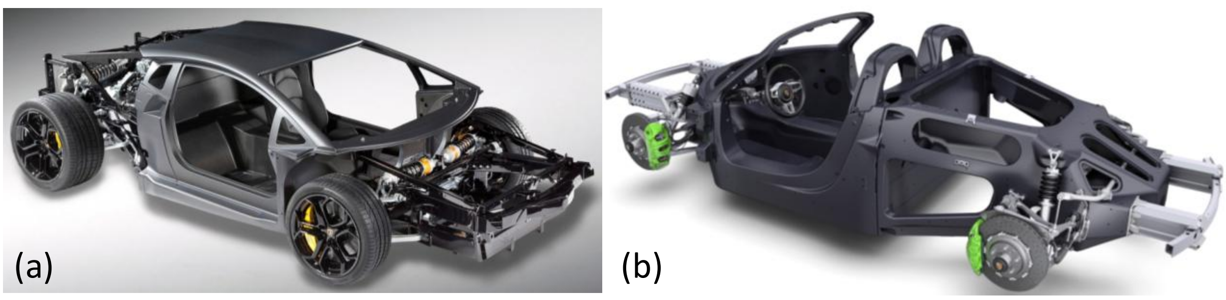

Figure 3.Composite body structure of two high-en cars with metal rear and front bumpers: (a) Lamborghini aventador [4]*; (b) Porshe 918* [5]

Although in the luxury segment, composites are becoming more used, the crash absorbers are not made out of composites, in spite of the fact that composites outperform metals in energy absorption, Figure 4.

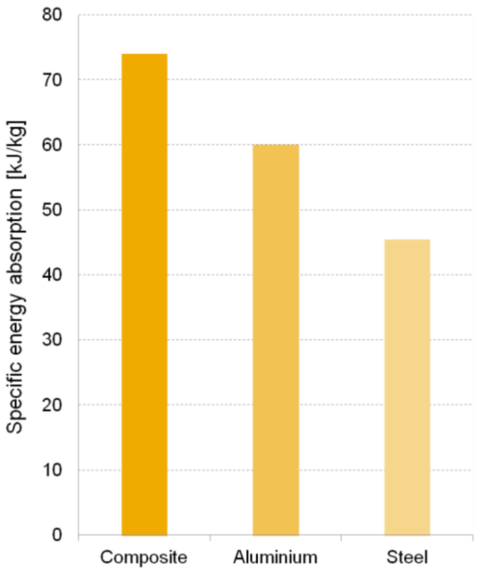

Figure 4. Average energy absorption of corrugated composite panels with cross-ply lay-up with aluminium and steel crash box, adapted from [6]

Crushing describes the continued compressive loading of the *material* beyond its compressive strength limit. A *crash* involves gross deformations of a *structure* under compressive loading beyond its elastic limit, and generally involves a combination of elastic deformations and crushing or yielding, as well as other failure modes, e.g. delamination. In order to protect the passengers (in a eventual car crash), the aim is to have a stable crushing with a low peak load and a high average crush load resulting in low initial impact force and high energy absorption. The car components should be designed to fail in a controlled manner. Using physical observation and CAE with physically based models will allow for the optimal design. Since crash takes only a split of a second it is difficult to follow even using high speed cameras. Therefore, most of the research made on cr*a*sh modelling actually is based on cr*u*sh modelling. By compressing a coupon in a quasi-static manner it becomes possible 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, [7,8]. Strain rate effects were not investigated in the current work.

1.3. UD prepreg vs. NCF

Unidirectional (UD) prepreg composites have excellent properties per unit weight but their manufacturing and poor drapability does not make them the most suitable option for the automotive industry. Textile composites have lower manufacturing times because there are no pre-impregnated plies to be stacked together and faster manufacturing is also possible with infusion. Several types of textile reinforcements have been proposed, e.g. woven, braided, knitted and NCF with stitched reinforcements. NCF are textile composites (almost) without crimp or weaviness, resulting in better mechanical properties. A drawback with NCF compared with UD prepreg is that the fibre tows still have some waviness, which triggers failure mechanisms like kinking. 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, [9]. Observing the geometry of an NCF one can notice: agglomerates of fibres in a fibre bundle, stitching yarns interlaced in the fibre bundles, small waviness (crimp) of the fibres, Figure 5(b).

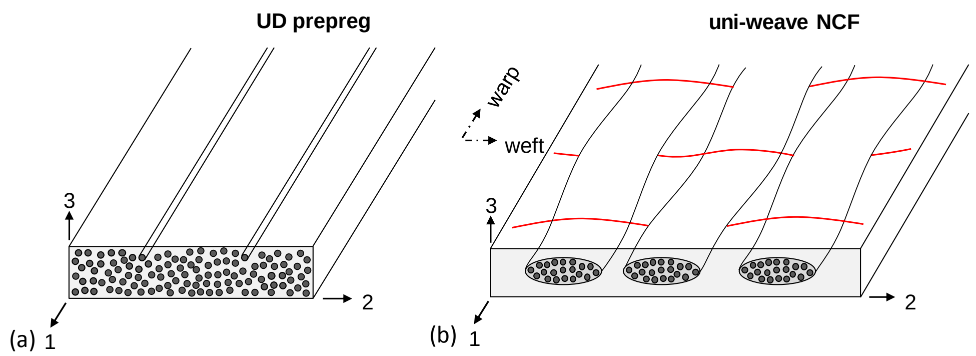

Figure 5. Representation of a composite ply: (a) UD pre-impregnated; (b) Textile uni-weave NCF, [10]

NCF composites are good candidates for the automotive industry due to their relatively high mechanical properties and low manufacturing times. NCFs also have excellent drapability which fulfils automotive industry needs to manufacture complex shapes, [11].

All the failure mechanisms observed in conventional unidirectional prepreg composites are present in NCF. The fibre misalignment in prepreg tape composites should be present inside the fibre tows of NCF, plus fibre tow waviness. Thus, the compressive strength of NCF is about half of the tensile strength. The layers of fibre tows require homogenization of elastic properties [9]. The stitching yarn will have an influence by keeping the fibre tows together.

Non-crimp fabrics offer a good trade off between properties and costs and are suited for large scale production, making them an excellent candidate material for the car industry. In this thesis the focus is on UD prepreg but the future work will be on NCF.

1.4. Ply and inter-ply damage

Due to the complexity involved in crushing of composites it is necessary to identify and distinguish the different mechanisms. Failure in composites may be distinguished either by failure of its components – intralaminar or translaminar failure – or in their interfaces – interlaminar failure. At the ply level, fibre failure (translaminar) and matrix cracking (intralaminar) are found depending on the loading and the fibre orientation. Interface failure may be either between fibres and matrix (debonding) or between plies (delamination or interlaminar failure). The mechanisms are depicted in Figure 6.

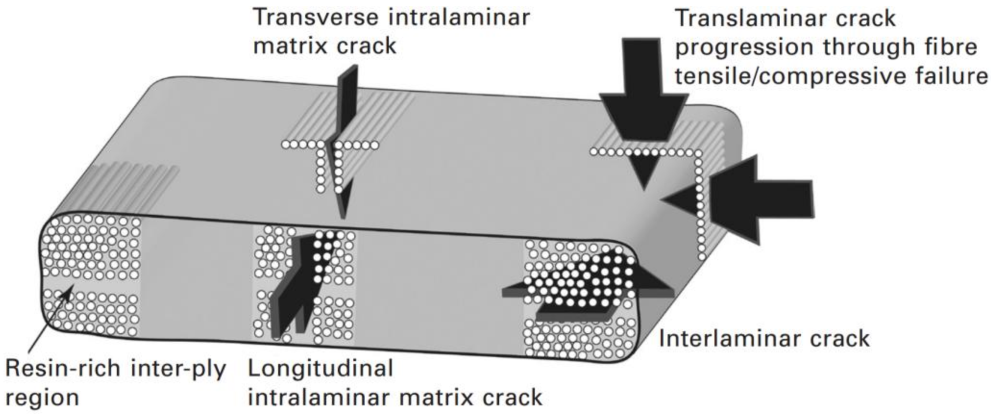

Figure 6. Ply-level fracture mechanisms exhibited by continuous fibre-reinforced composites, [12]

It is of high importance to account for delamination in crush simulations due to the likelihood of this failure mode and its influence on the crashworthiness. Interlaminar stresses are related to the angle between neighbouring plies, so a smooth variation of angle is preferable between plies in composite design. Delamination failure modes can be classified in Mode I, Mode II or mixed mode, according to the load direction.

The stitching in the NCF improves their delamination toughness, i.e. delamination growth. However the stitching seems to have little influence on delamination initiation, i.e. interlaminar strength [13].

Compressive failure in composites is the most complex, but highly relevant for crash modelling and industry in general. Therefore, it has been treated in more than 10 000 papers that have been published in the fields of materials science, mechanics, and engineering in the last decade [14].

1.5. Crash simulation of automotive structures

Modelling crash is essential to improve the design and ensure the crashworthiness of the automotive structures in a short time frame and budget. Current simulations are not predictive for crash of composites. Feraboli and colleagues [15] 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, [16]. A reliable crash model is required in order to rely more on the analysis and have less experiments, with the aim to shorten development times and reduce costs. A material model available in LS-Dyna (*MAT*

54) was used extensively by Feraboli with extra difficulties since the model does not have the capability to produce a predicted load-displacement curve based on the material properties gathered from coupon level tests.

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 which provides good energy absorption but causing difficulties in predicting the response. 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 able to capture the physical mechanisms involved during kink-band growth, such as friction, fibre rotation and transverse stresses.

2. Mechanisms observed during crash

Crash of composite structures is combinations 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 7(a) and/or fibre kinking, Figure 7(b). These interactions often depend on the properties of the constituents which complicates the analysis and the modelling.

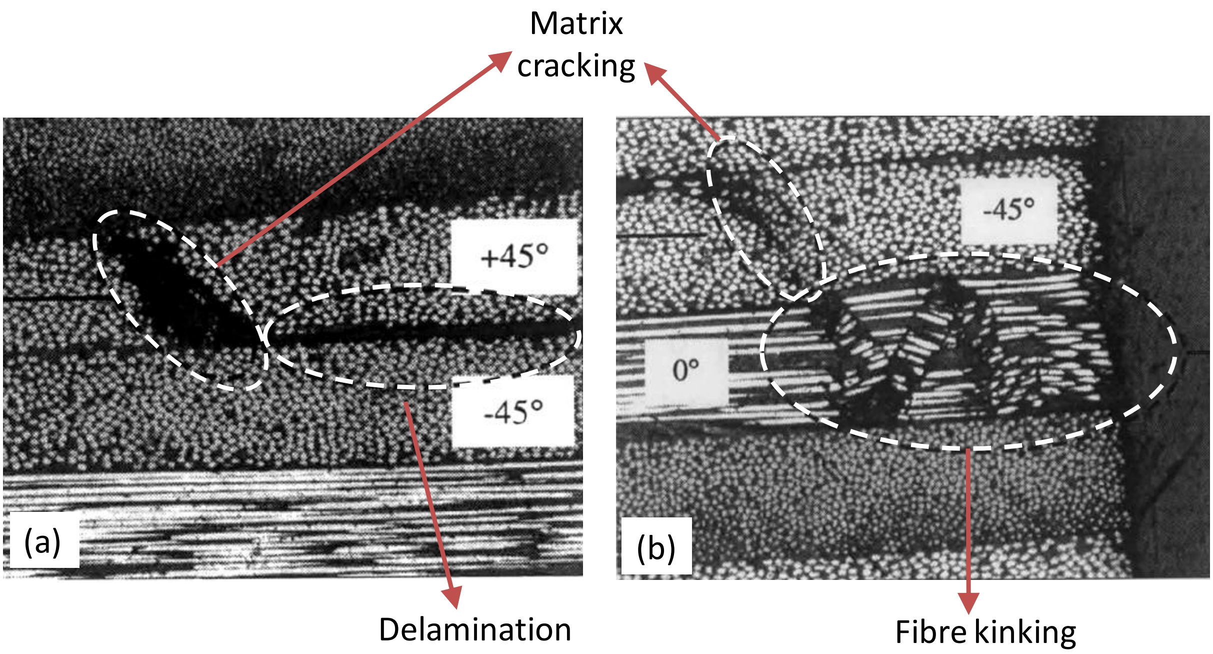

Figure 7. Interaction between failure modes: (a) Between matrix cracking and delamination (b)Between matrix cracking and fibre kinking, adapted from [17]

2.1. Corrugated panels

Corrugated panels are often used in the literature for crash tests mainly to reduce the risk of global buckling and furthermore they can stand by themselves [18]. Grauers et al, [6] 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 UD fabric and epoxy. The specimens tested fail partly in bending, and partly in pure compression (by crushing) with a mode I delamination separating these two regions, Figure 8(a). The part failing by bending has lower energy absorption and thus the aim is to eliminate bending failure and/or delaminations in compression. The part failing by compression absorbs more energy trough kink band formation, Figure 8(b). Looking at a single bundle, Figure 8(c), the kink bands induce interlaminar cracks at the interface.

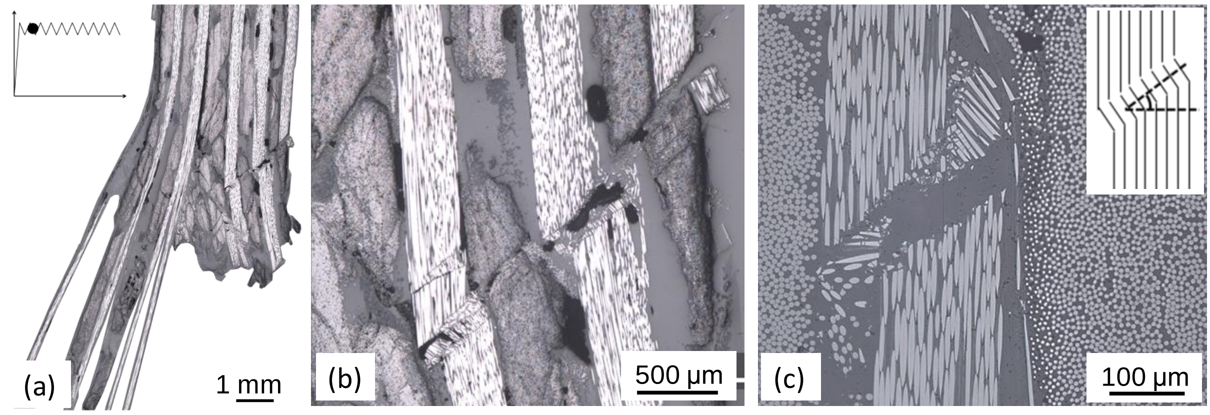

Figure 8. Micrographs through the thickness with different amplifications: (a) Bending failure and compressive failure; (b) Kink bands in several bundles with intermediate matrix cracking; (c) Kink bands through a single bundle, adapted from [6]

2.2. Flat specimens

Using flat specimens to study crushing behaviour one can avoid the influence of the structure on the crash response. In that context Bru et. al studied the influence of several crash triggers in the crash response of flat specimens [19,20]. In contrast to self standing specimens such as the corrugated panel, this experiment is able to reduce the amount of bending failure (splaying) and therefore identify the crush stress of a zero degree ply, Figure 9.

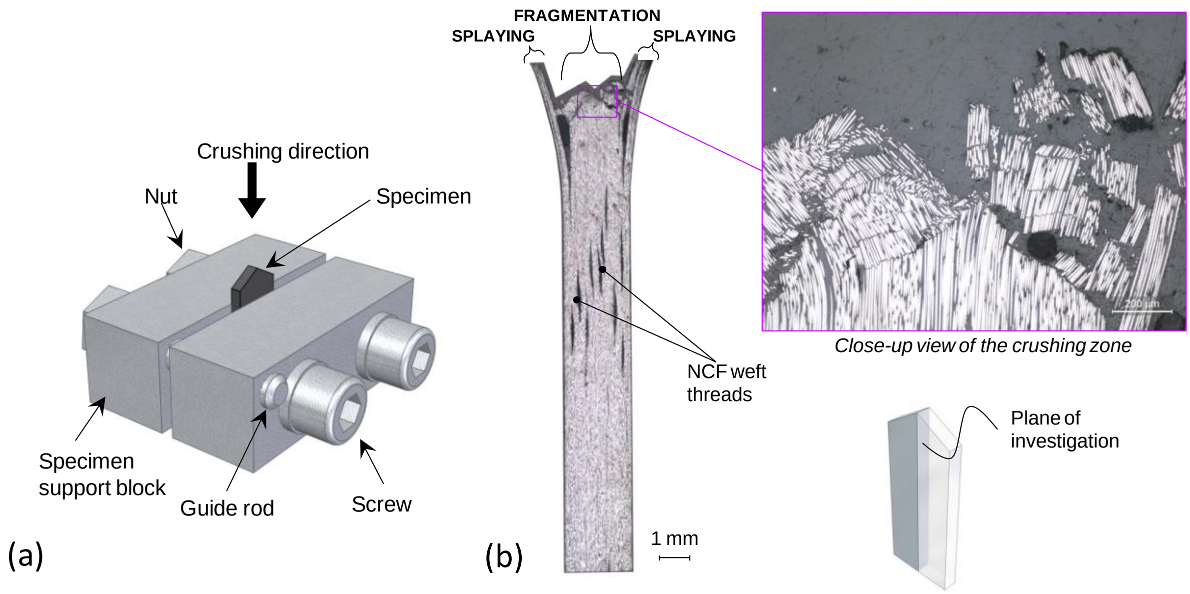

Figure 9. Crash of flat coupons: (a) Experimental set-up; (b) Micrograph of the cross section showing kink band formation, adapted from [20]

2.3. Energy absorption during crash

The legislation for automobiles requires that vehicles are designed such that, 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, [21]. To fulfil the requirements, the initial peak load must be avoided and large deformations must be obtained. 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 lower properties. Furthermore, an optimal design must avoid delamination and give raise to intralaminar mechanisms that absorb the most energy, such as kink band formation.

For a given fibre lay-up different tube geometries will have different energy absorption [22]. Circular tubes have the highest Specific Energy Absorption (SEA), followed by square tubes and finally rectangular ones. It is also claimed that the optimum composite crash box absorbs about 17% more energy than the optimum aluminium tube while it has about 26% less weight.

Therefore, 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 SEA during crash is defined as [23]:

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

where F is the applied force between δ and $\delta + \Delta\delta$, the initial and final crushing positions respectively 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.

3. Modelling damage

It is impossible to manufacture a composite without any imperfections, e.g. residual stress generated by manufacturing, misaligned fibres and voids during impregnation. Those imperfections degrade the mechanical properties and often lead to permature failure. To obtain the experimental information on the sequence of failure events is fundamental to develop predictive models. In contrast to metals, where the isotropic nature allows the use of relatively simple constitutive relations to predict their behaviour, composites require separation of the failure modes. For example in Figure 10 one can observe varying failure load and fracture planes (α) according to the fibre orientation. These differences are driven by different mechanisms that the criteria by NASA Langley Research Center (LaRC) seem to account for, such as the increase in shear strength caused by transverse compression.

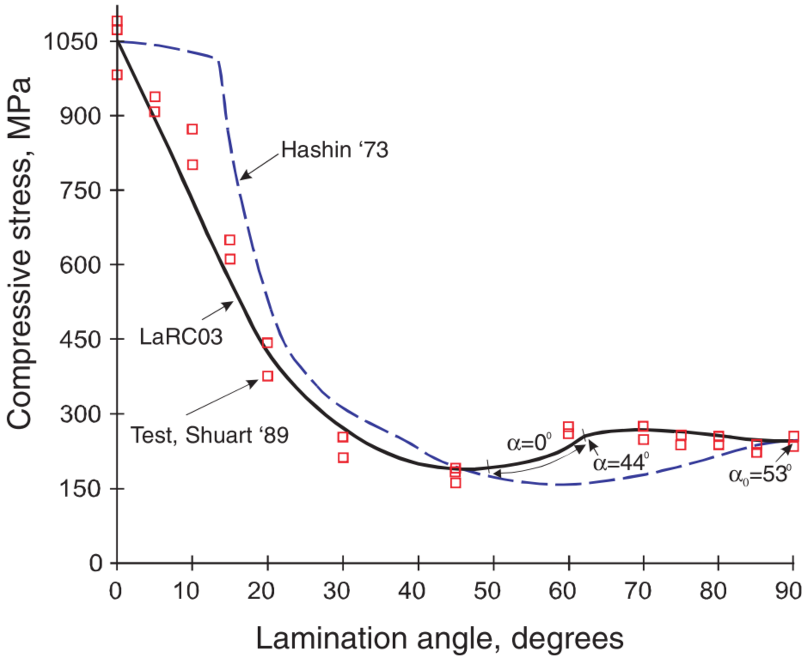

Figure 10. Compressive strength as a function of ply orientation for FRP [24]

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. Indeed, this has been the subject of a great number of research studies in the literature for several years [25–28]. Physically based failure criteria can predict the failure mode and also provide details about the failure process. The failure modes can be distinguished in 4 main modes, Figure 11.

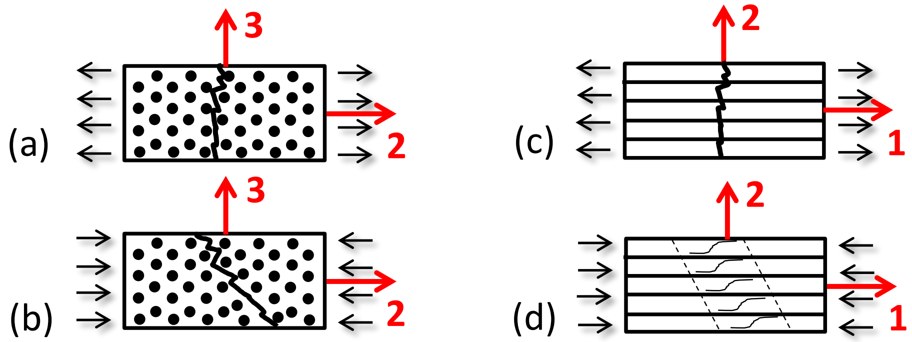

Figure 11. Intralaminar failure mode: (a) Transverse tension; (b) Transverse compression; (c) Longitudinal tension; (d) Longitudinal compression;

The LaRC failure criteria have been performing well at the world wide failure exercise. 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 fiber direction [29] and the other is consideration of the competition between matrix cracking and instability due to shear nonlinearity for the prediction of the compressive strength [28].

Fibre *longitudinal tension* is particularly simple compared to the other failure modes due to the lack of interaction between the different stress components.

Transverse failure modes occur when the load is normal to the fibre direction and it is dominated by matrix properties, [30]. For a pure compressive load, the fracture plane typically occurs at an angle of 53^{o} $\pm 3^{o}$, Figure 12. The deviation of this angle from a pure shear case with a 45^{o} is due to the friction stress occurring on microcracks in formation, [30]. Fracture results from the stresses created in the fracture plane, thus, increasing the compressive stress. For *transverse compression* the fracture plane is determined when the failure index, f_{mc} reaches unity.

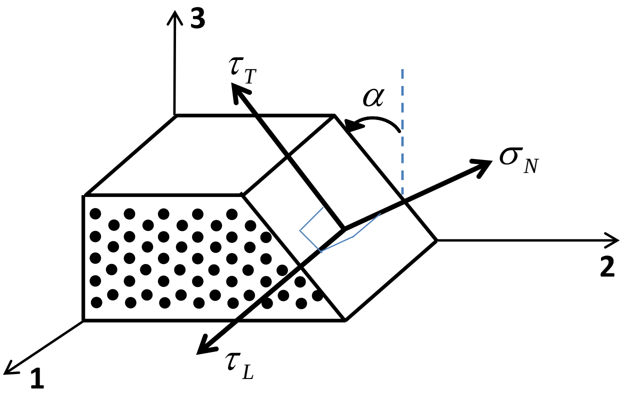

Figure 12. Coordinate system (123) rotated to the fracture plane system (LNT)

The LaRC contribution for transverse compression was a quadratic failure criterion accounting for friction when a compressive stress exists on the fracture surfaces [28]. Once the angle of the fracture plane (α in Figure 12) is obtained for pure compression, the transverse friction coefficient can be related to α according to:

$$\mu_T = -\frac{1}{\tan(2\alpha)} \tag{2}$$

Furthermore, the transverse shear strength is then defined as

$$S_T = Y_C \cos(\alpha)\left(\sin(\alpha) + \frac{\cos(\alpha)}{\tan(2\alpha)}\right) \tag{3}$$

According to Puck and Schürmann [30] the longitudinal friction coefficient is estimated as

$$\mu_L = \mu_T \frac{S_L}{S_T} \tag{4}$$

The equations of LaRC criteria for failure initiation of the matrix dominated failure modes are summarized in Table 1.

Table 1. Physically based criteria (LaRC) for matrix failure and fibre kinking

Tension $\sigma_N > 0$	*Compression* $\sigma_N \leq 0$
$f = \left(\frac{\sigma_N}{Y_T}\right)^2 + \left(\frac{\tau_T}{S_T}\right)^2 + \left(\frac{\tau_L}{S_L}\right)^2 = 1$ (5)	$f = \left(\frac{\tau_T}{S_T - \mu_T \sigma_N}\right)^2 + \left(\frac{\tau_L}{S_L - \mu_L \sigma_N}\right)^2 = 1$ (6)

The equations for matrix and fibre failure are the same but evaluated in different fracture planes. Matrix failure is evaluated in the potential fracture plane (α in Figure 12) and fibre kinking is evaluated in the kink-band plane (ψ in Figure 19). The in-situ effects were later included [28].

3.2. Foundations of the available damage models

The approaches for failure prediction presented in the literature can be divided into: failure initiation criteria, fracture mechanics, plasticity and Continuum Damage Mechanics (CDM). Many years of research resulted in reasonable predictions for failure initiation in composite materials, [31]. However, in crash simulations, models are lacking physical foundations, e.g. MAT 54, which assumes a total reduction of elastic properties at damage initiation, an is still used in industry and research, [3]. The damage mechanics approach is the most investigated in recent years, being applied to damage modelling efficiently. Depending on the model definitions, several damage variables can be defined, being activated when failure initiates, according to an existing criterion and degrading the material stiffness.

An in-plane model based on damage mechanics for UD composites was proposed by Ladeveze and Le Dantec [32]. Laminate damage is modelled at the ply level with two internal damage variables *d* and *d'* degrading the in-plane shear modulus and the transversal stiffness respectively.

The definition of a damage variable, *d*, allows the relevant stress components to be degraded. Once a failure criterion reaches one, the damage variable is activated and acts on its respective failure mode by degrading the stress. The damage variables increase monotonically from 0, at failure onset ($\varepsilon = \varepsilon_o$, representing the intact material) to 1 representing the fully damaged state ($\varepsilon = \varepsilon_f$).

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

$$\varepsilon_f = \frac{2G_c}{\sigma_o l_c} \tag{7}$$

The characteristic element length (l_c) is necessary to avoid mesh dependency 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.

$$d = 1 - \varepsilon_f \frac{\varepsilon - \varepsilon_o}{\varepsilon(\varepsilon_f - \varepsilon_o)} \tag{8}$$

Based on CDM models the applied stress is the result of the effective stress, σ^{ef} degraded by a damage variable as below:

$$\sigma = (1 - d)\sigma^{ef} \tag{9}$$

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. Once a failure criterion is met, the damage variable is activated and acts on its respective failure mode by degrading the associated stress components.

3.3. Modelling transverse damage growth in compression

From the previous sections, for example in equation (6), it is clear that failure initiation is shear dominated and influenced by friction. During crack growth, bigger crack surfaces are forming, Figure 13(a) making it more important to account for friction. The compressive stress can be decomposed into a shear component and normal component influencing the amount of friction, Figure 13(b).

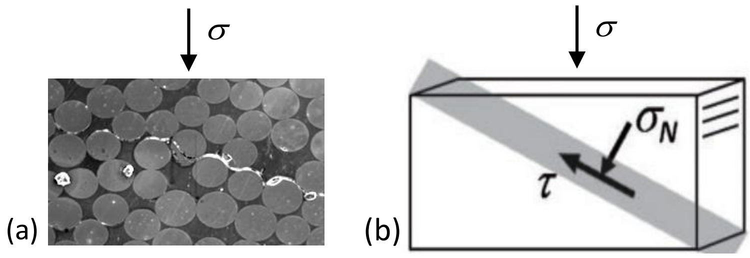

Figure 13. Transverse compression: (a) Matrix failure; (b) Representation with projection of the stresses in the fracture plane, adapted from [33]

Gutkin and Pinho combined damage and friction to model transverse compressive damage growth, [33]. Coupling damage with contact friction on the microcracks, partly accounts for some of the nonlinear response in shear. Taking advantage of the sticking/slipping behaviour it is possible to model the typical hysteresis loops observed in Figure 14.

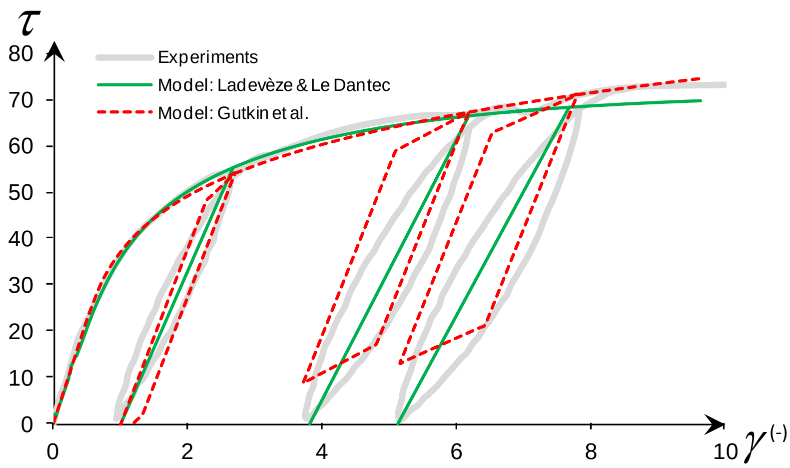

Figure 14. Shear response experiments and simulation, adapted from [34]

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 as

$$\tau = (1-d)G\gamma + d\tau^{friction} \tag{10}$$

where the friction term follows Coulomb's law. Identifying and modelling the shear response is fundamental for reliable modelling of the compressive damage modes. Furthermore, the matrix has a very important role during kink-band formation as it supports the fibres and controls their rotation.

4. Fibre kinking

4.1. Mechanisms of kink-band formation

Carbon fibre composites fail in compression by kink-band formation throughout the range 10-60% of fibre volume fraction [35]. Microbuckling of the fibre is the origin of fibre failure according to the first studies on the area, [36]. Argon [37] proposed that an initial fibre misalignment introduces shear stresses, which rotate fibres, thus increasing shear stresses in a progressive loop until failure is reached. Existing imperfections such as initial fibre misalignment, waviness and voids affect greatly the compressive strength. Fibre kinking failure is assumed to be a shear-dominated failure mode in a misaligned frame, under significant longitudinal compression.

Kink-band formation is a sequence of several stages, from formation, propagation and broadening, [38]. The mechanisms of kink band formation are difficult to investigate due to the unstable nature of the failure process and the impossibility to see the microscale while compressing the specimen. Gutkin and al. [39] 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 15. In this region, shear-driven fibre compressive failure is promoted by the large compressive stresses with small rotation of the fibres. After some propagation, the failure mechanism changes to kink-band formation.

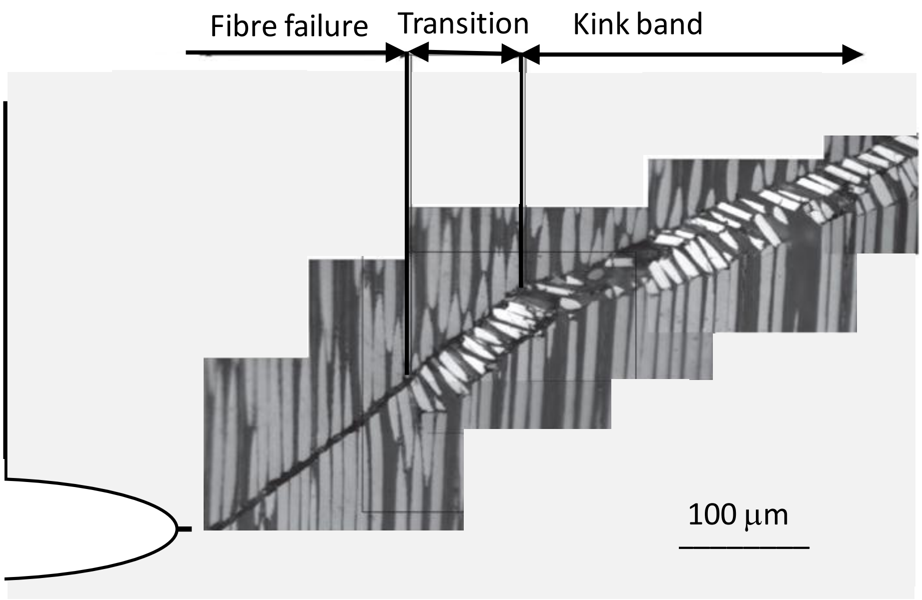

Figure 15. Compressive fracture process showing three different failure patterns, adapted from [39]

Micromechanical FE models are another useful alternative in the understanding of the kink band growth as in [40,41]. Kink band formation is not an in-plane mechanism and it becomes necessary to consider multi-axial stress states. Transverse compression is beneficial in raising the longitudinal strength of the composite while transverse tension lowers it, [42]. Therefore, predictive models need to account for the refereed mechanisms without modelling fibres individually (micromechanical).

The kink-band is usually a well defined band not perpendicular with the fibres, Figure 16(a). In this plane all the stresses and strains should be projected, Figure 16(b). The matrix supporting the fibres in the kink-band is more degraded than outside the band, thus cracks start to appear, Figure 16(c). These shear cracks are partially in compression and therefore friction develops.

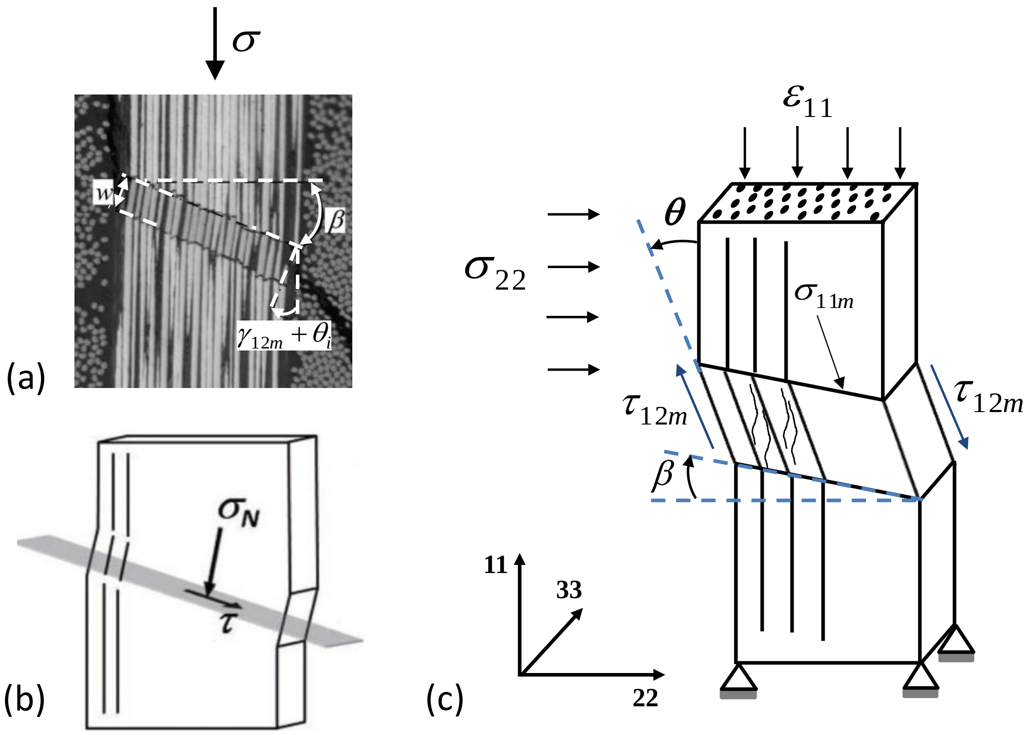

Figure 16. Kink band formation: (a) Experimentally; (b) Resolved normal and shear components of the traction vector in the fracture plane, [33]*; (c) Representation with associated angles and influence of stress components.*

The size effects in compression are also present in kinking formation and should be addressed [43]. Therefore a failure criterion based on an energy balance might be more appropriate [44].

4.2. Fibre lock up and breakage

The fibre lock-up angle defines the angle when fibres are not able to rotate further, typically about 40° [45], although there is no consensus on this value in the literature. Fibre lock-up occurs when the fibres enter in contact with each other and stop rotating, Figure 17.

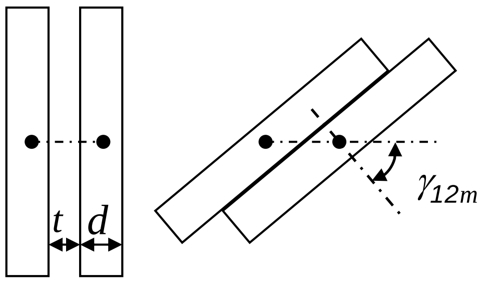

Figure 17. Representation of fibre lock-up in-plane

For high fibre rotations tensile stresses are produced in an angle to the fibre and an opening crack which eventually coalesce to form a split [46]. The interaction with splitting can also be further investigated using micromechanical models [47]. In many cases, the splits are open, which indicates that they were formed under tensile traction acting on their fracture plane [44]. The proposed model, even without being micromechanical is able to predict the raise of tensile transverse strains around the kink band, Figure 18(a).

Once the kink-band propagates through the whole width of the specimen, kink band broadening occurs [35]. Band broadening can also occur after fibre lock-up being represented by a constant friction stress on the crack flanks [45]. The kink-band spreads in the fibre direction into the unkinked material [38]. This phenomenon is also captured by the proposed mesoscale model, Figure 18(b).

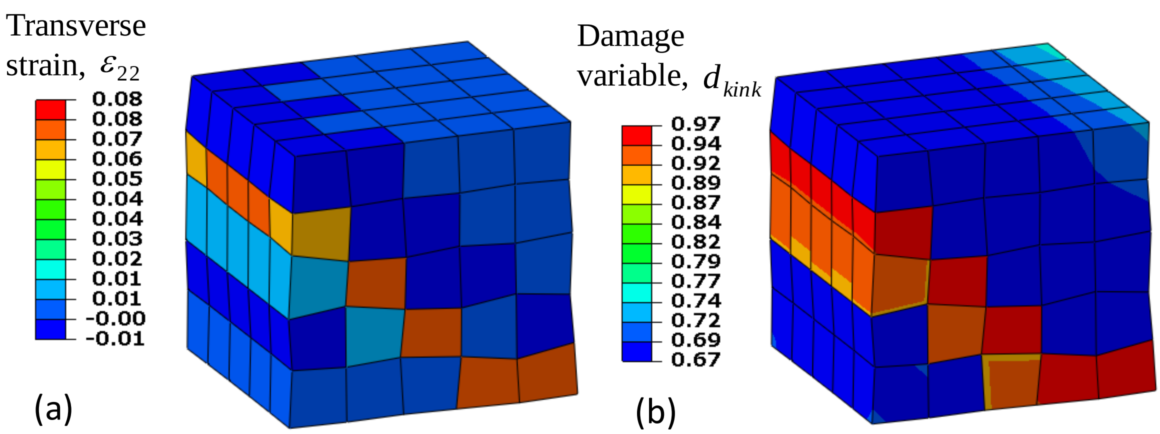

Figure 18. FE results of the proposed model: (a) Transverse strain; (b) Damage variable representing the kink band broadening

In the current work the material is homogenised, i.e. the properties of the fibres and the matrix are not considered separately. Homogenization is performed to gain speed, but it needs to capture the mechanisms at the microscale without losing information. The orthotropic characteristics of NCF materials are also not fully considered and will be evaluated in the upcoming work.

5. Summary of the appended papers

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

For computational efficiency, a homogenization at the ply level needs to be done. In **Paper A** we propose a physically based model for kink-band growth under a 3D stress state. The kinking theory proposed by Fleck and later extended to 3D by Pinho et al. [48] is developed further to predict the whole crush response. The same constitutive formulation is used for fibre kinking and for longitudinal shear and transverse responses. The kink-band plane, Figure 19(a), is obtained by:

$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{2\tau_{23}}{\sigma_{22}-\sigma_{33}}\right) \tag{11}$$

The ψ plane corresponds to maximum principal stress in the plane (2, 3). Then, stresses and strains are rotated to the kink-band plane (r) where τ_{23} is zero. The final equilibrium is solved in the m coordinate system, following the rotation of the fibres, Figure 19(b).

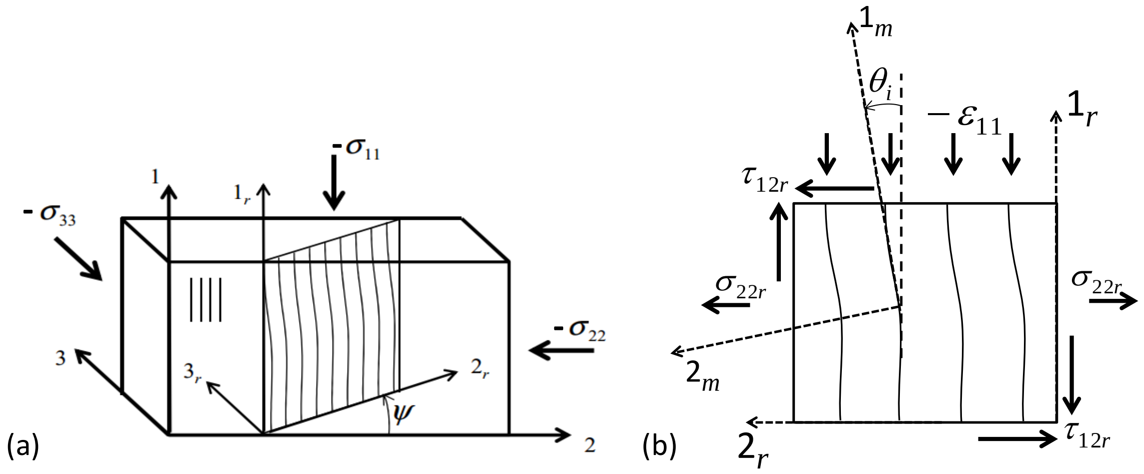

Figure 19. Illustration of a 3D kinking model: (a) Formation of the kink-band plane; (b) Stresses and strains acting in the kink-band plane.

The fibre kinking response is found from solving simultaneously the stress equilibrium, Eq. (12), between applied global stresses and nonlinear local stresses resulting from the nonlinear constitutive law of the material in the kink-band Eq. (13). The actual rotation of the fibres in the kink-band is resolved from the strain compatibility in Eq. (14)

$$\sigma_{11} = \left[\sigma_{22r}sc + \tau_{12r}(c^2 - s^2) - \tau_{12m}\right]/(sc) \tag{12}$$

$$\tau_{12m} = G_{12}\gamma_{12m}(1-d) + d\tau^{friction} \tag{13}$$

$$f(\gamma_{12m}) = \varepsilon_{11m}c^2 + \varepsilon_{22m}s^2 - \gamma_{12m}cs - \varepsilon_{11} = 0 \tag{14}$$

where $s = \sin(\theta)$ and $c = \cos(\theta)$.

5.2. FE implementation and mesh objectivity of the model – Paper B

In order to predict the crash response, it is necessary to have a fibre kinking model in an FE framework that captures the mechanisms of kinking. The model described in **Paper A** was implemented into a user subroutine (VUMAT) in the commercial FE code ABAQUS. This model must be mesh-size-independent in order to correctly account for the energy dissipation. In **Paper B** we describe the implementation and two methods for mesh objectivity with good results.

The numerical way to solve the stress equilibrium and stress compatibility equations simultaneously in an FE framework is presented. The results show that the current model is mesh-size-independent even for distorted meshes. The current numerical model can be used to predict the kinking response accounting for the correct energy absorption.

The current model builds upon previous development coupling damage with the friction induced at crack closure. It is combined with fibre kinking theory to provide a 3D constitutive law which gives the full response from initiation to crushing in longitudinal compression.

In order to solve the stress equilibrium and the strain compatibility it is necessary to use a root-finding method, e.g. the bisection method. The challenge with damage models is that they have a softening response, which makes it necessary to deal with the strain softening behaviour. Two methods were proposed, called Method 1 and Method 2. For method 2, the strain in the kink-band is distributed (smeared) over the whole element. When softening starts, i.e. when the peak stress has been reached, the strain in the kink-band is smeared over the entire element.

The fibre kinking model was successfully implemented and validated for a distorted mesh, showing successful mesh convergence.

6. Conclusions and outlook

By using composites one can take advantage of their excellent performance of energy absorption during crash events. In order to implement composites in structural components of mainstream cars it is necessary to overcome two major barriers, high price and lack of knowledge. Since the high price is partly due to long development times based on many experiments, a predictive simulation will be the solution for an optimized design at lower costs. Therefore, modelling damage onset and growth of composites is of crucial importance to introduce composite materials in mainstream vehicles.

In the present thesis we have seen the importance and the progress in understanding of compressive failure modes with focus on kink band growth. We have also seen the difficulties associated with the investigation of the damage mechanism and the importance of avoiding delaminations in crash.

We learn that the only models able to predict the full kink band response were micromechanical models not suitable to model large structures. Thus, in subsequent papers we present a homogenized mesoscale model and its implementation in commercial FE software.

6.1. What is missing on the modelling side?

Even though substantial progress was made with this work, there are missing mechanisms to include in the model. It is necessary to model the behaviour for large strains in longitudinal compression.

NCFs are very promising due to their balance of mechanical properties and manufacturing speed, but less knowledge is available about this type of composites and more experiments are needed for characterization and information about the failure modes in order to develop a physically sound damage model.

The essential considerations to adapt a material model for UD prepreg to NCF composites, based on their geometry, are: change in out-of-plane strengths due to the additional effects of the stitching yarn, decrease of in-plane strengths due to the in-plane fibre waviness, and account for orthotropic material behaviour instead of transverse isotropy.

7. References

[1] Park C, Kan CS, Hollowell WT. Investigation of Opportunities for Lightweight Vehicles Using Advanced Plastics and Composites, DOT HS 811 692. U.S. Department of Transportation, NHTSA: 2012.

[2] Verpoest I, Lomov S, Swolfs Y, Jaquet P, Michaud V, Manson J-A, et al. Advanced Materials Enabling High-Volume Road Transport Apllications of Lightweight Structural Composite Parts. SAMPE J 2014;50:30–7.

[3] Feraboli P, Wade B, Deleo F, Rassaian M, Higgins M, Byar A. LS-DYNA MAT54 modeling of the axial crushing of a composite tape sinusoidal specimen. Compos Part A Appl Sci Manuf 2011;42:1809–25.

[4] Lamborghini aventador P700-4. http://media.lamborghini.com/. accessed October, 19, 2016.

[5] Porsche media gallery 2013. http://press.porsche.com. accessed October, 19, 2016.

[6] Grauers L, Olsson R, Gutkin R. Energy absorption and damage mechanisms in progressive crushing of corrugated NCF laminates: Fractographic analysis. Compos Struct 2014;110:110–7.

[7] Ebert C, Hufenbach W, Langkamp A, Gude M. Modelling of strain rate dependent deformation behaviour of polypropylene. Polym Test 2011;30:183–7.

[8] Hufenbach W, Langkamp A, Gude M, Ebert C, Hornig A, Nitschke S, et al. Characterisation of strain rate dependent material properties of textile reinforced thermoplastics for crash and impact analysis. Procedia Mater Sci 2013;2:204–11.

[9] Edgren F, Asp LE, Joffe R. Failure of NCF composites subjected to combined compression and shear loading. Compos Sci Technol 2006;66:2865–77.

[10] Bru T. Behaviour and material properties of composites for crash modelling. Tekn. Lic Thesis. article. Chalmers Univ of Techn, Gothenburg, 2016.

[11] Greve L, Pickett a. K. Modelling damage and failure in carbon/epoxy non-crimp fabric composites including effects of fabric pre-shear. Compos Part A Appl Sci Manuf 2006;37:1983–2001.

[12] Laffan, MJ. Testing the toughness of polymer matrix composites. Ch 5 in Failure mechanisms in polymer matrix composites. Eds: Robinson P, Greenhalgh E, Pinho S. Woodhead. Cambridge: 110-128: 2012.

[13] Ghafari-Namini N, Ghasemnejad H. Effect of natural stitched composites on the crashworthiness of box structures. Mater Des 2012;39:484–94.

[14] Allix O, Feld N, Baranger E, Guimard JM, Ha-Minh C. The compressive behaviour of composites including fiber kinking: modelling across the scales. Meccanica 2014:1–16.

[15] Feraboli P, Deleo F, Wade B, Rassaian M, Higgins M, Byar A, et al. Predictive modeling of an energy-absorbing sandwich structural concept using the building block approach. Compos Part A Appl Sci Manuf 2010;41:774–86.

[16] Deleo F, Wade B, Feraboli P. Crashworthiness of composite structures: experiment and simulation. Am Inst Aeronaut Astronaut 2009:1–22.

[17] Camanho P. Application of numerical methods to the strength prediction of mechanically fastened joints in composite laminates, PhD Thesis. Imperial College of Science, Technology and Medicine, 1999.

[18] Feraboli P. Development of a Corrugated Test Specimen for Composite Materials Energy Absorption. J Compos Mater 2008;42:229–56.

[19] Waldenström P. Experimental crushing of composite NCF coupons. Open report TR15-009. Swerea SICOMP, Swerea SICOMP. Mölndal Sweden: 2015.

[20] Bru T, Waldenström T., Gutkin R, Robin O, Vyas G. Development of a test method for the evaluation of the crushing behaviour of unidirectional laminates. Compos Struct 2016;Submited.

[21] Jacob GC, Fellers JF, Simunovic S, Starbuck JM. Energy absorption in polymer composites for automotive crashworthiness. J Compos Mater 2002;36:813–50.

[22] Zarei H, Kröger M, Albertsen H. An experimental and numerical crashworthiness investigation of thermoplastic composite crash boxes. Compos Struct 2008;85:245–57.

[23] Grauers L, Olsson R, Gutkin R, others. Energy absorption and damage mechanisms in progressive crushing of corrugated NCF laminates: Fractographic analysis. Compos Struct 2014;110:110–7.

[24] Davila CG, Camanho PP, Cheryl A. R. Failure criteria for FRP laminates. J Compos Mater 2005;39:323–45.

[25] Puck A, Schneider W. On failure mechanisms and failure criteria of filament-wound glass-fibre/resin composites. Plast Polym 1969;33–44.

[26] Tsai SW, Wu EM. A general theory of strength for anisotropic materials. J Compos Mater 1971;5:58–80.

[27] Hashin Z. Failure criteria for unidirectional fiber composites. J Appl Mech 1980;4:329–34.

[28] Pinho ST, Dávila CG, Camanho PP, Iannucci L, Robinson P. Failure Models and Criteria for FRP Under In-Plane or Three-Dimensional Stress States Including Shear Non-Linearity, TM-2005-213530. 2005.

[29] Davila CG. Failure Criteria for FRP Laminates. J Compos Mater 2005;39:323–45.

[30] Puck A, Schürmann H. Failure analysis of FRP laminates by means of physically based phenomenological models. Compos Sci Technol 1998:264–97.

[31] Hinton M, Kaddour A, Soden P. A further assessment of the predictive capabilities of current failure theories for composite laminates: comparison with experimental evidence. Compos Sci Technol 2004;64:549–88.

[32] Ladeveze P, Le Dantec E. Damage modelling of the elementary ply for laminated composites. Compos Sci Technol 1992;43:257–67.

[33] Gutkin R, Pinho ST. Combining damage and friction to model compressive damage growth in fibre-reinforced composites. J Compos Mater 2015;49:2483–95.

[34] Bru T, Gutkin R, Olsson R, Vyas G. Use of the Iosipescu test for the identification of shear damage evolution laws of an orthotropic composite. Compos Struct 2016;Submited.

[35] Lee SH, Waas AM. Compressive response and failure of fiber reinforced unidirectional composites. Int J Fract 1999;100:275–306.

[36] Budiansky B. Micromechanics. Comput Struct 1983;16:3–12.

[37] Argon AS. Fracture of composites (Treatise on Materials Science and Technology). New York, NY Acad Press 1972.

[38] Moran PM, Liu XH, Shih CF. Kink band formation and band broadening in fiber composites under compressive loading. Acta Metall Mater 1995;43:2943–58.

[39] Gutkin R, Pinho ST, Robinson P, Curtis PT. On the transition from shear-driven fibre compressive failure to fibre kinking in notched CFRP laminates under longitudinal compression. Compos Sci Technol 2010;70:1223–31.

[40] Pimenta S, Gutkin R, Pinho ST, Robinson P. A micromechanical model for kink-band formation: Part I — Experimental study and numerical modelling. Compos Sci Technol 2009;69:948–55.

[41] Gutkin R, others. Micro-Mechanical modelling of shear-driven fibre compressive failure and of fibre kinking for failure envelope generation in CFRP laminates. Compos Sci Technol 2010;70:1214–22.

[42] Basu S, Waas AM, Ambur DR. Compressive failure of fiber composites under multi-axial loading. J Mech Phys Solids 2006;54:611–34.

[43] Bazant ZP, Kim J-JH, Daniel IM, Becq-Giraudon E, Zi G. Size Effect on Compression Strength of Fiber Composites Failing by Kink Band Propagation. Int J Fract 1999;95:103–41.

[44] Pinho ST, Gutkin R, Pimenta S, De Carvalho N V., Robinson P. On longitudinal compressive failure of carbon-fibre-reinforced polymer: from unidirectional to woven, and from virgin to recycled. Philos Trans R Soc A Math Phys Eng Sci 2012;370:1871–95.

[45] Sutcliffe MPF, Fleck N a. Microbuckle propagation in fibre composites. Acta Mater 1997;45:921–32.

[46] Lee SH, Yerramalli CS, Waas AM. Compressive splitting response of glass-fiber reinforced unidirectional composites. Compos Sci Technol 2000;60:2957–66.

[47] Gutkin R, Pinho ST, Robinson P, Curtis PT. A finite fracture mechanics formulation to predict fibre kinking and splitting in CFRP under combined longitudinal compression and in-plane shear. Mech Mater 2011;43:730–9.

[48] Pinho ST, Iannucci L, Robinson P. Physically-based failure models and criteria for laminated fibre-reinforced composites with emphasis on fibre kinking: Part I: Development. Compos Part A Appl Sci Manuf 2006;37:63–73.