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Abstracts

DAMAGE TOLERANCE AND HIGH TEMPERATURE IMPACT BEHAVIOR OF THERMOPLASTIC COMPOSITE MATERIALS FOR AERONAUTIC APPLICATIONS

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Keywords: Thermoplastic; Carbon fibers; Glass fibers; Impact; High temperature

ABSTRACT

The better impact behaviour and damage tolerance of thermoplastic-based composites have been thoroughly investigated over the past 30 years but most references available in the literature focus on room temperature testing [1-2]. This study was aimed at examining the impact behavior of hybrid carbon and glass fibers woven-ply reinforced PolyEther Ether Ketone (PEEK) thermoplastic quasi-isotropic laminates at a testing temperature (150°C) higher than its glass transition temperature (about 140°C). An instrumented Charpy pendulum was specifically designed [3] to estimate its capability to perform low velocity impact tests (Figure 1).

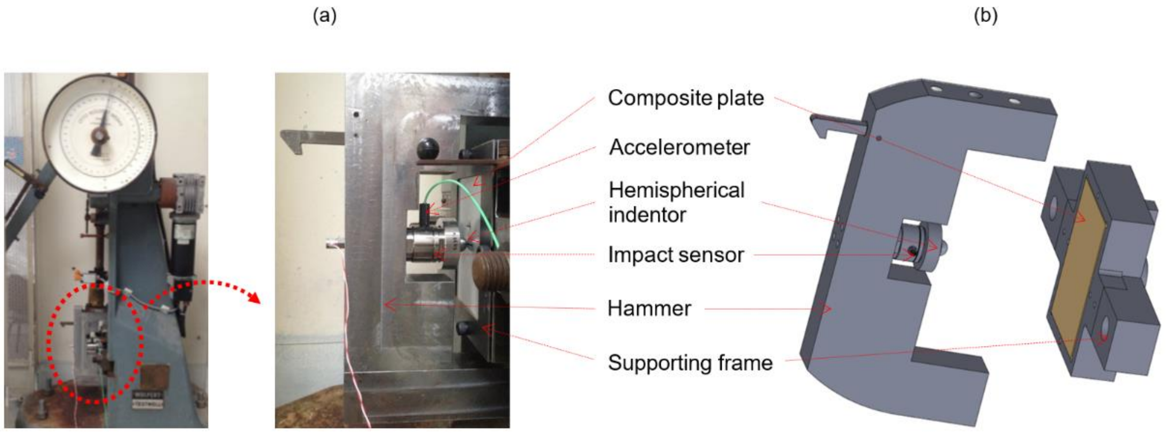

Figure 1: Low velocity impact testing: (a) Charpy pendulum and measurement devices – (b) Parts design

Through the comparison of different impact methods (Quasi-static indentation tests, Charpy and drop tower impacts), the influence of impact velocity on the impact behavior of this hybrid composite material was investigated. From the obtained results, it appears that the macroscopic impact response is similar in terms of force-displacement response. Indeed, the impact velocity is significantly higher (2.5 times higher) with falling weight impact testing. In

PEEK-based laminates whose mechanical behaviour is time-dependent, slow loading rates (e.g. Charpy impact testing) are instrumental in ruling the dissipated energy (+20% at 35 and 40J) as well as in increasing the permanent indentation (1.6 times higher) that is always higher than the Barely Visible Impact Damage (Figure 2). In addition, the first important effect resulting from temperature increase is a reduction of the impact energy required to induce BVID. The second effect is that matrix ductility (enhanced at T>Tg) contributes to significantly modify the permanent indentation. Not surprisingly, the plastic and viscoplastic deformation mechanisms being ruled by the PEEK matrix behavior at high temperature, the permanent indentation increases by almost 40% for all impact energies. Contrary to the external damage represented by permanent indentation, temperature has a tremendous influence on the internal damage (i.e. delamination) as the delaminated area is divided by three over the whole range of impact energies. As was observed in the case of impact tests conducted with a drop tower, a positive effect of the temperature on the permanent indentation. Then the impact damage tolerance, which is directly associated with the impact damage detectability, will be improved at high temperature [4]. Overall, both permanent indentation and delamination are expected to compete from the Compression After Impact behaviour standpoint. It was observed in laminates impacted with a drop tower that the increase in permanent indentation with temperature has surprisingly no influence on the CAI strength, which seems to be virtually temperature-independent.

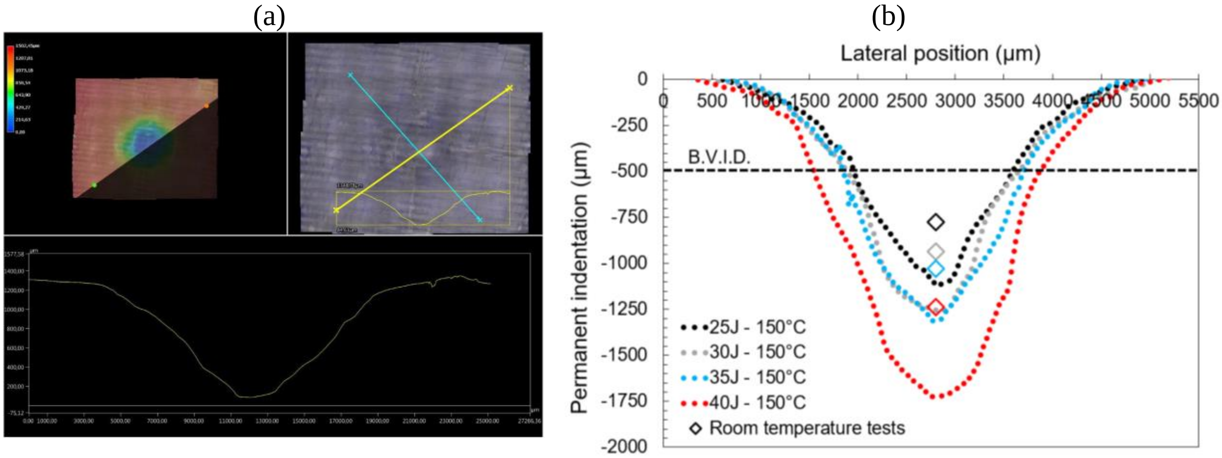

Figure 2: Influence of testing temperature on permanent indentation: (a) Indentation profile measurement from 3D microscope observations – (b) Comparison of permanent indentation

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INFLUENCE OF KEROSENE FLAME ON RESIDUAL MECHANICAL PROPERTIES OF HYBRID CARBON FIBERS REINFORCED PEEK COMPOSITE LAMINATES

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Keywords: Thermoplastic; Carbon fibers; Kerosene flame; Thermal analysis; Mechanical testing

ABSTRACT

This work examines the influence of kerosene flame exposure (Figure 1) on the residual mechanical behavior (tension and compression) of hybrid quasi-isotropic composite laminates consisting of carbon/glass fibers and a PEEK thermoplastic matrix. The influence of a kerosene flame exposure (116 kW/m^2 and 1100 °C), on the composites structural integrity was examined as a function of exposure time (5-10-15 min).

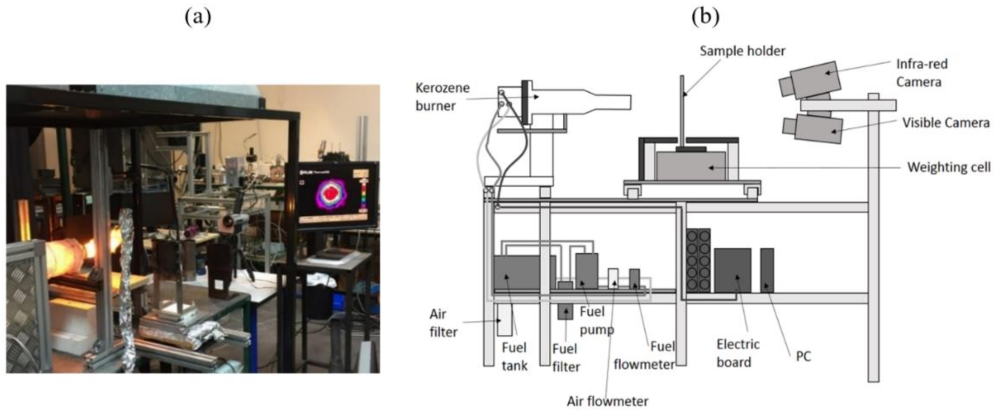

Figure 1: Kerosene flame exposure: (a) Picture of the experimental set-up device - (b) Schematic representation of the kerosene burner bench

The changes in the tensile and compressive properties (axial stiffness and strength) were compared with respect to the virgin materials (experiencing no prior flame exposure). The discussions on fire- and mechanically-induced damage mechanisms are supported by fractographic analysis of specimens. It is therefore possible to better understand how the fire-induced damages within the laminates micro- and meso-structures modify the mechanical behavior of flame-exposed laminates. Regardless the exposure time, the kerosene flame exposure involves in-plane and through-thickness temperature gradients, which ultimately create two well-defined areas within the laminates: an extensively delaminated one (the one close to the exposed surface) and a relatively well preserved one (close to the back surface). From the present work, it is possible to conclude that the mechanical properties in

tension are severely affected (-50% in stiffness and -70% in strength) by prolonged exposures to kerosene flame (15 min) with respect to as-received specimens. When compared to the 5 min case, flame exposure time (ranging from 5 to 15 min) seems to have little very influence on tensile properties and the effect is moderate on compressive properties. The barrier formed by an extensive thermally-induced delamination contributes to relatively preserve the structural integrity of the plies close to the back surface. The mechanical loading is taken up by the 0° fibers in non-delaminated areas of the specimens, resulting in preserving the residual mechanical in tension and in compression.

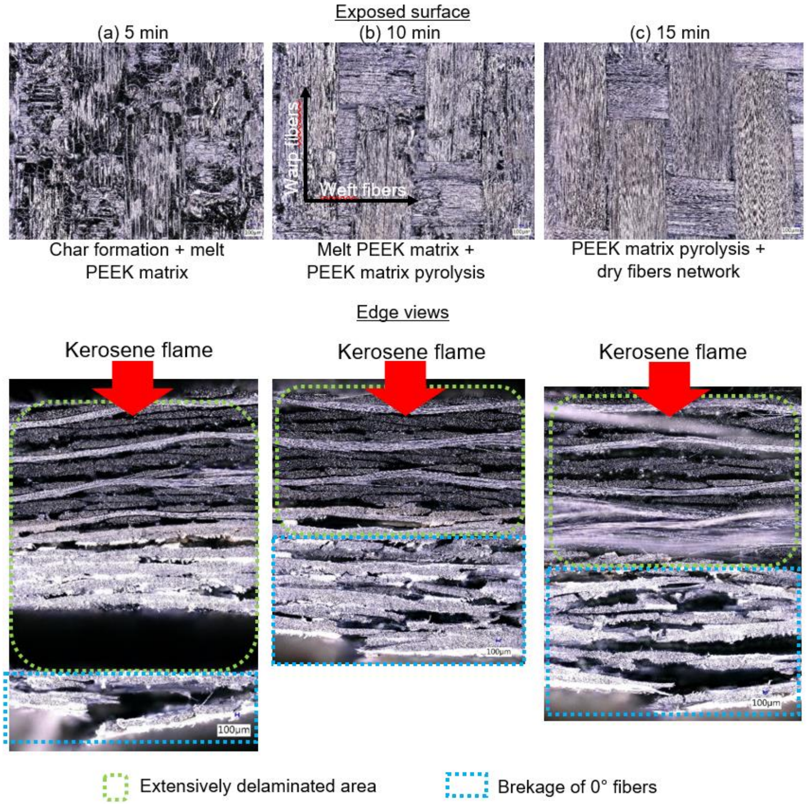

Figure 2: Microscopic observations of failure in tension of the CG/PEEK specimens (most degraded specimen in central position): (a) Front surface observation – (b) Through-thickness observation

The macroscopic tensile responses of specimens #3 under different flame exposure times also suggest that once the 0° fibres plies are broken, the ±45° plies tends to take up the tensile load. It results in shifting the fracture behavior from brittle (sudden breakage of 0° fibers plies) to ductile. As exposure time increases, the gradual failure of most degraded specimens subjected to a tensile loading comes along with the plastic deformation of ±45° plies as well as fiber/matrix debonding and delamination (Figure 2). Microscopic observations done on the most degraded specimen in central position clearly emphasize at small scale the two well-defined areas that play different roles from both thermal and mechanical responses, as was previously mentioned.

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DAMAGE TOLERANCE ANALYSIS OF IMPACTED COMPOSITE STRUCTURES SUBJECTED TO MULTIAXIAL LOADINGS

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Keywords: Thermoset composites, Digital Image Correlation, Impact, Discrete Ply Model, Multiaxial testing

ABSTRACT

The development and certification of aeronautical composite structures is still largely based on the pyramid of tests. This approach requires a large number of tests going from the coupon to the full-size aircraft. To reduce the associated costs, predictive modelling methodologies are developed in several research centers [1]–[4]. Out of plane stresses emanating from impacts are well known to be critical for the residual compressive strength of laminated composites. To design composites structures, engineers use a damage tolerance approach following standards of low velocity impact and compression after impact tests [1], [2]. These standardized tests do not represent real structural loadings because of their conservative uniaxial boundary conditions that do not allow post-buckling failures. In this work, medium-scaled specimens are impacted at medium velocities with a gas launcher then multi-axially loaded in order to analyze interactions between impact damage and post-buckling.

The material used in this study is a prepreg with carbon unidirectional fibers and epoxy matrix T700/M21 manufactured by HEXCEL of 0.25 mm-thickness ply. The selected stacking sequence is [45°2/-45°2/0°2/90°2/0°2/-45°2/45°2] with a total thickness of 3.5 mm. This composite laminate is quasi-isotropic and is closed to aeronautical composite structures. Specimens are flat panels of 558*536 mm2 dimensions (Figure 1). Eight specimens are studied, seven of them are impacted to evaluate the delaminated areas and determine the impact damages. A multiaxial test rig for medium-scale structures has been developed at the Institut Clement Ader (Toulouse, France) and has already made it possible to test notched panels [7], [8]. Two actuators (1 and 2 - Figure 1) are used to generate bending of the central box and therefore tension or compression in the flat specimen that constitutes its upper side. The two other actuators (3 and 4 – Figure 1) are used to generate torsion within the central box and therefore shear in the specimen. Different loading paths have been investigated: compression, compression+shear and tension+shear. Two techniques of in situ monitoring have been used to characterize the failure scenarios: digital image correlation an infrared thermography.

Behaviors have been analyzed, differences have been highlighted and some explanations are proposed. B. Castanié and J. Serra have shown that it is very difficult to estimate stress flows directly entering the specimen because of the numerous structural redundancies [8], [9]. Therefore a specific methodology using Digital Image Correlation has been developed to extract experimental boundary conditions in terms of nodal displacements and to apply them on a finite element model. Numerical predictions have been performed first using an implicit non-linear elastic model then using the “Discrete Ply Model” [10], [11] to model accurately the damage propagation. Promising results have been obtained. The way is now paved to model more complex structures such as stiffened panels with defects (large cuts or impacts). This is the objective of the VIRTUOSE project [12].

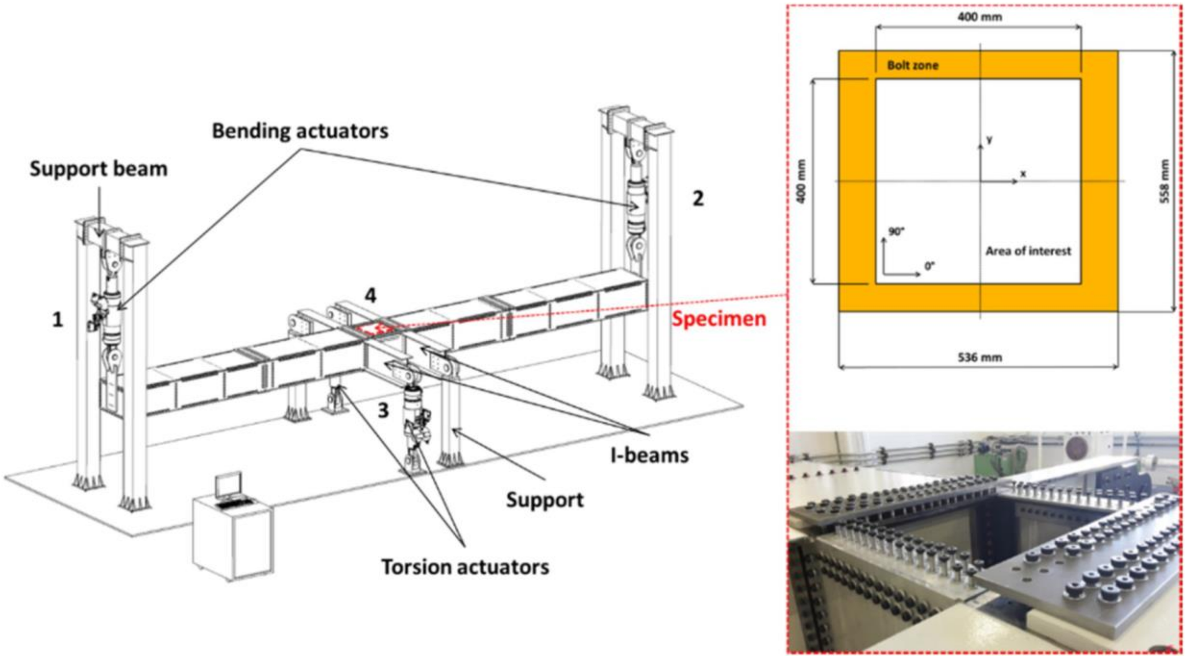

Figure 1: VERTEX test rig and specimen bolting area

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EXPERIMENTAL CHARACTERIZATION OF THE MODE I TRANSLAMINAR FRACTURE TOUGHNESS OF CFRP USING INFRARED AND DIC MEASUREMENTS: COMPACT TENSION AND COMPACT COMPRESSION TESTS

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Keywords: CFRP, Digital Image Correlation, Compact Tension, Compact compression, critical energy release rate

ABSTRACT

The extensive use of carbon fibers reinforced polymers (CFRP) in the aeronautics field has created a need for a deeper understanding of their failure mechanics, one of them being cracks propagation. The failure of CFRP occurs according to 3 primary damages: interlaminar, intralaminar, translaminar [1]. Translaminar failure occurs at the mesoscopic scale (at the scale of multiple plies), and cracks propagate through the thickness of the laminate.

The goal of this study is to analyze the translaminar fracture toughness of a carbon fiber reinforced thermoset material (UD carbon/epoxy). The stacking sequence is $[-45/45/(90/0)_4]_s$. CT (Compact Tension) and CC (Compact Compression) specimens are used to study respectively tensile and compressive damage. The critical strain energy release rate in mode I, G_{IC}, (opening mode) is calculated with 3 methods. A particular attention is paid to detecting secondary damage, i.e. damage not directly linked to the crack growth [2].

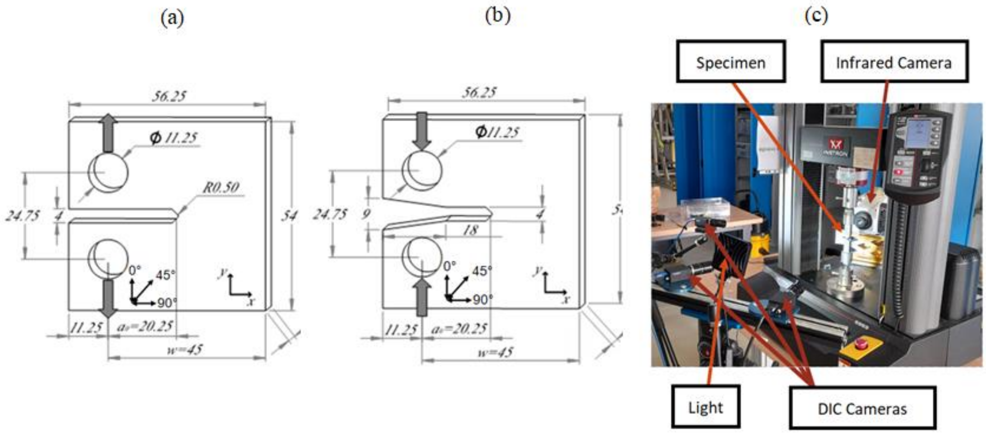

Figure 1: (a) CT geometry – (b) CC geometry – (c) Experimental setup

Geometries and experimental setup can be seen on Figure 1. Two cameras film the face of the specimen to calculate displacement and strain fields using digital image Correlation (Figure 2b).

Another camera films the opposite side of the specimen to detect respectively compressive or tensile secondary damage. An infrared camera is placed behind the specimen to follow the crack during its propagation (Figure 2a - b).

G_{IC} is calculated using three different methods: the ASTM-e399 method [3], the area method [4], and the compliance method using the Irwin-Kies formula. Three laws are compared to approximate the compliance of the specimen as a function of the crack length ([1], [3], [4]).

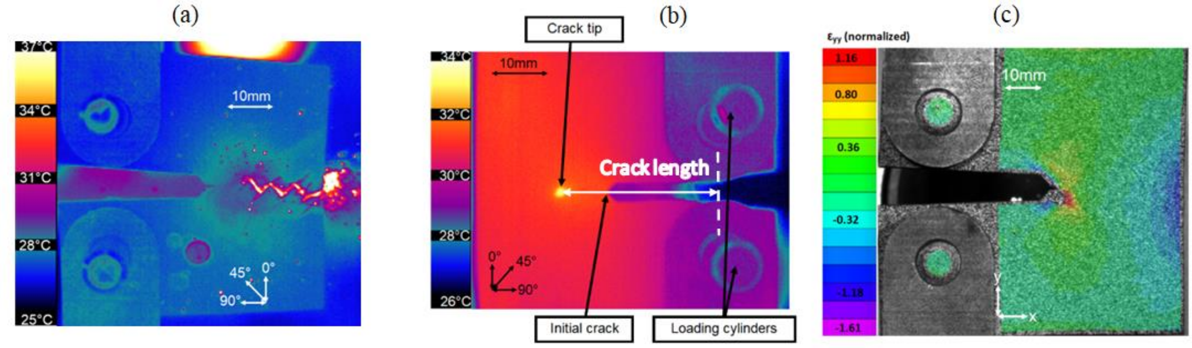

Figure 2: (a) IR image showing compressive failure at the end of the test on a CT specimen - (b) IR image showing local heating after a crack propagation on a CC specimen – (c) Strain fields in the *y* direction on a CC specimen, showing compression exceeding the fibers maximum allowable

G_{IC} computing resulted in the plotting of R curves, i.e. G_{IC} as a function of the crack length. These showed an initiation value around 100 kJ/m^2 for CT tests and around 15 kJ/m^2 for CC tests. A large increase of G_{IC} with the crack length was observed on both tests, which for the CT tests can be linked to the damage zone size increase, and for the CC tests crushing phenomena largely contribute to this increase. Finally, the fiber fracture toughness of the ply in mode I G_{IC}^{ply} was calculated using the rule of mixtures [1].

Particular attention was paid to secondary damage. None was observed on CC specimens. However, CT with 11.25 mm wide loading holes suffered from failure around loading axis; although this is the value recommended by the ASTM test standard E399-12. This resulted in a geometry modification to 8 mm holes. CT specimens also suffered from compressive damage on the side opposite to the loading axis [2]. Although, this damage occurred for a measured compressive strain 40% higher than the value given by the manufacturer and observed on CC specimens.

Contrary to other studies, ±45° plies are placed in surface. Their primary role is to hold shear force and avoid plasticity of the resin [3]. These plies seem to be beneficial to CC specimens, as the damage zone and thus the heated dots indicating the tip of the crack remain small compared to other studies [3]. However, this architecture resulted in large delamination of the surface plies and an increasing size of damage zone on CT tests, making the identification of the crack tip more difficult (figure 2a).

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Predicting composites failure under crash and impact loading using advanced material models

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Present abstract showcases the impact and crashworthiness modelling of composites using intraply mesomodel [*International Journal of Impact Engineering*, 147,103701, 2021] proposed by the present authors. This interply model is based on continuum damage mechanics and accounts for progressive damage. Interply (delamination) between the plies is accounted using cohesive elements. Both intraply and interply behaviors are implemented in commercial finite element software LS-Dyna as user subroutines.

Authors conducted low velocity impact followed by compression after impact, high velocity impact and axial crushing on the carbon fiber reinforced polymeric composite laminates.

In the low velocity impact studies, AS4/8552 material system with three stacking sequences i.e. $[(45/0/\text{-}45/90)_4]_S$, $[(45_2/0_2/\text{-}45_2/90_2)_2]_S$ and $[45_4/0_4/\text{-}45_4/90_4]_S$ are conducted. Each laminate is subjected to 20 J, 30 J and 40 J of impact energies according to ASTM D7136 using a 16 mm diameter hemi-spherical impactor with a 5 kg mass. The compression after impact study following ASTM D7137.

In the high velocity impact studies, a clamped AS4/8552 quasi-isotropic $[45/90/\text{-}45/0]_{2s}$ laminate is subjected to a steel sphere of 20 mm or 30 mm diameter. Impact velocities between 50 and 110 m/s are considered.

In axial crushing of composites study, IM7/8552 material system with $[90/\pm45/0]_{2S}$, and $[902/02/\pm45/02]_S$ stacking sequences are considered. A rectangular composite strip with a nominal dimension of 40 mm x 130 mm is used in the study. A saw too of 3 mm is used to trigger crushing behavior.

A comparison is made between present finite element simulations and tests in all the three test cases. Typically, load-time, load-displacement, absorbed energy versus time, damage sizes and ballistic limit velocity curves are considered in the FE-test correlation activity.

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Simulation of energy absorption mechanisms in braided composite tube at the mesoscopic level

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1 Abstract

Keywords: braided composites, virtual testing, multiscale simulation, crushing, energy absorption

Textile-based composites and more particularly braided composites are suitable for energy absorption in crash or impact loaded structures [1]. Their specific energy absorption (SEA) level is increased by the additional reinforcing effect of the crimped yarns in thickness direction at the cost of reduced in-plane mechanical properties. This reinforcing effect is moreover directly dependent on the chosen yarn pattern, angle of the yarn transverse to the loading direction and on the fraction of yarn in loading direction. Finally, due to their textile architecture with a two-yarn or a three-yarn system, these materials offer promising possibilities of hybridisation using various fibre types or sizes to steer the mechanical properties for specific applications [2][3]. This multiplicity of potential configurations and architectures represents a high effort for mechanical characterisation on flat specimens and on crushing tubes and therefore challenges the field of experimental testing. Moreover, the mechanical characterisation of braided composites lacks so far of a consistent normalisation and many authors have developed new testing methodologies in the past [4][5].

The present contribution focuses on the progressive replacement of experimental testing methods for braided composites through numerical simulations at the mesoscale. It focuses on the investigation of triaxially-braided composites with STS40 24k carbon tows manufactured on a Herzog RF 1-176-100 braiding machine at the Institute of Aircraft Design in Stuttgart and infiltrated with a Baxxodur epoxy resin. Three-dimensional finite-element models of the braided composites are generated for use within the explicit software LS-DYNA. The simulation models undergo a first compaction step to reproduce the complex intertwining of the different yarns. Secondly, the mechanical properties are virtually investigated on Representative Unit Cells (RUCs) loaded under tension, compression and shear. Together with the realistic geometry of the braided material, state-of-the-art material models for the yarns and resin allow for a precise reproduction of the failure patterns dependent on the local loading conditions. In a last step, the RUCs are duplicated and transformed to form a cylindrical tube section. Crushing simulations are then performed to investigate in detail the different contributions to the energy absorption. The presentation introduces the overall methodology for model generation and illustrates some key aspects of the mesoscale simulation framework (Figure 1).

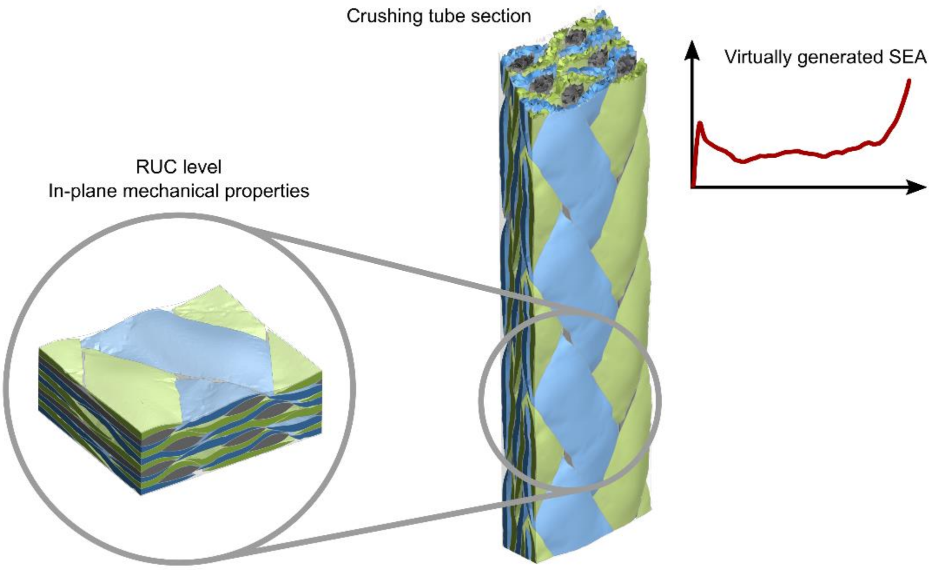

Fig. 1: Multiscale framework for the study of energy absorption mechanisms in braided composites

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3 Acknowledgements

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Type : **Oral presentation**

Influence of loading rate on the performance of ultrasonically welded thermoplastic woven composite joints - an experimental and numerical study

Objectives and significance of the research work

Thermoplastic composites possess excellent mechanical properties and low manufacturing costs. In addition, these materials can be welded to assemble structural parts. The ultrasonic welding process is one of the intensely studied technologies in the literature and appears as a fast and efficient process [1]. Most of the studies on this process focus on the set-up parameters' influence on the joint performance for quasi-static loadings and the process modelling [2,3]. However, certain safety-related constraints in the transport industry require an understanding of the behaviour of structures over a wide range of loading speeds. The literature review shows some effects of loading rate on the bonded interface behaviour of composite structures or their delamination [4,5]. However, no studies investigate the influence of loading speed on welded composite structures to the authors' knowledge. Hence, the study's objective is to investigate the behaviour of thermoplastic composite welded structures at several loading speeds from an experimental point of view. Then, a numerical model of the welded interface is defined based on the experimental results.

Methods

The composite used in this study is a four-ply PA66 reinforced by a glass fibre 2x2 twill woven. Tensile tests were conducted on single lap joint (SLJ) specimens welded ultrasonically. Three configurations were considered: $[0/45]_S/[0/45]_S$, $[45]_4/[45]_4$ and $[0/45]_S/[45]_4$. High-speed cameras registered all the tests to access the displacement fields using Digital Image Correlation, and the force signal is registered. Lap shear strength was calculated as the maximum force reached during the test divided by the welded area. In addition, force-displacement curves were extracted for all the tensile tests. The experimental campaign was conducted at room temperature and in a dry state to limit the influence of these environmental parameters on the specimen's behaviour and focus on the loading speed influence. To this end, specimens were dried in a desiccator before tensile tests.

In terms of simulation, a subroutine developed by Mbacké et Rozycki [6] defines the substrate's behaviour using the finite element software Abaqus. This VUMAT includes the strain rate sensitivity of the substrates in shear and its plastic behaviour. A numerical SLJ was created and takes the experimental displacements of the specimens around the grips as boundary conditions. Cohesive elements describe the interface using a bi-linear traction-separation law. The behaviour of the substrate and the boundary conditions of the problems are known, so the bi-linear traction-separation law is the unique unknown behaviour of the problem. Parameters of the law were determined by inverse method for the configurations considered and the several loading speeds.

Results and discussion

The results of the experimental part show the loading speed dependence of the performance of the three configurations. The lap shear strength increases with increasing loading speed. Moreover, the increase is larger for the stiffer substrates: 11.2%, 22.9% and 19.5% for $[45]_4/[45]_4$, $[0/45]_S/[45]_4$ and $[0/45]_S/[0/45]_S$, respectively. The force-displacement curves expose a stiffening for configurations $[45]_4/[45]_4$ and $[0/45]_S/[45]_4$.

This phenomenon is caused by the significant strain rate sensitivity of $[45]_4$ substrates. No change in the fracture mechanism is noticed with the increasing loading speed.

On the numerical part, the traction-separation law does not significantly depend on the loading speed for the configurations considered. The stiffening and strengthening of structures are observed only considering the substrate strain rate sensitivity in shear. This result is consistent with experiments, as a large part of the impact energy is absorbed by substrates. The behaviour of SLJ specimens significantly depends on the substrates' behaviour. Nevertheless, traction-separation law parameters differ depending on the substrate stiffness. Numerical results also permit a more in-depth analysis of the joint behaviour considering the plastic strain and damage in the substrates. For the configuration $[45]_4/[45]_4$, joint fracture occurs for low levels of plasticity in the substrates around the edges of the welded joint. Finally, investigations show that for these environmental conditions (T23℃ and dry state), the SLJ's interface behaviour does not depend significantly on the loading speed compared to the substrates' behaviour.

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A kinking model for simulation of continuous crushing

In the largest group of material models used for analysis of damage and fracture of laminated composites, see e.g. [1] and similar models, the evolution of damage is described by a stress-strain relation formulated in terms of the material strength and associated fracture energy for the particular failure mode. A common choice is to adopt a bilinear stress-strain relation (with linear softening), where the maximum stress is given by the material strength and the strain at zero stress (complete failure) is defined to (ideally) achieve the proper energy dissipation. Here, the volumetric energy dissipation (the area under the bilinear stress-strain relation) corresponds to the fracture toughness regularised with a characteristic element length with the aim to achieve mesh-independent results, see illustration in Figure 1a. Although there have been proposed more physically based models, e.g. Gutkin et al. [2] for kinking, these models often have a similar characteristic in the resulting stress-strain relation. And for most of these models (physically based or not), when used in finite element simulations, fully damaged elements are typically deleted. Such a modelling approach is suitable for a tensile failure, where cracks are formed and the material separates, but in compressive failure it is generally not. Instead, in compressive failure the element deletion causes a volume loss of material and prohibits prediction of continued loading (and e.g. kinking) in compression.

As a remedy, some more phenomenological models, e.g. mat054 and mat058 in [3], include a non-zero stress plateau after failure. This type of models is mainly intended for large scale simulations of component crushing using shell elements and the plateau value can be adjusted to better fit experimental crushing data. However, although such models can be calibrated to pre-conducted specific tests, they are hardly predictive as the relevant physical mechanisms are ignored.

In contrast to the above, the end objective with the current work is to build a framework for physically based modelling of compressive failure at the mesoscale level, i.e. at the level of individual plies, that can be adopted for industrial crash analysis. As a first step, presented in this contribution, a progressive kinking model has been developed. In the second step, the intention is to complement the kinking model with a model to predict final failure on a component scale.

The resulting longitudinal, compressive stress-strain behaviour from the present model after kink initiation is shown in Figure 1b. In particular, the graph shows the model response for different levels of superimposed constant shear stress. From the results, it can be seen that after kink initiation at the maximum stress level a rapid decrease in stress occurs. This behaviour has a lot in common with the physically based kinking models referred to above. However, in contrast to these, in the present model the stress reaches a minimum value and starts to increase again at larger strains. This stress increase represents the compaction of the material after kinking. This is an important feature to facilitate the modelling of continuous crushing, in the sense that when the stress increases at large compaction compressive failure in neighbouring finite elements can be initiated. However, as previously mentioned a complementary failure model is needed in order to predict final failure, e.g. a mechanism for out of plane shear failure will be added in future work.

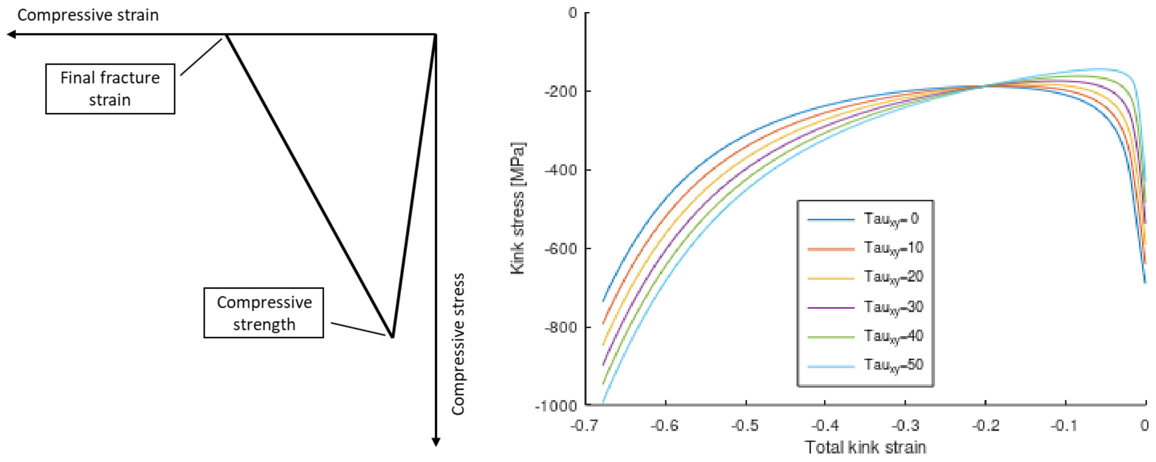

Figure 1 (a) Illustration of bi-linear stress-strain relation for fracture modelling (b) Present model kinking stress versus compressive strain relation for different levels of shear stress

In more detail, the basic idea of the kinking model is very similar to the well-known kinking model by Budiansky and Fleck [4]. Prior to kinking, the material behaviour is described as transversely isotropic, linearly elastic. Further, kinking initiation is then predicted by a failure criterion inspired by the Budiansky-Fleck model. Subsequently, during kink band formation (and evolution) the model response is calculated based on stress equilibrium of fibres rotating in a kink band under large shear deformations. However, in the present work a different choice of kinematics has been made, which leads to more physical stresses in the local fibre and transverse direction in the kink band for large deformations. It also results in the already demonstrated minimum of the predicted global kinking stress, followed by a subsequent increase to represent compaction. Interestingly, the fibre rotation in the kink band at minimum compressive stress is very similar to the lock-up angle in the kink band as measured from experiments.

For the case when the element size is larger than the width of the kink band, kink band broadening is implemented based on the model in [4]. The kink band width grows under constant kinking stress until it spans the full element and then the kink stress increases.

The kinking model has been implemented in Ls-Dyna as a user material. Results to be shown at the conference will include basic compression and bending examples that demonstrates the ability to model subsequent compressive failure of neighbouring elements as well as the effect on the bending response from the residual stress after failure in compression.

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Stacking sequence optimization of composite tubes submitted to crushing using the discrete ply model (DPM)

In the aviation industry, there has been an increased interest in utilizing CFRP (Carbon Fiber Reinforced Plastic) structures due to their high strength-to-weight ratio. The behavior of composite structures subjected to crushing, therefore, becomes a subject of immense importance.

The development of numerical modeling techniques for composite structures has been a necessity due to a few important factors (a) Physical testing is costly and time-consuming (b) Manufacturing quality of parts affects the results (c) It is often of interest to vary as few of the parameters as possible while studying the effect of change in geometrical or material properties on the crushing response, which is not always possible with physical tests. For this work, the Discrete Ply Model has been used, which is a mesoscale model composed of volume and interface elements. In DPM the ply is divided into small strips with cuts parallel to the fiber direction and interface elements are used to connect these strips, thus helping DPM to respect cracks that occur in the direction normal to the transverse direction. This ply is then connected with other plies using a second set of interface elements, thus giving DPM the flexibility to model both matrix cracking and delamination, while giving DPM the ability to also model degradation of the structure. Since it was first proposed, DPM has been used to simulate a wide variety of cases, including the crushing of composite plates, with a good agreement with experimental results.

The objective of this work is "To study the applicability of Discrete Ply modeling to the crushing of composite tubes and subsequently use DPM to study the effect of stacking sequence and trigger geometry on the energy absorption by composite tubular structures submitted to crushing". DPM was first implemented in Abaqus for the case of tubular structures and validated with experimental results. Following the validation, various stacking sequences comprising 0° and 90° plies were simulated to optimize the stacking sequence with an aim of increasing the Specific Energy Absorption (SEA). A set of triggers were also tested in the simulation with an aim of increasing the SEA.

The stacking sequence [90/02/90/03/90/0/90] resulted in the highest SEA value. None of the triggers showed an increase in the SEA but for the external cone and external cylinder triggers, the plies close to the trigger walls contributed more to the SEA.

Nevertheless, these results should be taken with caution because while the DPM delivers fairly accurate results for some draping sequences, it seems less confident to simulate the trigger effect. Further simulations with different orientations, stacking sequences, and triggers will be required to improve the confidence in predictions obtained from the DPM.

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Near-site simultaneous impacts response of carbon/epoxy composite laminates

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Keywords: composite materials, simultaneous impacts, near-site impacts, damage tolerance.

Abstract

Composite structures are frequently subjected to multi-impact loads from falling hailstones, projection of foreign object debris, bird strikes, etc. These impacts can significantly reduce the residual strength of composite laminates that are vulnerable to the transverse impact loads resulting in significant damages such as matrix cracks, delaminations, and fibers breakages. Therefore, the impact-induced damage problem has attracted notable attention in the literature ([1], [2]), but such studies are usually limited to the case of a single point impact or repeated impacts. Although, in real scenarios, many structures are potentially exposed to multi-impact loading. Recently, researchers have been more interested in the case of multi-impact by distinguishing between sequential and simultaneous impacts on composite structures, where the difference is linked to the stress wave interaction (constructive or destructive interference) ([3], [4], [5]). In the present study, we also distinguish between impact in damaged and undamaged areas, which may amplify or avoid the interaction of local effects.

The main purpose of this study is to compare the sequential and simultaneous impacts behavior, in a damaged zone configuration, of a laminated composite with unidirectional carbon fibers and an epoxy matrix. The same tests have already been conducted in undamaged areas, the comparison of the two test campaigns is performed.

The experiments are carried out using a compressed air cannon developed in the laboratory and instrumented with various measurement means (pressure sensors, laser displacement sensors, high-speed camera, etc.) to allow the control of several parameters such as the number of impacts, location, time offset, speed and impact energy. The different impacts are made with steel balls of 20mm diameter on laminated plates of 8 plies $[0/45/90/-45]_s$.

Two configurations are tested: In the first configuration, two successive impacts are performed with two different cannons with a distance between impacts of 5 mm. In a second step, the tests are carried out by performing two simultaneous impacts, for the same distances between impacts as in the previous cases.

The results show that the total delaminated surface in the simultaneous configuration has on average 2.35 times more than the sequential configuration and the maximum of displacements is +36% in the simultaneous configuration for just a maximum of 4% difference in dissipated energy which confirms that combined global and local effects of the interaction between cracks propagation, stress waves and complex bending effects govern the fracture mechanisms and the damage extent. The average impact duration is 1 ms higher in simultaneous configuration which leads to more permanent deformation.

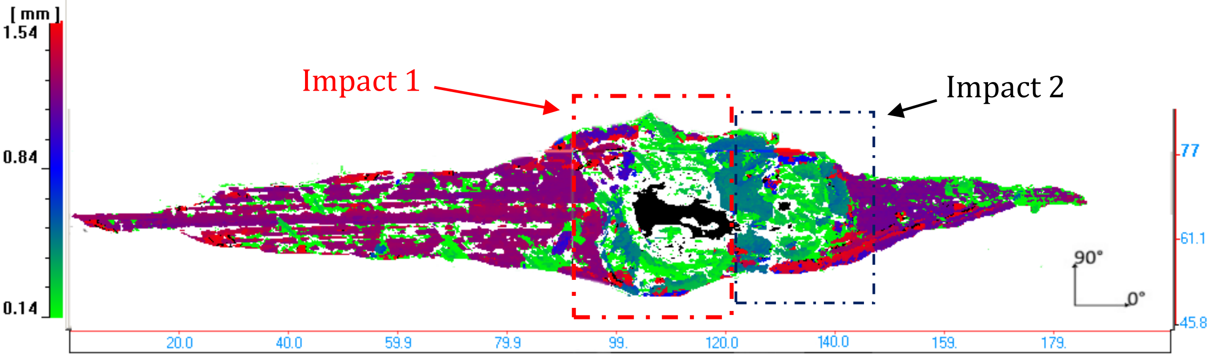

Figure 1- Configuration 2 (C-scan): 2 simultaneous impacts.

Comparing these results with another test campaign where the distance between impacts was greater, we found 1.36 times more delaminated surface in near-site (5mm) simultaneous impacts than a simultaneous configuration with a distance between impacts of 20mm due to local effects, which shows the correlation between the impact distance and the total delaminated area.

Table 1- Impact time and maximum of displacements.

Configuration	Cannon	Average impact time (ms)	Maximum of displacements (mm)	Delaminated surface (cm2)	Dissipated energy (J)
1	1	3,41	3,05	7.04	13.87
	2	3,285	2,74	8.39	14.19
2	1 & 2	5,695	4,16	30.81	14.52

The present work has shown that the response of carbon/epoxy composite laminates to simultaneous impacts test cannot be extrapolated from sequential and single impact tests. Moreover, extensive through-thickness cracks are more important when the distance between impacts decreases due to the activation of local effects as the stress wave and dynamic crack interactions.

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New materials for aircraft structures abrasion and heat protection during wheels-up emergency landings

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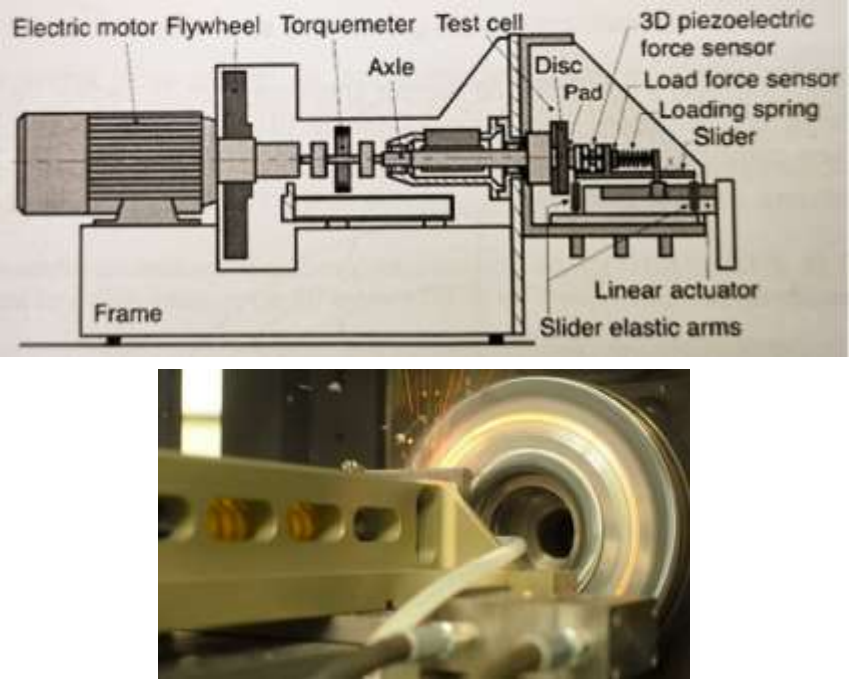
During aircraft wheels-up emergency landings, wear and heat phenomena occurring due to the dry friction between the aircraft and the runway might endanger the passengers if integral or complementary fuel tanks are concerned, and must then be protected. Thus it is important to study and characterize these phenomena: the most accessible mean at first step for solution developments consists in laboratory experiments. In the frame of the REACT'EU project ALTYLAB, and the PYROBRAS study, and in parallel to the DGAC PHYSAFE research program where a preliminary PhD work [Devo, 2021] has been performed, the proposed presentation will first briefly explain the objectives of the experimental study, then describe a laboratory test protocol which relies on the use of an existing test mean at Ecole Centrale de Lille: a tribometer system initially developed and used for high energy braking studies.



Tribometer used for abrasion tests (top) and test in progress (bottom)

Once having formulated the problem in terms of thermal and mechanical behavior of candidate material solutions, the second part of the presentation will present some new composite material solutions proposed by PYROMERAL company in order to better deal with this problematic (objective of mass reduction of protecting parts). Indeed Pyromeral Systems develops and manufactures advanced materials and composite parts for applications requiring resistance to high temperatures, friction & fire barrier. Pyromeral technologies (Ceramic Matrix Composite based on innovative ceramic matrices) are designed for continuous exposure to thermomechanical environment up to 1300°C. The 2 CMC solutions to be studied, Tactylit® and PyroSic®, offer good mechanical strength and superior resistance to abrasion, and a formulation that provides an excellent stability at high temperatures. Large-scale prototypes (more than 3 meter wingspan) can thus be produced in one shot, displaying aerospace surface quality.

Basic mechanical tests results will be first presented that are done for the CMC materials to better prepare the high energy tribological tests. They will be followed by friction test results, and their comparison with those obtained with a reference material studied in T. Devo's re PhD works (Au2024). Last, the analysis of the test results will be proposed in order to identify possible ways of improvement of the PYROMERAL material solutions, on the one hand, and of the laboratory test protocol, on the other hand.

[Devo, 2021] Tovignon W. Devo, Étude et caractérisation de l'usure et l'échauffement des matériaux structuraux aéronautiques en cas d'atterrissage d'urgence « trains rentrés » / *Study and characterization of wear and heat phenomena for aircraft's structural materials during wheels-up emergency landings*, Thèse de doctorat de l'Ecole Centrale de Lille, November 2021.

Analysis of impactor mass effect on the damage response of woven carbon/vinylester laminates by Electronic Speckle Pattern Interferometry

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The diffusion of composite materials for advanced applications in several sectors such as aeronautics, naval and automotive continues to need the development of innovative solutions to withstand particularly difficult conditions of use as well as compliance with increasingly stringent sustainability constraints.

Composite materials have interesting performance and they are used for advanced applications in several sectors, but, among their criticalities, they have a relatively low resistance to impact events and the consequent internal damage is often not visible to the naked eye. Commonly, this disadvantage produce a significant reduction of the mechanical properties and composites residual strength.

In the past, some authors [1,2] analysed the effect of the most important impact parameters on the responce of composite structures. Several papers [3-5] deal with the study of the impact parameters effect on the damage start and evaluation in carbon/epoxy laminates evaluating also the residual strength after the impact [6]. This is an important aspect for aeronautic structures since damage tolerance is a critical factor in their design requirements. Knowing if the damaged panel in service can continue to work or if it is required to replace the component is crucial. The issue can be attributed to the difficulty of inspecting internal damages, which are very complex, as usually deriving from the combination of different damage modes, and often not visible [7,8] even when substantial reductions in mechanical performance occur.

Most of the experimental efforts are focused on constant mass methods. The impact velocity is usually modified by varying the height of the impactor altering the strain rate with effects on the behaviour of the composite laminates depending on their architecture [9].

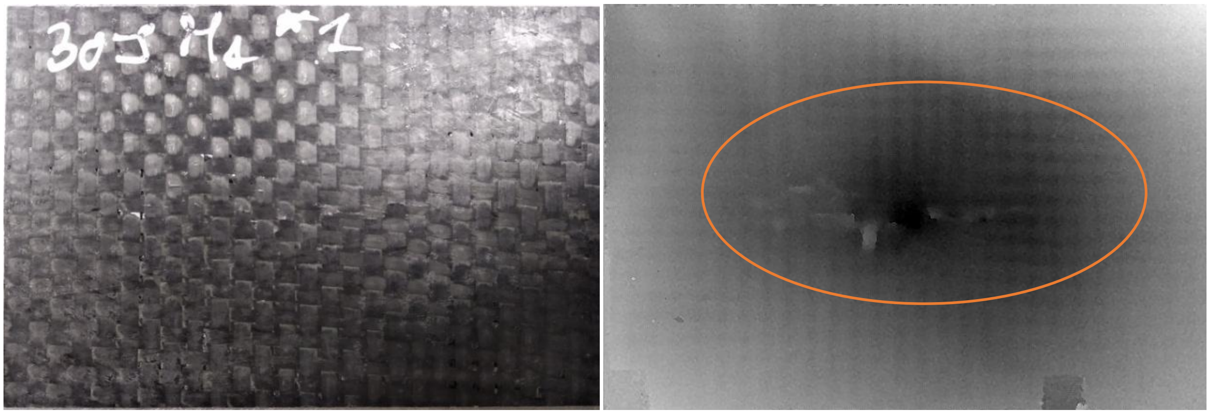

Fig.1 ESPI detection damage for CFRP/vynilester sample impacted at U=30J

Few articles, on the other hand, have analyzed the influence of the impactor mass on the response of flat laminates impacted at low velocity, but some aspects are still not completely cleared. For example, controversial considerations are reported regarding the effect of impactor mass on the dynamic behavior of epoxy-based laminates containing carbon fabric and no work is available on vinylester-based composites. Therefore, the present contribution discusses the influence of impactor mass on impact behavior and damage response of vinylester / carbon laminates using three different impactor masses at one energy level (U = 30J).

Damage inspections were performed by speckle interferometry (ESPI) technique (Fig.1). Results are compared to the absorbed energy in order to relate the damage effects with in-plane and through-thickness delamination evolution.

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A method for the efficient modelling of delamination in large structures

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Abstract

Capturing delamination is essential to correctly evaluate the crashworthiness of composite materials. Cohesive zone modelling associated with layerwise modelling, where each layer is represented with elements, is currently the most popular option to simulate laminate delamination. However, on top of the out-of-plane refinement, this method entails a fine in-plane discretisation (typically smaller than 1 mm) so that the interface fracture process zone is represented by several cohesive elements [1]. As a result, the conventional approach leads to an unbearable computational cost when it comes to large assemblies.

The present work aims to develop an efficient modelling strategy to enable the dynamic simulation of large structures undergoing delamination. To do so, a Stress Recovery method is used to evaluate transverse stresses in simple shells [2], allowing to detect delamination in an unrefined state. Where necessary, the model is enriched with additional nodes to kinematically describe the interface discontinuity [3, 4]. The delamination propagation is modelled with elements much larger (typically from 2 mm to 8 mm) than the fracture process zone, thanks to a novel ERR-Cohesive method [5]. In this latter method, crack propagation is assessed by an estimation of the energy release rate based on the Virtual Crack Closure Technique, while the progressive opening is ensured by a nodal cohesive law dissipating the appropriate amount of energy (for any mode mixity).

The method has been implemented as a user subroutine for explicit finite element simulations with the commercial software LS-DYNA. The accuracy of the present method will be assessed in several numerical examples and compared either to analytical solutions, or to refined solid models with cohesive zone modelling. The ability of the method to detect and propagate delamination with large elements is demonstrated, opening possibilities for the crashworthiness assessment of large structures.

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MEASUREMENT OF DAMAGE APPEARANCE AND GROWTH DURING LOW VELOCITY IMPACT TESTS BASED ON HIGH-SPEED INFRARED THERMOGRAPHY

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Keywords: Infrared thermography, Impact tests, Damage, Composite materials

ABSTRACT

The measurement of damage appearance and propagation during a low velocity impact test is still a challenging task. Only few studies deal with the characterisation of damage appearance during low velocity impact tests [1,2] with in-situ measurements. Moreover, in these studies, damage appearance and propagation is monitored with low frequency infrared cameras (f < 1kHz). Consequently, only the extent of damage after the impact test is accurately captured, but the damage scenario cannot be evaluated due to the small amount of images captured during the loading of the plate. In order to obtain more information on the damage scenario and its relation to the load applied to the composite plate, a fully coupled in-situ measurement during low velocity impact tests has been developed in this study. For that purpose, two high-speed Infrared cameras have been used to monitor damage appearance during the impact test. The camera with the higher acquiring frequency (Telops Fast M3k) has been used to monitor the rear face opposite to the impact. The frame size used for this camera was 128 pixels x 100 pixels with an acquiring frequency of 12500 Hz. The tests have been performed for 4 different energy levels: 6.5 J, 11 J, 20 J and 35 J on a quasi-isotropic stacking sequence made from T700/M21 UD plies. For the different tests, the infrared camera measurements allow to link the load applied to the composite plate to the first crack appearance on the opposite face, to the delamination growth observable on the opposite face and to the compressive failure observed on the impacted surface.

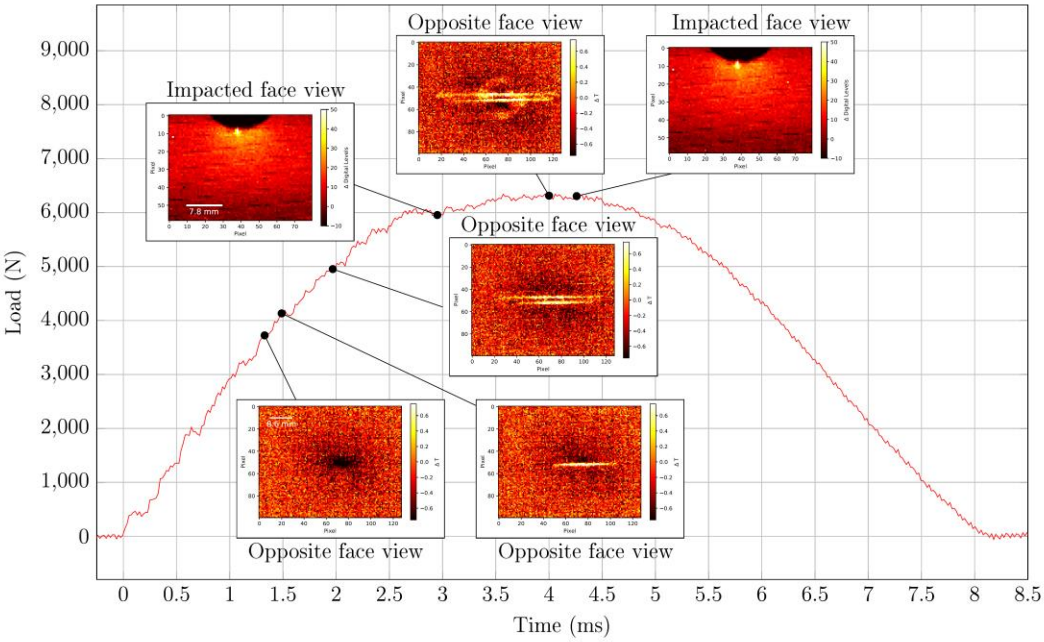

Figure 1: Analysis of the damage appearance and growth observed with the two infrared cameras for a 11 J impact test.

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HIERARCHICAL INTERFACES AS FRACTURE PROPAGATION TRAPS IN NATURAL LAYERED COMPOSITES

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ABSTRACT

Compared with their monolithic version, layered structures are known to be beneficial in the designing of materials, especially ceramics, for enhanced fracture toughness, mechanical strength, and overall reliability. The source of property enhancement is the ability of layered structures to deflect and often arrest propagating cracks along internal interfaces between layers. Similar crack stopping abilities are found in nature for a broad range of fibrillary layered structures. The simultaneous occurrence at several scales of different types of interfaces, designated here as hierarchical interfaces, within judiciously designed layered biological composites, is a powerful approach that constrains cracks to bifurcate and stop. This is examined here using selected biological examples, potentially serving as inspiration for alternative designs of engineering composites.

Keywords: Interfaces, natural composites, layered structures, crack deflection, fracture arrest.

INTRODUCTION

The issue considered in the present communication, in a mostly observational and qualitative way, deals with sophisticated design solutions offered by specific natural architectures to the problem of stalling fracture propagation in layered composite structures. The interest in this problem, extensively examined over the last few decades, originated in the brittle nature of engineering ceramic materials under tension or bending but which otherwise offer excellent thermomechanical properties. Indeed, modern structural materials are often used in critical applications such as aircraft jet engines, where reliability is the key property and thus sudden, unstoppable fracture is unacceptable. It is only recently that physics- and materials-based research has heavily dealt with the quest for materials and/or structures possessing high simultaneous strength and toughness (Launey & Ritchie, 2009). Remarkably, such structures are often found in nature. Here, an account is given of less well-known design patterns produced by nature to generate crack bifurcation and arrest in complex layered structures.

RESULTS AND CONCLUSIONS

Recently we investigated the microstructural features of the Scorpio maurus palmatus (SP)(Greenfeld et al., 2020). High-resolution scanning and transmission electron microscopy (SEM and TEM, respectively) and atomic force microscopy (AFM) images of the cylindrical SP tibia cuticle revealed an unusual Bouligand architecture. It included varying chitin-protein fiber orientations, including in-plane twisting of laminae around their corners rather than through their centers, and a second orthogonal rotation angle that gradually tilts the laminae out-of-plane. The resulting Bouligand laminate unit (BLU) is highly warped, such that neighboring BLUs are tightly nested and mechanically interlocked. SEM images revealed that moving radially from the external side of the cylindrical cuticle down to its hollow core, the layers become increasingly thinner (Figure 1).

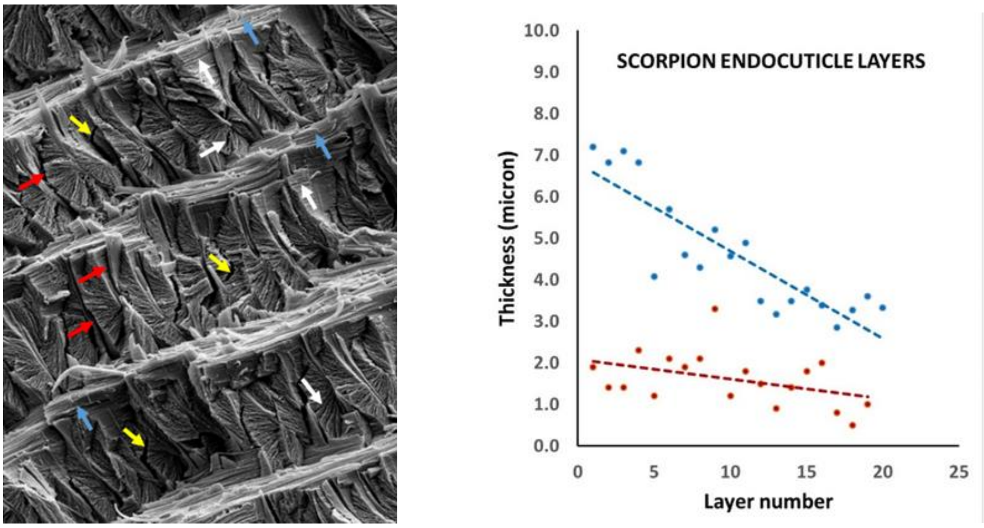

Fig. 1 - (**Left**) Scanning electron microscope imaging of the scorpion layered endocuticle and Bouligand laminate units (BLU) layers. White, red and blue arrows point to different interfacial failure types termed here hierarchical interface failures: White, interlamellar (nanoscale) within BLUs; Red, intralayer (microscale) between BLUs; Blue, interlayer (microscale) between layers; Yellow arrows designate non-interfacial (Griffith) internal cracks within BLUs. (**Right**) Endocuticle layer thickness (blue symbols) against distance from the external side of the cylindrical cuticle (layer 1) down to its hollow core (layer 20). The much smaller interlayer thickness (red symbols, from 1 to 19) is plotted for comparison.

By comparison, in the silica sponge spicule, the thickness of silica sponge layers diminishes with radial distance from the core, reaching a minimum value at the outer surface where, under bending, the stress is highest and tensile in nature (Monn et al., 2015). In the scorpion cuticle, however, the minimum thickness of the layers is at the core (thus the inner surface), likely because when a scorpion undergoes sharp blows or indentations from unfriendly incidents, the highest stress occurs at the core and is again tensile. Since for layered architectures the stress needed to cause cracking of an individual layer of thickness t is proportional to $t^{-1/2}$, the thinnest layer should have the highest strength. Thin layers also significantly limit the depth of straight crack penetration into the structure interior. The key point is that layer thickness variations appear to be a natural consequence of increased applied stress to the scorpion cuticle and sponge spicules. In addition, strength no longer depends on size if a characteristic dimension of a structure is smaller than a certain critical length scale (Gao et al., 2003). In other words, at that point, nature needs not generate thinner layers.

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2nd European Conference on Crashworthiness of Composite Structures
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Physics-based drone impact analysis of composite aerostructures

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Abstract

Steadily increasing sales and operation numbers of privately piloted lightweight hobby drones also increase the likelihood of collisions with larger aircraft operating in the same airspace, especially in areas beyond restricted commercial flight paths. Consequently, the topic of drone collision is receiving a lot of interest by researchers to fully understand the threat and potential consequences of such an impact load case for the safety of aerostructures. While a few experimental full-scale drone impact test campaigns have been performed, e.g. by Lu et al. [1], the focus of most research groups is on simulative studies to efficiently assess variations in impact location, angle or velocity. In contrast to simplified drone models developed by Warsiyanto et al. [2] or Schroeder et al. [3], physics-based modelling of drones builds up on the full experimental characterisation and physical representation of the drone components' failure behaviour to derive accurate, predictive simulation models for impact analyses. This paper describes extensive test campaigns that were performed to characterise all relevant components of a common lightweight hobby drone under quasi-static and impact-dynamic loads, the development of a respective finite element (FE) simulation model in Abaqus/Explicit and drone impact simulations of a large-scale composite aerostructure, i.e. an aircraft radome made of composite sandwich materials.

The drone type was selected to be the DJI Mavic 2 Zoom, one of the most sold consumer products in the quadcopter segment, which has a weight of 0.9 kg (Fig. 1). The drone components and joints were tested in all relevant orientations under quasi-static loads first (Fig. 2). While a rather linear behaviour was observed for the motors, nonlinear and even complex failure behaviour is visible for the camera, batteries and arms. High-velocity gas gun impact tests of batteries and motors onto instrumented plates were performed next. Whilst under quasi-static conditions the motors are stiffer and stronger than the batteries, impact tests at velocities ranging from 100 to 150 m/s revealed that due to the high mass of the batteries (battery: 292 g, motor: 30 g), the forces generated during an impact event are significantly higher for batteries than for motors (Fig. 3). An optical 3D scanning system was used to extract geometrical data of the drone components for an accurate drone simulation model (Fig. 4). Nonlinear constitutive models were derived based on the test data and validated in component test simulations.

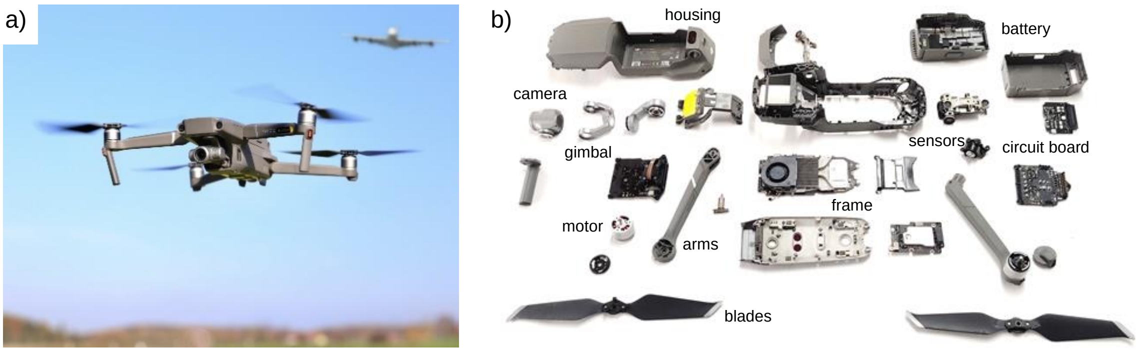

Figure 1: a) Typical lightweight drone (DJI Mavic 2 Zoom) imposing risk of aircraft collision, b) drone components for characterisation

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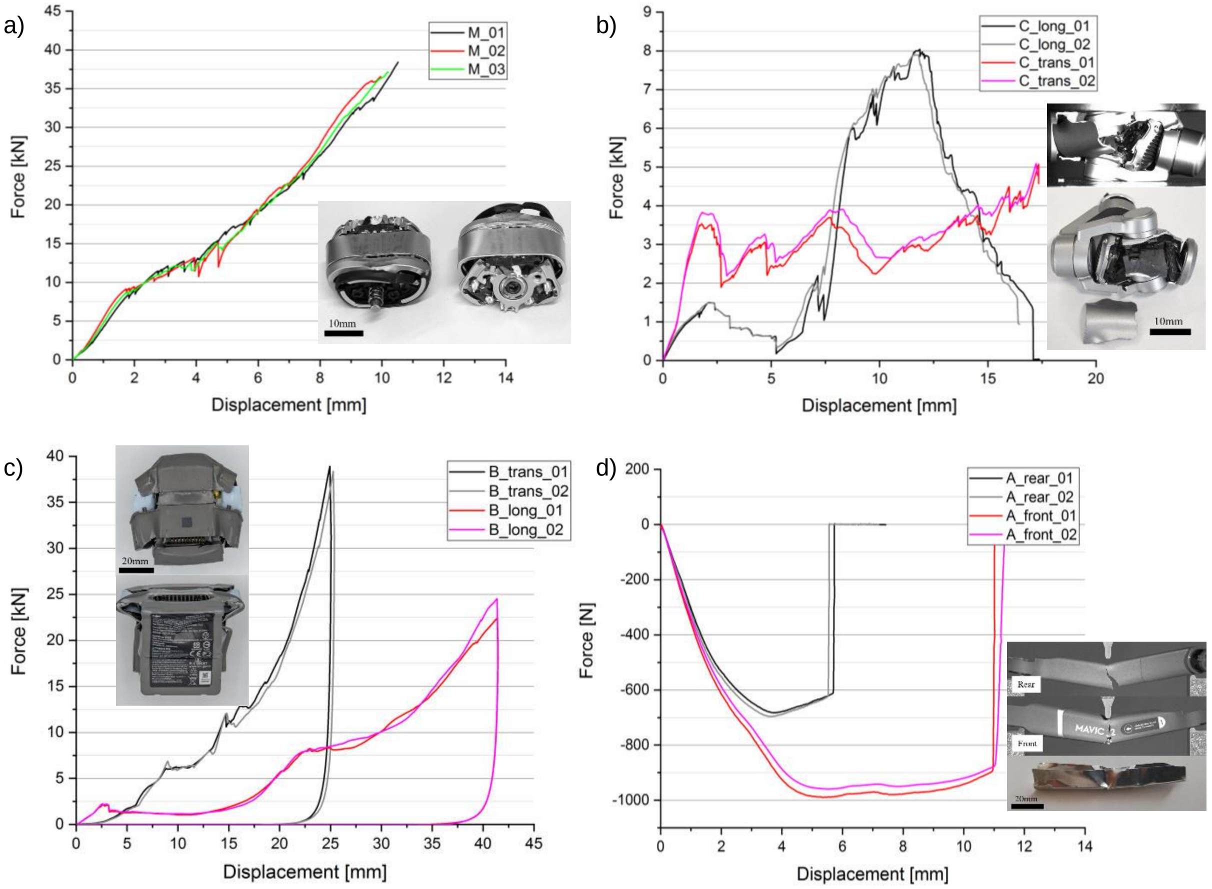

Figure 2: a) Compression testing of drone motor, b) compression testing of camera in longitudinal and transverse direction, c) compression testing of battery in longitudinal and transversal direction, d) bending and fracture testing of front and rear arms

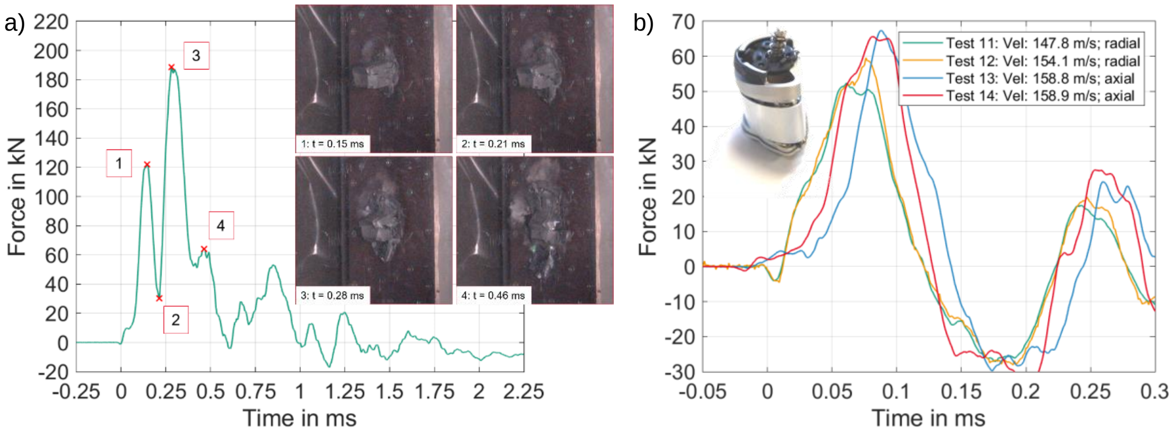

Figure 3: Force-time recording of high-velocity impact test on instrumented plate of a) battery, b) motor with different orientation

The application use case for the drone impact analysis is a generic radome as it may come into operation in a MALE (medium altitude long endurance) RPAS (remotely piloted aircraft system), such as the Eurodrone [4, 5]. It is designed to resist a bird strike impact of a 2 lbs = 0.9 kg bird, which is directly comparable to the drone weight of also 0.9 kg. The aircraft radome consists of a sandwich structure with quartz fibre-reinforced skins and a honeycomb core. In addition to the full experimental characterisation of these materials under quasi-static and high-rate dynamic conditions, impact tests on flat and curved sandwich panels were performed for a sufficiently large database for FE model validations. Finally, a bird strike test with a full-scale radome prototype of 3 m length was performed. This allowed for the accurate validation of the high-velocity bird impact simulation model to be used as basis for predictive drone impact simulations (Fig. 5).

Figure 4: DJI Mavic 2 Zoom drone geometry and FE modelling

There is a substantial difference between these two projectiles, bird and drone: while the bird behaves as a fluid without shear strength and significantly spreads during impact and flows along the structure's surface, the drone consists of many hard, metallic components that are prone to induce local failure and penetration of the thin-walled sandwich structure. For lower impact velocities the global structural response and indentation of the radome is similar for both load cases showing no penetration. But differences occurred when increasing the impact velocity. The limit velocity, when penetration of the sandwich structure occurs, turned out to be much lower for the drone. Fig. 5 shows two simulations with identical impact velocity and impact energy, where the bird flows along the surface but the drone penetrates. The assessment of structural damage of these simulations reveals further differences. While the area of honeycomb core shear damage is significant for both load cases and slightly differs in size and shape, fracture damage of the composite skin only occurs in the drone collision load case. Since such high impact velocities are at the limit or exceeding the sum of typical MALE RPAS speed and maximum drone speed, it is worth mentioning that the initial radome design is resistant against both impact load cases.

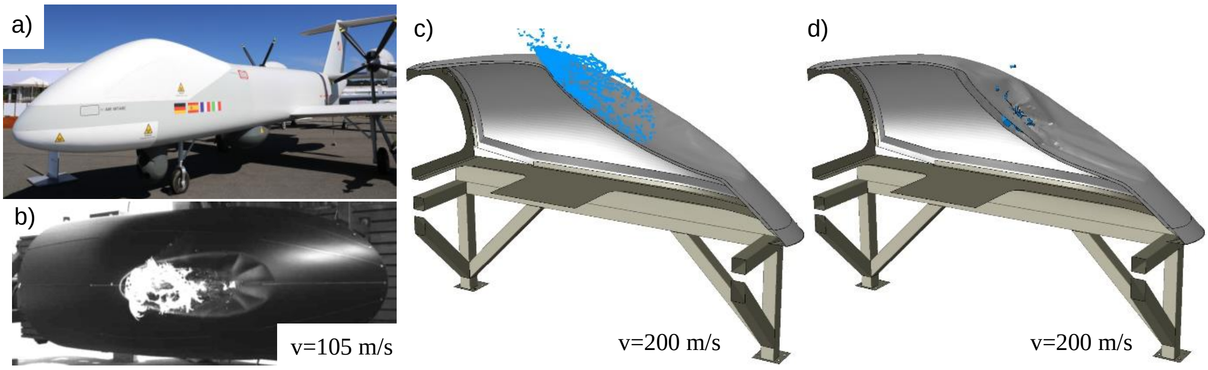

Figure 5: a) MALE RPAS aircraft, b) bird strike test on radome, c) sectional view of bird strike simulation showing no penetration, d) sectional view of drone collision simulation with penetration of sandwich skin

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Acknowledgements

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On the crashworthiness properties of plywood

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Keywords*:* Crash, wood, compression after impact, sandwich

1 General Introduction

Wood is a serious candidate for a sustainable transportation industry because of its light weight, its low embodied energy, its availability and its ability to store carbon. It is, in fact, a rediscovery because wood was used at the beginning of automobile construction, ship building and aviation [1]. A summary of the recent research works on the crashworthiness of plywood alone or sandwich with a plywood core is presented in this abstract. Firstly, the impact [2] and Compression After Impact (CAI) behaviour are showed [3]. Some configurations show a very low knowdown factor (less than 10 %) under CAI. Following these good results, static and dynamic compressive tests were conducted on tubes made of plywood (with poplar, birch or oak veneers) or sandwich tubes with the same species for the core and carbon or glass skins [4-7].

2 Impact and Compression after impact of sandwich panels with a plywood core

Sandwich panels with two different types of plywood and four different skins (aluminum and glass, CFRP, or flax reinforced polymer) are tested under low-velocity/low energy impacts at 5, 10 and 15J. the plywood structure with glass fiber skin fabricated by the thermo-compression process seems to present a good compromise between absorbed energy (close to that of the material with flax reinforced skins) and permanent indentation (close to that of the structure with carbon reinforced skins). Following the plywood with glass skin, the plywood with flax skin, which is bio-based, offers a good compromise between energy absorption and specific energy absorption due to its lower density. In conclusion, the development of these structures with plywood cores seems to be a good solution regarding impact concerns.

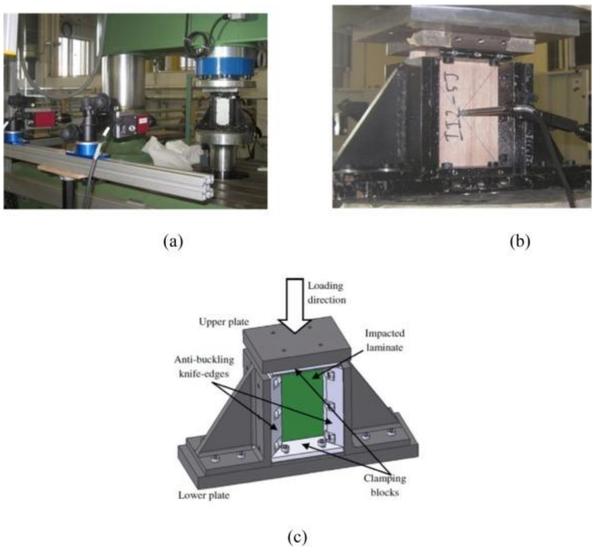

Figure 1: Compression After Impact test, a) On front side using stereo correlation, b) On rear side using LVDT, c) Whole test set-up.

One of the most interesting points highlighted by this study is a long plateau for plywood, flax composite skin and aluminum skin structures, which characterizes progressive damage in both pristine and impacted samples and shows great accommodation to the stress. These results suggest that ductile materials should be used in skins to dissipate a maximum of energy, especially for crash-type applications. Plywood structure with glass skin is found to provide the best compromise between residual strength and stiffness reduction. Plywood with flax skin, which could be produced from bio-resources, is identified as another good compromise solution based on factors such as residual stiffness, strength reduction, specific properties (stiffness and strength) and eco-aspects. In general, these structures have a very good specific compressive strength and a very good specific compressive strength after impact. These results show that these structures with plywood cores have great potential for use in the transport field - and for a cost 20 times lower than the reference sandwich. Optimization is needed with regard to both stacking and the choice of plywood species, as well as with regard to the manufacturing methods and the bonding of skins to plywood in particular.

3 Static and dynamic crushing of wood-based tubes

Static and dynamic crushing tests were carried out on laminated tubes made from veneer plies of poplar, oak and birch. The tubes were designed to have roughly the same volume of wood although this generated a different number of interfaces due to the different ply thicknesses. It appears that birch has a higher absorption capacity than oak and poplar. The energy absorbed dynamically by birch for the same volume of wood is + 105% compared to poplar and + 27% compared to oak. A large part of this was certainly due to the anatomy of the oak veneers, which had very significant defects linked to vessel diameters being large in comparison with the thickness of the veneers, and the presence of multiseriate woody rays. The behaviors in static and in dynamic conditions are relatively close except in the case of oak, for which there is an absence of plateau in static tests – certainly due to its brittle behavior. The dynamic Specific Energy Absorption values are 32 J/g, 35.5 J/g and 38.5 J/g on average for poplar, oak and birch, respectively and are reprted of figure 2. The energies absorbed in dynamics are 1581 J, 2544 J and 3245 J on average for poplar, oak and birch, respectively. These characteristics, which are quite comparable with those of tubes made of composite materials show that these materials are serious candidates for energy absorption at low carbon cost and with renewable materials.

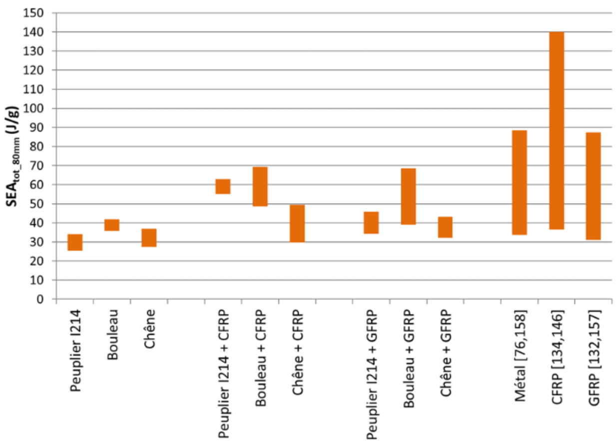

Figure 2: Specific Energy Absorption for different species and tubes

The same hierarchy is found with tubes with carbon or glass skins and a core make of veneer plies made of poplar, birch and oak. The best result was obtained with a birch core and carbon skins with 7000 J absorbed. Moreover, by changing the number of birch internal plies from 2 to 6 the energy absorbed is twice which demonstrate the significant contribution of the birch core to energy absorption.

3 Conclusions

The study demonstrates that poplar and birch, which are very cheap and available species are very good candidates for crashworthiness while diminishing significantly the CO_2 emission, been renewable, and fulfilling the requirements of circular economy.

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Investigation of the ballistic performance of multi-material protection systems

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Ballistic protections usually result from an incremental and empirical approach and accordingly strongly depend on the experience and know-how of the manufacturer. Yet, in order to improve their specific ballistic resistance, current ballistic protections are more and more complex, based on functional, multi-layer and multi-material systems, and thus require the optimisation of a great number of parameters (e.g. layering order, thicknesses, number of layers, etc). In this context, numerical simulation-aided design has become indispensable.

An engineering ballistics-oriented methodology based on the correlation between experiments and simulations is under development. It has proven efficient for bi-layer protection systems, see Cosquer et al. (2021), and still needs to be applied to more complex configurations.

In this aim in view, an experimental campaign has been conducted on multi-material protection systems consisted of assemblies of plates made of ceramic, metal or/and fiber reinforced polymer fabric, each material having its own function in the protection system. In the framework of a calibration and V&V approach, impact tests were carried out employing ICA STIMPACT impact facility (3 gas launchers and their high-speed diagnostics) on ceramic/metal, metal/fabric and ceramic/metal/fabric protection systems. The interaction between the projectile and the protection systems was video-recorded using high-speed cameras, and residual velocity vs impact velocity curves were plotted for estimating the ballistic limit for each configuration.

A first attempt of numerically reproducing the experimental results was then made employing the finite element computation code Abaqus-Exp and using the engineering nonlinear constitutive models implemented by default in it.

Experimental results will be presented and commented and the limitations of the numerical simulations and ways of improvement will be discussed.

Cosquer Y., Longère P., Pantalé O., Gailhac C., 2021, Optimisation of ballistic protection systems based on impact test/simulation correlation, EPJ Web of Conferences 250, 04001

TEST METHODS FOR DYNAMIC CHARACTERIZATION OF POLYMER-BASED COMPOSITE MATERIALS

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When advanced polymer-based composite materials are to be used in aeronautical structural components, a design development program is generally initiated during which the performance of the structure is assessed prior to its use. Typically, the process of design starts with the analysis of a large set of simple small specimens and, when sufficient knowledge is acquired at this level, it is changed over to a more complex structure but carrying out fewer tests. This methodology is quite mature and well stablished for static loads, and even, for fatigue loads. However, for intermediate and high dynamic loading conditions, the test methods are still under development and often limited to academic research levels, without any type of standardization even for basic material characterization. Indeed, the literature is very scarce, and, in some cases, there is no clear consensus between authors for a given property. This experimental limitation occurs in any associated task, which are the adequate definition of: specimens, test setup (including the test machine to be used, the instrumentation, and the clamping system), and the data reduction methods. Therefore, the need for well-designed dynamic test methods is of clear interest.

The European Clean Sky project *"BEDYN - Development of a methodology (test, measurement, analysis) to characterize the BEhaviour of composite structures under DYNamic loading (GA. 886519)"* is focused, in part, on the definition of well suited experimental tests at coupon level for a whole characterization of polymer-based composite materials under dynamic loading. A definition is purposed at each of the large number of material properties that must be characterized to later simulate a composite structure accurately. In the present communication, an overview of the test methods considered for the dynamic characterization of a unidirectional tape of epoxy/carbon fibre prepreg material and an epoxy adhesive film will be described. Different coupon geometries will be used to obtain the different properties at desired strain rates. The tests considered are summarized in Table 1 and Table 2.

In addition to the basic characterization, it will be also analysed the dynamic loading on notch effect (size effect), flexural behaviour and the bearing effect. Accordingly, dedicated specimens and test setups are designed, all summarized in Table 3 (called *Element,* i.e. small size demonstrator). The scope of these tests are: two stacking sequences, two notch sizes and two fastener diameters for bearing tests. For all tests considered, the use of the SHPB bar will be required for both compressive and tensile configurations. Two different strain rates, plus static tests will be performed. The use of the Split Hopkinson Pressure Bar (SHPB) bar will be required for both compressive and tensile configurations. The specimen sample considered for each test configuration will be of 3+1 specimens.

Table 1: Coupon specimens I/II.

Type	Tester	Reference	Results
Longitudinal compression	SHPB-C	Ploeckl et al. (2017) [1] BEDYN research	E_{11C}, ν_{12}, X_C
Transverse and off-axis tensile	SHPB-T	Kuhn et al. (2015) [2] Quino et al. (2020) [3] BEDYN research	E_{22T}, ν_{12}, Y_T Failure envelope: σ_{22T} - σ_{12}

Transverse and off-axis compression	SHPB-C	Koerber et al. (2010) [4] Ploeckl et al. (2017) [1] BEDYN research	E_{22C}, Y_C Failure envelope: σ_{22C} - σ_{12}

Table 2: Coupon specimens II/II: interlaminar and adhesive bonded joint specimens.

Type	Tester	Reference	Results
Double Cantilever Beam - Pure mode I (DCB)	Instron servo hydraulic dynamic	AMADE-UdG procedure (see Fig. 3)	G_{IC}: onset and propagation, interlaminar and adhesive bonded joint
End Notched Flexure - Pure mode II (ENF)	SHPB-C	Lißner et al. (2020) [5] Shamchi et al. (2022) [6] BEDYN research	G_{IIC}: onset and propagation, interlaminar and adhesive bonded joint
Single Leg Bending Test - Mixed-mode 41% (SLB)	SHPB-C	Lißner et al. (2020) [5] BEDYN research	$G_{\%C}$: onset and propagation, interlaminar and adhesive bonded joint
Butt Joint (BJ)	SHPB-T	Neumayer et al. (2016) [7] BEDYN research	τ_I: pure mode I strength adhesive bonded joint
Single Lap Shear - SLS	SHPB-C	BEDYN research	τ_{II}: pure mode II strength adhesive bonded joint

Table 3: Element type specimens.

Type	Tester	Reference	Results
Three point bending (3PB)	SHPB-C	Zhang et al. (2012) [8] BEDYN research	Flexural strength
Filled Hole Tension (FHT)	SHPB-T	BEDYN research	Notch effect: Remote strength
Filled Hole Compression (FHC)	SHPB-C	BEDYN research	Notch effect: Remote strength
Compact Tension (CT)	SHPB-T	Hoffman et al. (2018) [9] BEDYN research	Notch effect: G_C translaminar fracture toughness. A cross-ply laminate is considered for G_{X_TC}
Composite-aluminium bolted joint (Bearing)	SHPB-T	BEDYN research	Bearing: Remote strength

This work has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No. 886519. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.

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EXPERIMENTAL TESTING AND NUMERICAL SIMULATION OF MODE II AND MIXED-MODE CRACK PROPAGATION UNDER DYNAMIC LOADING

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Crack propagation in adhesive joints between two adherents as well as, interlaminar crack propagation, are commonly characterised under different loading scenarios such as in mode I, mode II and mixed mode, following a quasi-static test. Especially, the failure strength and the fracture toughness are key parameters to be determined [1]. Under dynamic conditions, most research has made use either of hydraulic testing machines, or especially, the Split Hopkinson Pressure Bar (SHPB) [1–3].

Currently, it has been reported that there is a significant dependence of the material properties, especially the fracture toughness, due to the strain rate [1]. However, work dealing with crack propagation under dynamic loading is still scarce. Besides this, the majority of the methods to obtain the fracture toughness from experimental tests are meant to be used with quasi-static scenarios. Consequently, it is unclear not only how to perform the tests, but also the data reduction method to apply. A further complication is to ensure that the inertial effects are not affecting significantly the measurements. Recently, two different methods have been published to obtain the fracture toughness in dynamic tests using the SHPB [1, 2]. One option is to use strain gauges to obtain the strain signals from the incident and transmitted bars in the SHPB in order to compute the force [2], while the displacement of the specimen can be obtained by using high speed cameras [1, 2]. Alternatively, Lißner et al. [1] used digital image correlation to track the displacement and the crack length during the tests. Afterwards, based on beam theory, the load-displacement response is derived.

The current literature shows that there is no clear methodology to obtain the interlaminar strength and fracture toughness or that of adhesive joints under dynamic loading. Moreover, the influence the strain rate has on the fracture toughness and strength is unclear. In this work we will employ the SHPB technique to test an End Notch Flexural specimen (ENF, for mode II) and a Single Leg Beam (SLB, for mixed mode) under dynamic conditions, see Figure 1. Two cases are considered, in one case we analyse interlaminar crack propagation, while the second case corresponds to a bonded joint. The fracture toughness is obtained as a function of the strain rate. Two different approaches are used to compute the fracture toughness [1, 2] and their validity is discussed. A finite element model was developed to design the real experimental tests (Figure 1) and verify that it is convenient to obtain the fracture toughness without significant inertial effects. The experimental tests are carried out based on the finite element model, and the predictions obtained to design the tests are verified.

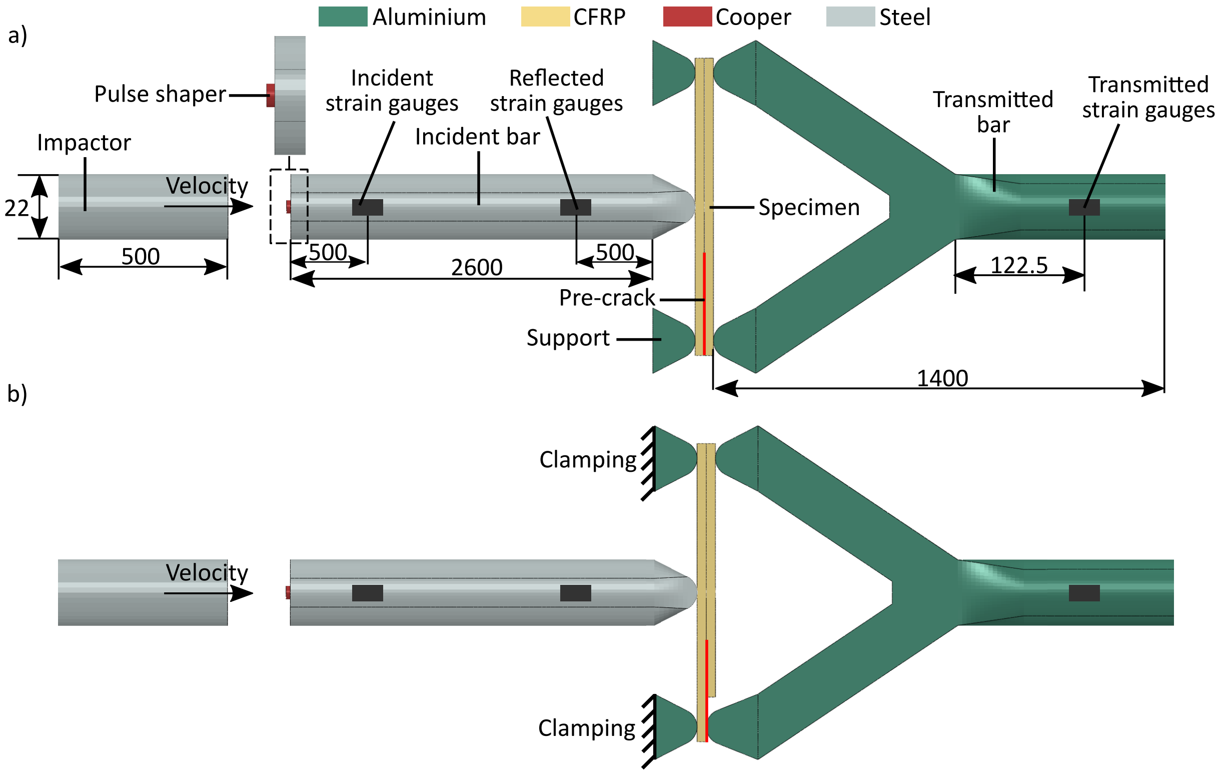

Figure 1. Schematic representation of the split hopkinson pressure bar test. a) Mode II crack propagation with ENF specimen and b) mixed-mode crack propagation with SLB specimen.

This work has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No. 886519. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.

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FREE EDGE STRESS ANALYSIS OF COMPOSITE LAMINATES SUBJECTED TO LOW-VELOCITY IMPACT USING HIGHER-ORDER LAYER-WISE MODELS

Authors: S. Saputo,M. Nagaraj, A. Pagani, M. Petrolo, E. Carrera

Composite materials are reinforced structures to obtain lightweight aircraft primary structures with high flexural stiffness and resistance to buckling phenomena. Although reinforced panels represent a viable design avenue for obtaining high strength-to-weight ratio structures, they may be extremely sensitive when subjected to impact phenomena. Furthermore , when subjected to low-velocity impact, such materials can suffer damages that vastly reduce their load-bearing capacity and may not be detected by visual inspection. For example, accidental dropping of tools during manufacturing or maintenance can create more complex failure mechanisms if they involve the free edge of the reinforcement compared to the panel. The difference in elastic properties among two adjacent laminae causes a concentration of stresses, known as the free edge effect [1]. In other words, a three-dimensional stress concentration can appear at the interface of two laminae near free edges. The prediction of the stress state of a composite structure subjected to an impact phenomenon or the evaluation of stress intensifications due to the free edge effect cannot be accurately predicted using classical laminate theory (CLT) as it does not consider the out-of-plane strain components [2]. This effect is emphasized even more when the structure is subjected to impact, and out-of-plane stresses become predominant [3-4].

The numerical approaches adopted in this work introduce higher-order structural theories based on the Carrera Unified Formulation (CUF) [5], a modelling strategy capable of generating one-dimensional and two-dimensional models with kinematic descriptions expressed by functions of higher-order expansions on the cross-section or through-the-thickness (2D case). Introducing more complex kinematic models allows the creation of numerical models of refined beams and plates capable of accurately evaluating the 3D stress state. Within this context, the proposed research introduces a numerical model based on the CUF in conjunction with the layer-wise approach, where the displacement components are expanded through the thickness using the Lagrange polynomials.

The numerical formulation adopted in this work allows an accurate evaluation of the stress state, which could be subsequently used to evaluate the structural integrity. Under these circumstances, user material could be used to introduce ad hoc failure criteria to assess the damage's initiation and evolution. A possible development could be evaluating the energy dissipated in the form of delamination. The interlaminar damage can be carried out with the Cohesive Zone Model (CZM), which can also investigate the nucleation and the evolution of the delamination. To appreciate the advantages of the formulation introduced by the CUF, a further comparison was made by introducing a numerical model based on the classical theory of the laminate and performed employing commercial finite element software. The comparison between the two numerical models of the force trend diagram as a function of time before and after the displacement show, in general, a good correlation between the numerical models with more accurate detail when using the Layer-wise formulation compared to the CLT. The results show the numerical efficiency of the proposed formulation if compared to 3D solid elements without accuracy loss.

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Type : **Oral presentation**

Effect of seawater aging on the in-plane and out-of-plane impact of C/Epoxy composites

Due to their excellent properties in a marine environment (high specific stiffness, low corrosion, flexible manufacturing, good fatigue performance), composite materials are increasingly being used in marine structures, from oil platforms to naval ships and submarines [1]. A recent application of Carbon Fiber Reinforced Plastic (CFRP) composites concerns propellers and turbine blades: this is a particularly demanding application, combining high stresses, cyclic loading and permanent seawater immersion. The technical feasibility of such composite propellers to replace metallic structures has been shown [2] but the mechanical behavior during an impact event after prolonged water immersion is not well known. The aim of the present study is to characterize and understand the influence of seawater aging on the in-plane and out-of-plane structural behavior of a C/Epoxy composite.

In order to do this, out-of-plane impact tests (ASTM D7136) followed by compression after impact (ASTM D7137) have been performed. Ultrasonic C-Scans show interlaminar damage initiates at a lower impact energy after seawater aging. The damage propagation is also affected by the aging as the interlaminar fracture toughness is decreased. These observations are corroborated by quasi-static mechanical tests.

In-plane impact tests have also been performed following the approach described in recent work [3]. Results of this innovative test will be presented and discussed.

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Type : **Oral presentation**

Characterization of the crash behavior of a carbon fiber reinforced epoxy

Composite materials are progressively substituting metals in high performance structures for crashworthiness applications thanks to the high Specific Energy Absorption (SEA), that allows for a significant reduction of the weight of the vehicle. Despite the high SEA, in many cases even higher than metals, the diffusion of composite materials in crashworthiness applications is slowed down by their complex behavior during crash failure.
From many researches carried out in last decades it is known that different structures made of the same material can show, in a crash test, very different failure modes and levels of energy absorption. This is due to the complexity of failure mechanisms occurring during crash, that involve delamination, fiber fracturing and interface debonding. In general, structures having small curvature radii tend to fail causing tearing of the material and with a high level of energy absorption, while structures with large curvature radii or flat geometry tend to buckle or splay, absorbing less energy.
In this research, an investigation on the failure of a carbon fiber/epoxy laminate in crash conditions has been performed, comparing the different SEA values obtained from different coupon geometries. The testing campaign has involved flat specimens tested using an anti-buckling fixture developed by the authors to run in-plane compression tests on flat coupons. The fixture can be set up to trigger two different failure modes, splaying and tearing. Similar tests have been carried out on a self-supporting sinusoidal specimen with small curvature radius having same material, layup and production process used for flat specimens. All the tests have been performed in the same conditions under impact load in a drop tower testing machine.
Test results show a significant effect of the failure mode for the flat specimens, with the tearing test causing significantly higher SEA than the splaying test. The sinusoidal specimens showed the highest SEA due to the tearing failure mode.

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Tyre Impact on Optimized Composite Wing

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Abstract

Thanks to the confidence gained in the numerical simulation methods through correlation with a wide range of tests, nonlinear “realistic simulations” are taking more and more place in the design and sizing of aeronautical components during development and Certification phases. Airworthiness Authorities agree more and more to use the “virtual testing” or “realistic simulations” as means of compliance for all the items for which an acceptable level of validation of methodologies has been demonstrated.

The main objective of the TIOC-Wing project supervised by the Topic Leader DASSAULT-Aviation is the development and the validation of criteria and a virtual testing methodology that will allow to predict the resistance of a representative stiffened composite wing panel subjected to the impact of tyre debris and the residual strength capability of the damaged structure.

This will be reached by means of a test program focused on tyre debris impact events on composite aircraft structures and using the acquired experimental data to develop and validate numerical computational tools. The Consortium of TIOC-Wing project joins expertise in composite material knowledge, testing and manufacturing, in tyre tread impact testing and numerical simulations from 3 partners: SONACA, DGA-TA and CENAERO coming from Aeronautical Industry, referenced Test Laboratory in foreign objects impact capabilities and Research and Technology Center in advanced numerical simulations.

TIOC-Wing will give the opportunity for the partners of the Consortium to enhance the level of expertise in the field of foreign objects impact aircraft vulnerability. For the industrial partners, the anticipation of such particular risks in the early stage of the development of an aircraft will reduce inherent costs due to possible modifications in a more advanced phase of the program, needed to satisfy the Certification requirements. This also enables to increase the competitiveness through innovation by the integration of advanced computational tools in the sizing loop. Decrease of development tests will have as consequence the decrease of non-recurrent costs.

Finally, during future development of the next generation of aircraft thanks to less conservative approaches, TIOC-Wing offers the means for possible optimization of design concepts and weight savings strategies with reducing the CO2 emissions."

PREDICTION OF LOW ENERGY/LOW VELOCITY IMPACT DAMAGES IN A LATEST GENERATION OF CARBON-EPOXY LAMINATES

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Keywords: Impact, damage and failure approach, Finite elements simulations

ABSTRACT

In aeronautics, composite laminates are used for the manufacturing of primary structures, such as wings and fuselages. These structures can be subjected to low-velocity impact threats, such as tool drops, which induce damages within the parts. Thus, the sizing of composite structures must be damage tolerant for satisfying safety requirements. However, it is currently based on long and costly experimental test campaigns due to the use of phenomenological criteria for sizing in industry.

Therefore, this work is dealing with an experimental and numerical study [1] regarding the global response and strength of a new generation of carbon/epoxy toughened composite material subjected to low-velocity/low energy impact. The major objective is to provide a robust model able to predict the response of composite laminates subjected to low-velocity impact in an industrial context based on fine experimental evidences.

Experimental testing on coupons have been performed with advanced instrumentation technologies (such as infrared thermography and digital image correlation associated with superfast cameras) to monitor in-situ damage, which enhances the understanding of the chronology of damage events [2]. Additionally, 3D non-destructive evaluation methods (X-ray tomography, ultrasonic scans) have been considered in order to assess and understand the damage mechanisms in such an enhanced composite material.

In parallel, an impact model, named OPFM, has been developed and consists in a 3D finite element model using an implicit solver which takes into account contacts (impactor/composite and set-up/composite), geometrical non-linearity, transverse cracking thanks to a continuum damage model, delamination using cohesive elements and fibre failure considering a phase-field approach. A special attention has been paid to the couplings between the different damage and failure mechanisms, which have been clearly experimentally observed. Moreover, the impact tests have also been simulated with the Discrete Ply Model (DPM) developed for many years in ICA [3] in order to define the complementarity between those two damage models, considering either a continuum or a discrete damage modelling strategy.
Comparisons between the experimental results and simulations for both models are very promising, as reported in Fig 1., considering the load/displacement curves, the dissipated energy, the projected damaged area, but also considering the distribution of the damage/failure mechanisms within the composite plates.

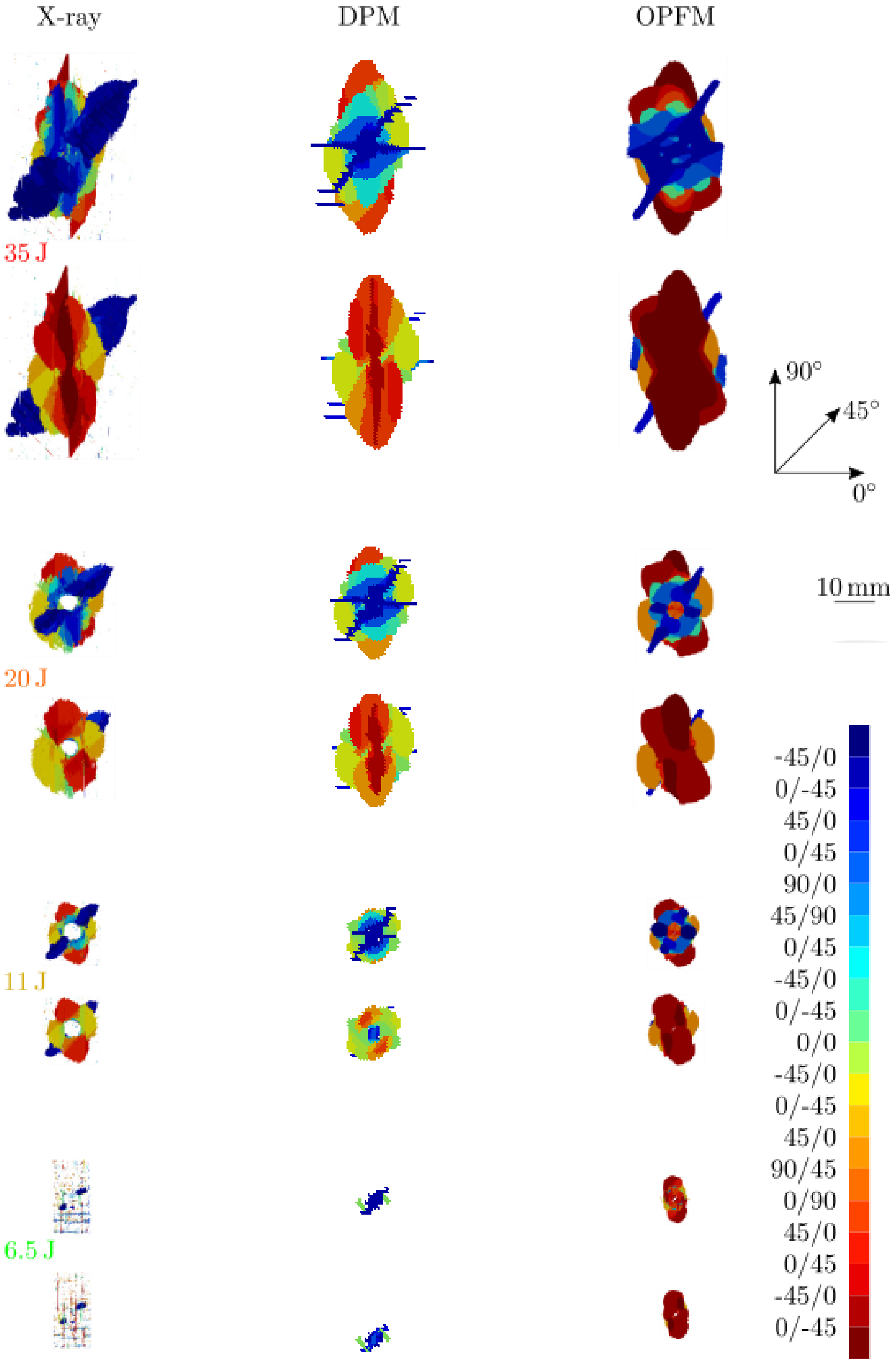

Figure 1: Projected damaged area compared for an oriented laminate.

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Numerical modeling of the crushing response of hybrid wood-filled aluminium hollow sections for highway safety barriers.

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ABSTRACT

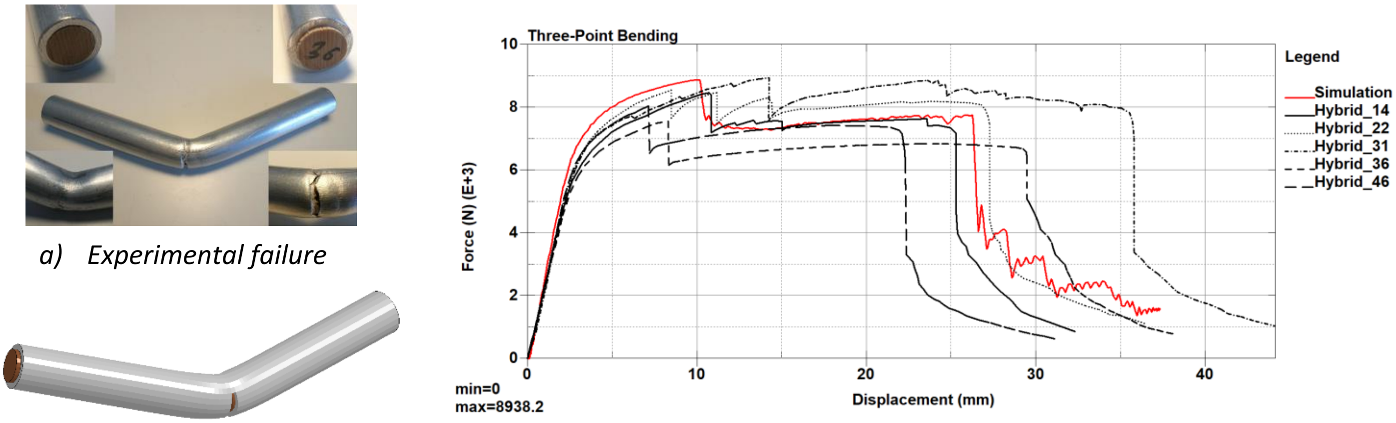
The *Ministère des Transports du Quebec* (MTQ) is responsible for 5495 road structures counting 4264 highway bridges in the province of Quebec, which are mostly made of concrete and steel [1]. From the last annual report [1] of the MTQ, it is known that 20 % of the road structures show some degradations and their maintenance cost raised by 33.9 % from 2018 to 2021. Therefore, in order to reduce the expensive maintenance cost of the highway bridges made of concrete and steel and their environmental impact, a possible novel solution would be the use of multi-materials such as wood and aluminium [2].

The use of an aluminium deck for highway bridges is challenging and requires a special safety feature. Current safety barrier for highway bridges used in Canada are made of a unique material such as concrete, wood, steel, aluminium for the whole structure. For multi-material structures, safety barriers are often made of concrete/steel, wood/steel or steel/aluminium [3]. At our best knowledge, safety barriers made of the combination of wood and aluminium are not common in practice.

The new hybrid safety barriers will be made of wood-filled aluminium hollow sections envelop. Wood is known for its good energy absorption capabilities [4], but suffers from brittle failure modes. The use of aluminium hollow sections envelops with filler wood material forms promising structural components which will prevent brittle failure of wood and protect it from direct exposure to environmental conditions (rain and humidity).

However, the crash safety of such hybrid structure with confined wood is a challenging task due to the complexity of wood. Therefore, their mechanical behavior and energy absorption capabilities should be more investigate for an accurate prediction of the crushing response during an impact due to a car accident.

Based on experimental tests of some hybrid systems (timber-to-aluminium connections assembled using wood-filled aluminium hollow tube dowel [5, 6]), we investigate and evaluate a numerical procedure for the design and the analysis of new generation of hybrid safety barriers for highway bridges. We investigate the capability of the wood material formulation (*MAT_143/*MAT_WOOD) available in LS-DYNA for simulating the mechanical behavior and the crushing response of hybrid assembly (Wood/Aluminium) using either hybrid dowel with confined wood or steel dowel. The material parameters identification is first conducted based on various experimental data. Based on these first results (Fig.1 & 2), many opportunities can be found to develop new generation of hybrid safety barriers for highway bridges, to optimize the material parameters identification and to improve the quality of numerical simulation of hybrid structures with wood confined into aluminium protection.

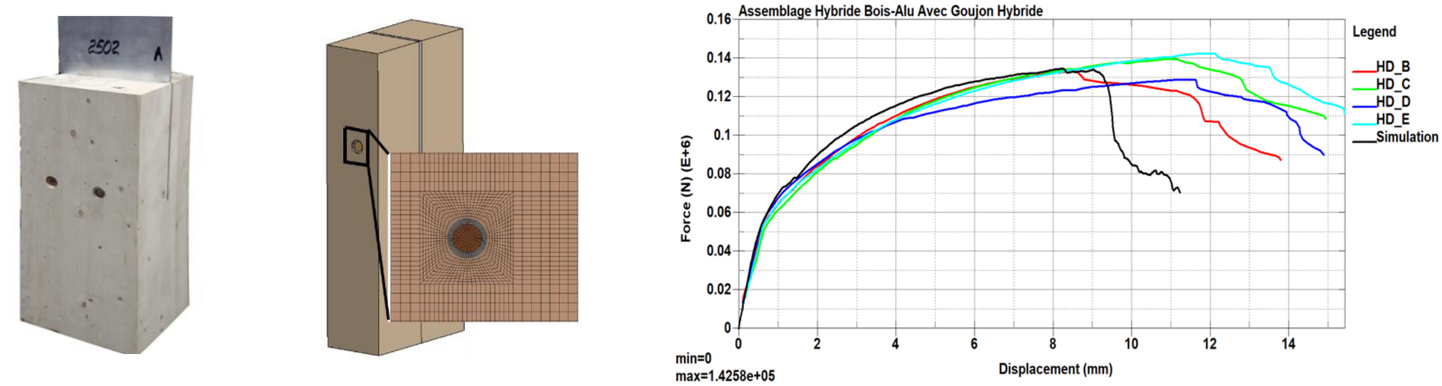


a) Experimental failure

b) Numerical failure

c) Load-deflection curves

Figure 1: Experimental/Numerical comparison of wood-filled aluminium hollow tube dowel



a) Experimental setup *b) Numerical setup* *c) Load-deflection curves*

Figure 2: Experimental/Numerical comparison of timber-to-aluminium connections assembled using wood-filled aluminium hollow tube dowel

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Contribution ID : **146** Type : **Oral presentation**

3D MODELLING AND TESTING OF CRUSHING AND DYNAMIC LOADING OF COMPOSITES – APPLICATION TO CRASH, IMPACT AND BOLTED JOINTS

The behaviour of composites during crushing in the plane of the laminate is crucial during crash events, but is also important for the failure of e.g., bolted joints in composite structures. Design for crashworthiness requires reliable material models not only for the damage initiation but also for any subsequent increase in stress, as well as for the post-peak behaviour, where significant portions of the energy are absorbed. A three-dimensional (3D) material model is required as the damage initiation and the subsequent growth are strongly affected by stresses perpendicular to the primary compressive load.

During the last decade, RISE has worked on characterising and modelling the behaviour of composites under in-plane compression in crash events, with focus on unidirectional non-crimp fabrics. The work has been performed in several projects in collaboration with the Swedish automotive industry. The crush stress may be described as the stress during sustained compression beyond the peak stress ("compressive strength") and may be reduced by plies folding outwards from the laminate (splaying) and delamination growth ahead of the crush front, as well as resulting local buckling. The crush stress is also influenced by friction between the laminate and other objects and within crack surfaces of the laminate, as well as by rate dependency of the material.

This contribution briefly describes the current version of our material model [1], which merges a previous model for fibre kinking with a model for transverse failure and shear into a fully 3D model for failure initiation and growth under triaxial stresses, including large deformations and friction at microcrack surfaces. To allow use by the industry, the model has been implemented in both Abaqus and LS-Dyna. Predictions have been verified for elementary load cases and have been validated for industrial component tests.

Application examples include composite crash tube tests, Fig. 1 [1], impact on a composite laminate, Fig. 2 [2], and progressive failure of bolted joints in a composite laminate, Fig. 3. Comparisons are also given with an in-house-developed test for in-plane crushing of an arrow shaped coupon [3], which may be used for model validation, or as a direct input for simplified "elastic-plastic" models with a specified crush stress. The suggested arrow shaped coupon eliminates most of the bending that is present in chamfered specimens as well as the splaying and delaminations seen in steeple-triggered specimens.

An important observation is that delamination growth and resulting sublaminate buckling may have a significant influence on the crush stress. Figure 1 illustrates the effect of an apparent overestimation of delamination growth and local sublaminate buckling in a crash tube.

More recently RISE has developed a 3D model to account for rate effects during in-plane compressive loading of composite laminates [4]. The model considers elastic fibres embedded in a viscoelastic-viscoplastic matrix with damage and uses a simplified homogenisation approach to describe the response at ply level. The model has been validated by comparisons with various split Hopkinson bar tests performed on unidirectional and angle-ply laminates.

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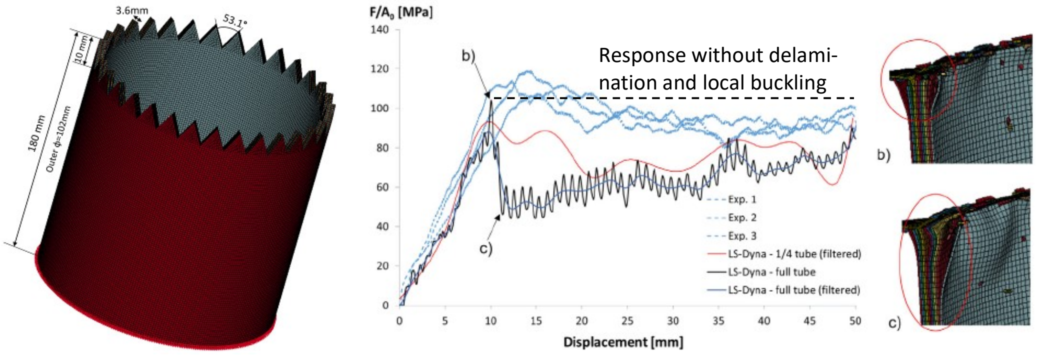

Figure 1: Simulation vs experiments for axial crushing of a crash tube [1].

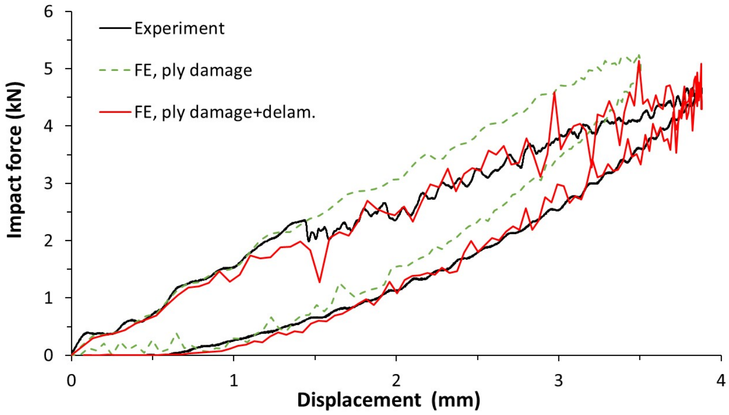

Figure 2: Simulation vs experiments for impact on a [-45/90/45/0]$_s$ CFRP laminate, adapted from [2].

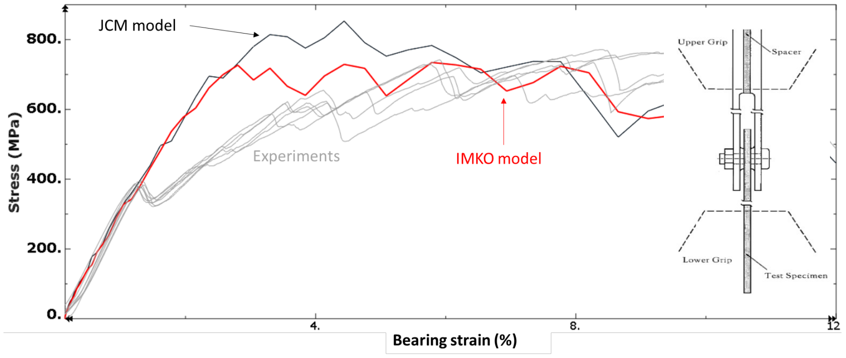

Figure 3: Simulation with current model (IMKO) vs tensile tests on a bolted joint in a laminate.

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A surrogate functionally graded material modelling of High-Voltage connectors for electric vehicle crash simulations

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ABSTRACT

Strict emission regulations are progressively imposed on the way to ban the use of combustion engines due to the increasing pollution in urban areas. This global strategy promotes for electric vehicles. A pioneer in this challenge, Mercedes-Benz will switch to produce only electric vehicles by 2025 [1].

As with combustion engine vehicles, electric vehicles would have to meet stringent safety standards. In fact, failure and damage of electric High-Voltage connectors during a crash accident can cause electrocution and a fire hazards [2]. It is therefore necessary to develop a reliable numerical connector model able to reproduce the same mechanical behavior of a real connector and predict efficiently its failure initiation. This model is intended to be used in full-vehicle crash simulations during the predevelopment phase of a car.

This work focuses on the development of a new surrogate numerical model for high-voltage connectors in a response to all these arising industrial limitations. The proposed simplified model is based on the use of shell elements together with functionally graded materials to reproduce the hybrid multi-material behavior in a real connector. The complex geometry of the high-voltage connector is first simplified using a basic representative geometrical model, where most sensitive physical and material parameters are identified based on experiments. A generalized incremental stress state dependent damage model is used under the assumption of plane stress state condition in order to capture the connector failure initiation. The resulting surrogate model has been implemented in LS-DYNA® explicit software and validated by comparison to the solution obtained by means of a full three-dimensional fine mesh modeling [2] as well as component and full vehicle crash experiments at Mercedes-Benz company. The good response quality obtained on full vehicle crash simulation [3], in terms of failure mode representation, of reduced CPU time and computing resources, demonstrates the efficiency of the proposed surrogate model.

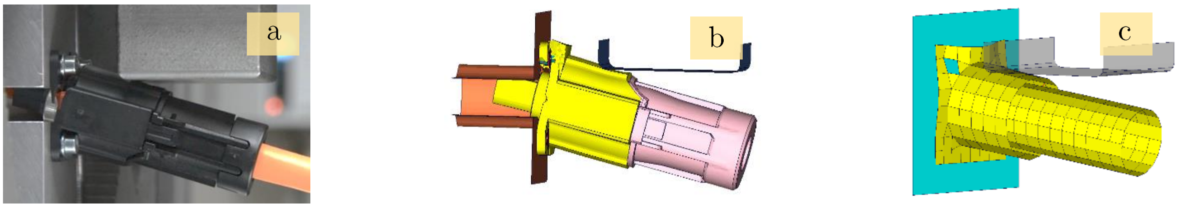

Figure 1. Example of an electric high-voltage connector: (a) experiment. (b) Detailed and (c) simplified models

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Crushing of Composite Tubular Structures involving New Innovative Triger Mechanism, from Quasi-Static to Dynamic to Numerical modelling

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Keywords:
Crashworthiness, Composite tubes, Specific Energy Absorption (SEA), Energy dissipation, Aeronautics

Abstract:

With many prospects and a vast range of industrial applications, composites tubular structures are worthy of investigation. They have already proven their worth and usefulness, especially in the aeronautical sector due to their lightness and interestingly robust mechanical properties, but the interest for lighter, thinner and stronger laminates using optimum stacking sequences still carries a lot of attention. In addition, in regards of the safety regulations and aircraft passengers/cargo protection when crash-like accident occurs, composite structures are known to be very efficient energy absorbers when submitted to crushing, therefore providing a solid alternative to metallic material parts in aircrafts or helicopters. To that end, this study focuses on testing CFRP tubular structures with different staking sequences and various fiber orientations to compare their behavior under crushing and try and enhance the SEA values for possible implementation in aircraft seating. Furthermore, to help initiate the crushing, stabilize the tubular structure and reach higher SEA values, several different innovative trigger mechanisms were tested. (cf. Fig 1).

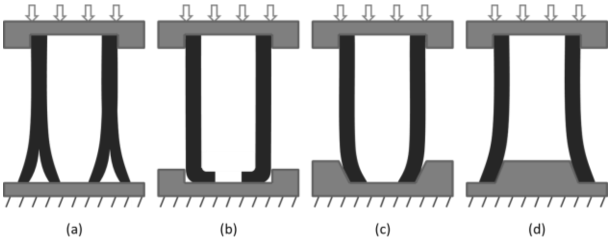

Figure [1]: Experimental testing configurations (a) free plan Crushing, (b) Inner Crushing,
(c) Inner Conic Crushing with sloping initiation, (d) Outer Conic Crushing with plug initiation.

The study covers investigations and results from Quasi-Static testing (constant loading speed of 0.2 $mm.s^{-1}$) to Dynamic testing (drop speed of 4.95 $m.s^{-1}$) to numerical modelling of the performed experimental tests. Such modelling was achieved using the Discrete Ply Model (DPM) developed since 2009 by Bouvet et al. [1-4] and which relies on a meso-scale Finite Element Model specifically developed for unidirectional laminates behavioral prediction, using Abaqus Explicit solver combined with a user material law. The strength of the DPM model is that it allows individual ply information retrieval. Thus, not only global crushed shape and plies behavior, as well as global Mean Crushing Stress level were compared to experimental testing, but a ply-by-ply analysis was also performed.

Experimentally, SEA values up to 140 $kJ.kg^{-1}$ were obtained for a 0°/90°-ten plies UD-oriented tube, achieving better than most instances from the literature, reaching around 80 $kJ.kg^{-1}$. Overall, specimens with 0°-oriented fibers coincidental with the direction of crushing reached the highest SEA values in quasi-static while those with low or no fiber oriented in this direction performed poorly.

Generally, the crashworthiness performance of CFRP tubes displaying fibers orientation at low winding angle is better than those displaying fibers orientation at high winding angles, relatively to the direction of crushing. It has consequently been established that in quasi-static loading, a unidirectional laminate oriented at 0° and stabilized by few 90° or 0/90° woven plies strongly meets the expectations in terms of energy dissipation. However, it was found that this result was also dependent of the crushing speed.

While it was established that in quasi-static loading, CFRP tubular structure with a predominance of unidirectional laminate oriented at 0° strongly performed best, in dynamic loading however, it has been observed that a stratification with 90°-oriented fibers stabilized by woven plies performed better and best meets the expectations in terms of energy dissipation. Furthermore, unidirectional laminate oriented at 0° performed lesser by 50% between quasi-static and dynamic rates. Incidentally, an inner constrained containment is more effective in most cases, reducing the initial peak load without drastically reducing the SEA value, as demonstrated by Chambe et al. [5-6].

Inner-crushing performed best for all tested tubes, compared to plan crushing or outer conic crushing. A visual representation is given below. (cf. Fig 2).

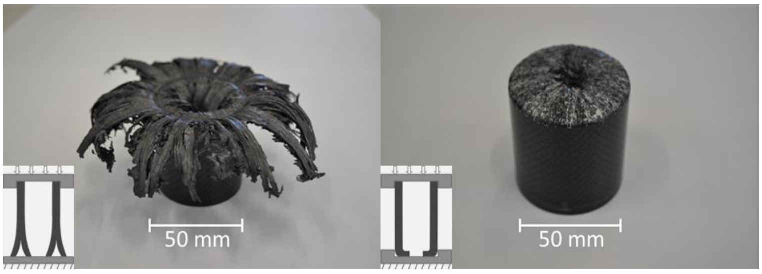

Figure [2]: Crushed CFRP tubes (1) showing outer spreading (left) and inner folding (right) based on boundary condition (a) free Crushing and (b) Inner Crushing, respectively.

Finally, attempts at modeling such experimental results using the DPM proved successful, with an experimental-model correlation of 80 to 95% when comparing the mean crushing stress or SEA values and of 100% when comparing the laminates' plies damage and final shape of the CFRP tubes.

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EFFECT OF PROCESS PARAMETERS ON IMPACT ON COMPOSITES AND COMPRESSION AFTER IMPACT

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Keywords: Composites, Liquid resin infusion, impact testing

ABSTRACT

The purpose of this article is the question of the possible link between composite processing and impact and post-impact behaviour [1,2,3,4].

A Taguchi method of design of experiments was used to establish possible links between processing parameters and impact and compression after impact behaviour. The processing method studied is liquid resin infusion of stitched or unstitched preforms made of carbon quadri-axial Non-Crimp Fabric (NCF). Five process parameters were selected (stitching, cure temperature, preform position, number of high porous media and vacuum Level). The parameters used are shown in Table 1.

Table 1: parameters used in experimentation.

Plate N°	Plate side	Stitching	Curing temperature (°C)	Number of HPM	Vacuum level (mbars)
1	Vacuum	Without	180	1	1.3
2	Injection	Without	180	1	1.3
3	Vacuum	Without	160	2	1.4
4	Injection	Without	160	2	1.4
5	Vacuum	Yes	180	2	1.6
6	Injection	Yes	180	2	1.6
7	Vacuum	Yes	160	1	1.4
8	Injection	Yes	160	1	1.4
9	Vacuum	Yes	170	2	1.3
10	Injection	Yes	170	2	1.3

Table 1 gives an idea of parameters that have been varied and how, during experimentation (fabrication of plates).

The general equation of a linear model for a property Y takes the form of equation 1.

$$\mathrm{Y = C + a.CO + b.Tc + c.NHPM + d.Cp + e.VL} \tag{1}$$

Where

- CO is stitching
- Tc is cure temperature
- NHMP is number of high porous media
- Cp is plate side of composite
- VL is vacuum level

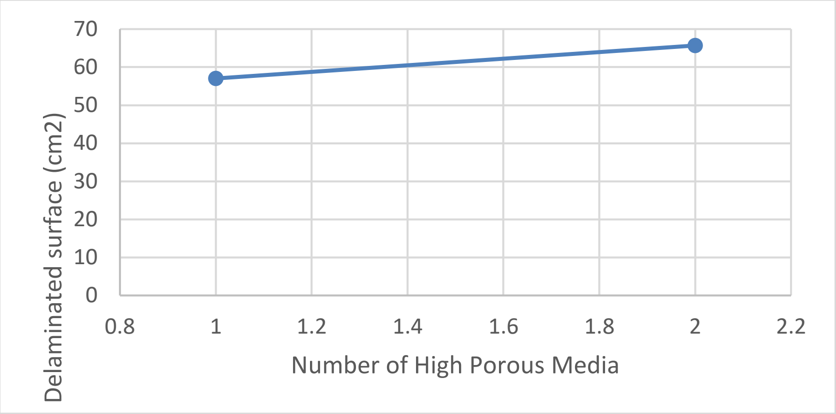

Figure 1: Delaminated surface as function of number of high porous media.

The statistical analysis done showed a very high sensitivity to stitching of many properties what was of course expected.

Stitching was found influent on After impact compression strength, elastic energy, absorbed energy and residual dent depth. Damaged area was found sensitive to number of high porous media (Figure 1)

Residual dent depth was found sensitive to stitching, cure temperature and side of the plate.

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LOW VELOCITY IMPACT BEHAVIOUR OF A NEW SANDWICH PANELS BASED ON FLAX FIBRES REINFORCED EPOXY BIO-COMPOSITES

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Keywords: Bio-Composite Laminates, Low velocity Impact, Damage, Failure, Sandwich panel

ABSTRACT

Due to more and more binding regulations on environment, natural fibres and biocomposites have received a growing interest in the past years. Natural fibres have been widely studied for production of panels and laminate and their applications in transport industry are now very large. These materials are also provided for unidirectional and woven fabric composite laminates applications. So, some part of structure piece could now be realized with these materials and may be replacing of glass fiber. Indeed, Flax fibre has been shown to be comparable to, or even exceed, Glass fibre in specific strength (1300 vs 1350 MPa/g cm3), specific modulus (20–70 vs 30 GPa/g cm3), cost-savings by weight (0.5–1.5 vs 1.6–3.25 USD/kg).

However, in order to design flax fiber composite laminate structures static and dynamic behavior of this type of composite have to be understood. Many authors have described flax fiber composite behavior with experimental studies for 15 years, but few authors have provided numerical behavior damage model. Some exist for impact but not consider some non-linearity as damage of the fibers.

Objective of this work is to present a damage and failure model of flax fiber woven fabric composite laminate and the damage model application to impact behavior prediction of a specific sandwich panel. First part of the work is devoted to the damage model presentation and identification of all the damage and failure parameter. Model is based on Linde [1] damage model where damages are described by an exponential function defined with strain criteria and energy at failure. In order to consider, the progressive damage of flax fibers because flax fibers non continuous fibers, we define diffuse damage parameters and failure damage parameters. Diffuse damage parameters are expressed according to energy and failure damage parameters depend on strain failure criteria [2-3]. Experimentation is presented in order to identify all the damage/failure parameters. The Diffuse damages identification is realized with cyclic tensile tests [4-5]. Failure energies are determined with CT/CC tests. The model is implemented in an Abaqus VUSER fortran Routin for explicit computation. Validation of the model is realized on simple samples (Figure 1).

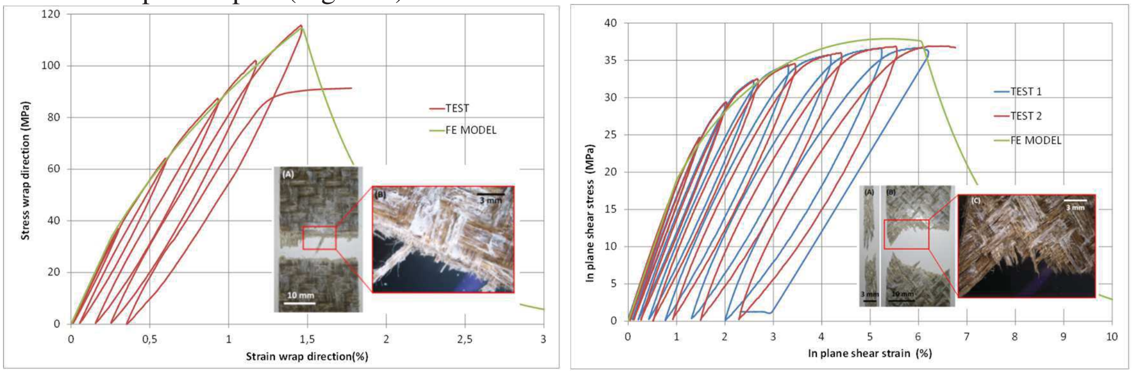

Figure 1. Exemple of numerical/experimental comparison of Flax composite behavior

Second part of the work present failure prediction of a new sandwich panel design. The core of this panel is realized with a specific shape named "corrugated" in order to minimize the mass and increase his stiffness. After presenting the making process of this panel, different impact tests are realized and analyzed [6-7]. Velocity and energy of impact changed, and damages occurs from upper skin to the lower one [8-9]. Finally, a 3D finite element model of the panel using the damage/failure model is achieved and compared to global load-displacement behavior of the panels and local damages observed during the experimental campaign. Numerical and experimental Damage and failure are compared (Figure 2.).

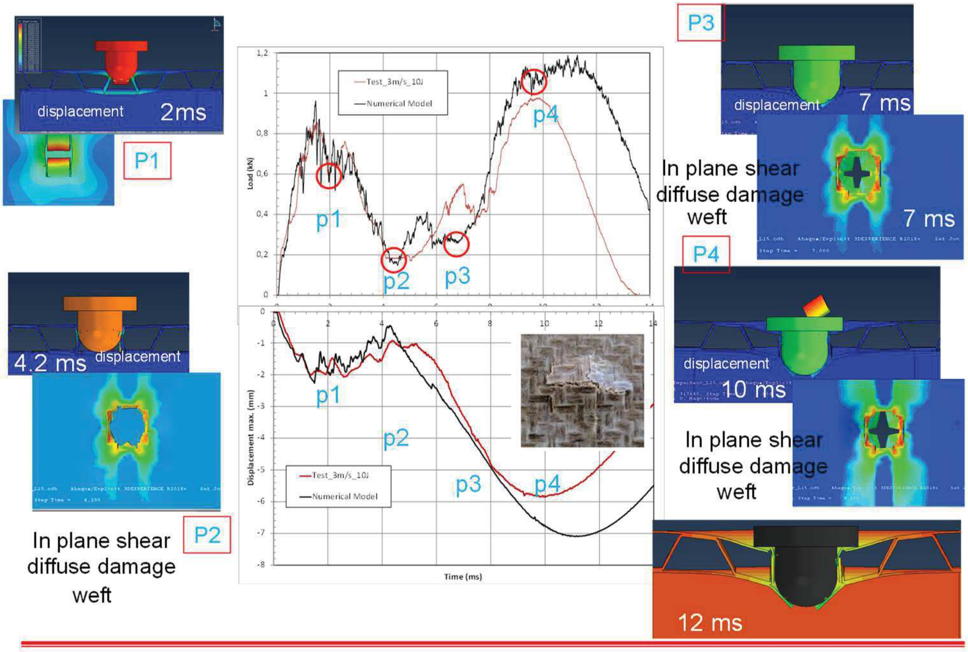

Figure 2. Numerical/Experimental comparison of an impact of a flax sandwich panel.

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STRUCTURAL TESTING OF IMPACTED STIFFENED PANELS ON THE VERTEX TEST RIG

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Keywords: Compression after impact, Stiffener debonding, Post-buckling, Experiments, Finite Elements

ABSTRACT

The process of sizing and certification of aeronautical structures is organised according to the test pyramid, where numerous coupon tests form a basis for the design of larger-fewer tests, up to the full aircraft structure. Considering stiffened panel structure like the fuselage, it needs to withstand Ultimate Loads despite damaging incidents such as an impact generated by a tool dropped during maintenance. On composite materials, it notably leads to extensive tests of Compression After Impact to assess damage tolerance. These tests mostly take place either at small scale (coupon) or on large stiffened panels (structural details), which are either cheap and not representative of large structural effects, or costly and too complex and prohibitive for laboratory developments. Therefore, there is a need for structural testing at the intermediate scale, representatively of large structural issues, to notably study damage tolerance of composite stiffened panels at moderate cost. The VERTEX test rig allows to generate combinations of tension/compression-shear-pressure, representatively of large structural issues, on specimens with a 400 mm × 400 mm area of interest [1]. This study gets on with the opening of VERTEX tests towards compression after impact on stiffened panels, to study stiffeners debonding under post-buckling conditions [2].

Figure 1 illustrates the specimen geometry and a compression after impact configuration. Three identical samples were considered: Sample1 was impacted at 30 J on the stiffener flange (Figure 1), Sample2 impacted at the location but at 45 J, and Sample3 was impacted at 45 J on the skin. After impact, all three samples were subjected to compression up to complete debonding of the stiffener.

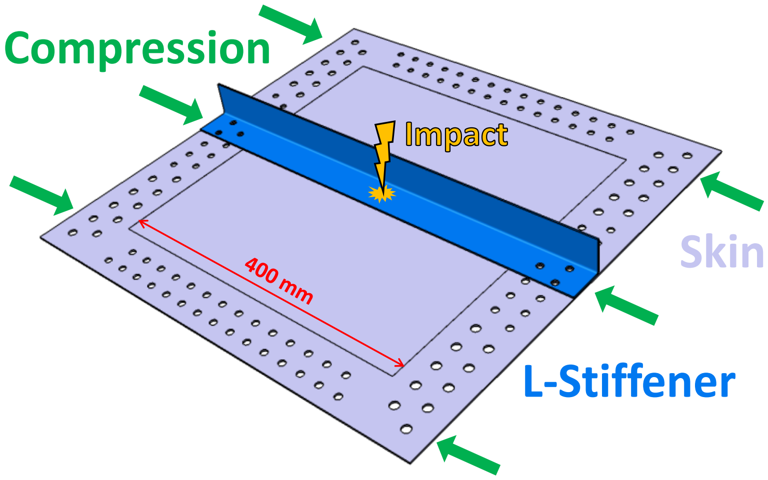

Figure 1: Stiffened sample considered under compression after impact.

A numerical model was developed to represent stiffener debonding of a specimen under compression: the composite was modelled with thick shell elastic elements, and cohesive elements at the skin/stringer interface allowed to represent the progressive debonding with an explicit solver (Figure 2). The model was used to perform virtual testing regarding the stiffener geometry (flange-web length and some technological solutions on the tips) in order to design the sample such as the desired phenomenology appeared during the tests.

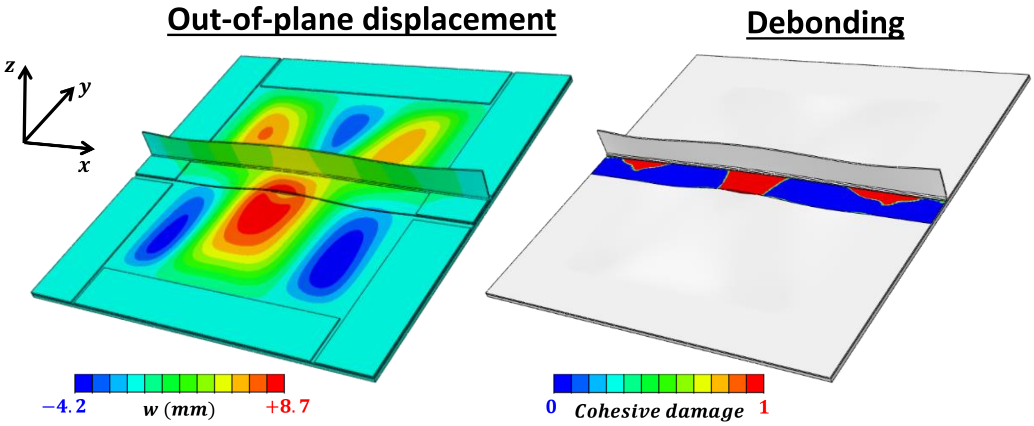

Figure 2: Model developed for virtual testing of some technological solutions, in order to ensure the intended phenomenology during the tests.

Compression after impact experiments were performed with the VERTEX test bench (Figure 3) and the observed debonding scenario were consistent with the numerical simulations. The effect of the impact (location and energy) on the debonding (strength and scenario) was not substantial.

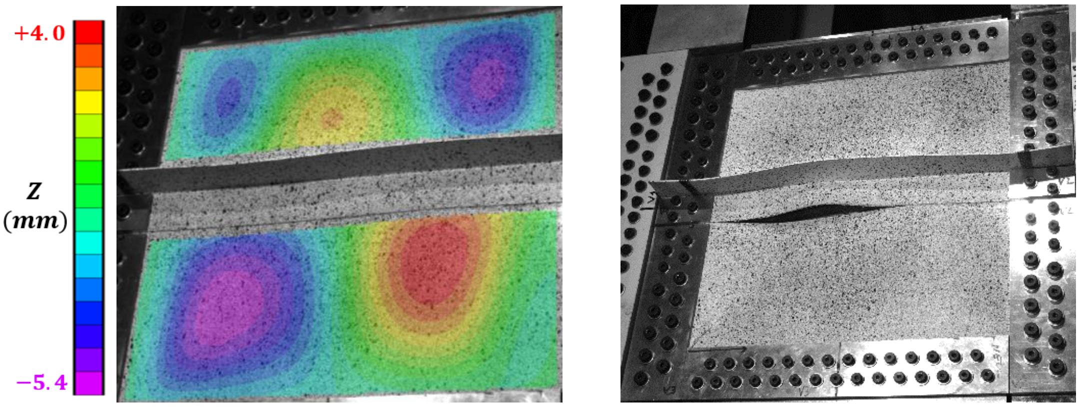

Figure 3: Experiment of compression after impact with the VERTEX test rig: (left) out-of-plane displacement field obtained with stereo-correlation before debonding, (right) picture of a sample after debonding.

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PARAMETRIC STUDY OF THE DESIGN OF A 3D-PRINTED CRASH ABSORBER

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Keywords: Energy absorption, Lattice structures,
Additive manufacturing, Explicit finite elements, Response surface design

ABSTRACT

With the maturity of the means of production, the use of metal additive manufacturing techniques has increased considerably in the aerospace industry over the last decade [1]. The great freedom of shape offered to designers by these processes makes it possible to achieve a high degree of optimization of parts based on specific structural performance criteria [2]. In this context, the development of energy absorbers with alveolar microstructures benefits from great opportunities for innovation to address various impact cases [3, 4].

In this study, the mechanical behaviour of a family of lattice structures (Fig. 1a) embedded between thin walls (Fig. 1b) is investigated under crushing loading conditions (Fig. 1c).

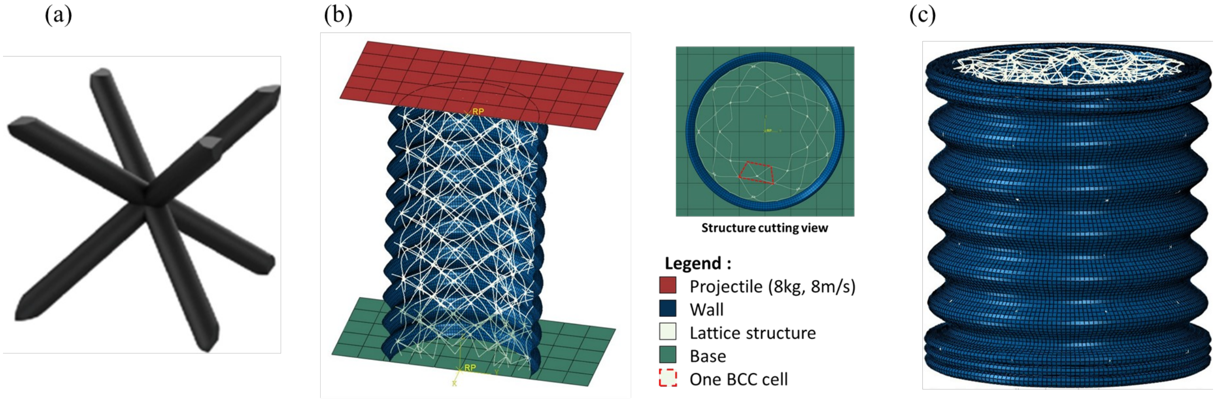

Figure 1: (a) Unit parametric cell. (b) Model description (c) Crushing of a representative structure

The lattice structures are obtained from a linear repetition of a BCC unit cell pattern composed of 8 beams. The parameters investigated are: the size of the cell, the diameter of the beams, the number of beams both in the circumferential, radial and height direction and the thickness of the walls. On top of that, the effect of a modulation of the radius performed along the extrusion direction is studied.
Both cells and boundary walls are made of titanium (TA6V).

A finite element model, with explicit integration scheme, is developed to compute the mechanical response of the proposed absorbers. It allows a comparison of the obtained performances, in relation to the mass of the concepts. Thus, the SEA, the peak of force, the displacement at the end of crushing, the absorbed energy and the height of the plateau are recorded.
Response Surface Designs are then used in order to estimate the characteristics of not tested crash absorbers and to optimize the design (Fig. 2).

Figure 2: Example of response surface drawn from the design of numerical experiments

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EXPERIMENTAL AND NUMERICAL STUDY OF IMPACTS AND POST-IMPACT BEHAVIOUR ON HELICOPTER BLADES

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Keywords: Impact, woven composite, sandwich structures, Explicit finite elements, Semi-continuous modelling

ABSTRACT

Helicopter blades are complex composite sandwich structures. An example of a classic architecture is given Figure 1. During flight, they can be impacted by numerous objects like birds, hailstones, metallic parts from the helicopter, etc… which can leads to a catastrophic failure.

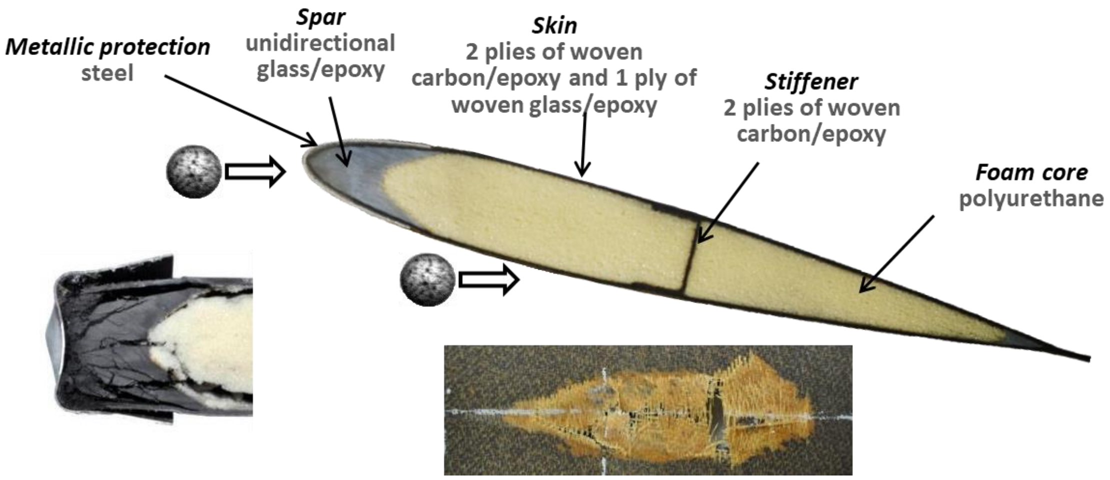

Figure 1: Architecture of a helicopter blade.

Impact loading is one of the most critical loading for composite structures. In this particular case, the impact can occur either on the leading edge, which induce the failure of the roving and a large debonding of the composite skin, or directly on the skin, which causes a local failure of the composite woven plies. Then, the damage induced can propagate under the cyclic loading due to the rotation of the blade.

The failure scenario of composite laminates is complex, and depends on many parameters like the stacking sequence, the material parameters, the loading or the dimensions of the structure. The damage chronology can be summarized in three steps described in [1] : matrix cracking, delamination and failure of the fibers.
To handle impact damage modelling for woven composite laminates, a semi-continuous finite element modelling has been developed [2,3,4,5]. It relies on the separation of the role of the bundles of fibers (represented with rod elements) and of the resin (represented by damageable shell elements). The results provided by this modeling have been validated by comparing with several low and medium velocity impact tests. They are accurate enough to represent the damage scenario.
Concerning the study of the propagation of impact-induced damages during flight. Tensile tests on pre-impacted woven composite laminates have been performed to identify the mechanisms involved in the

damage growth. The semi-continuous strategy for the modelling of woven composite laminates has been adapted to represent the propagation observed experimentally. A good correlation between experimental and numerical results is found [6,7].

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ON THE RELEVANCE OF USING MEAN CRUSHING STRESS DUE TO LOCALISED FRAGMENTATION IN THE CRASHWORTHINESS MODELLING OF COMPOSITE

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Keywords: virtual testing, energy absorption, mean crushing stress, finite element simulation, experimental identification

ABSTRACT

In the field of crashworthiness, virtual testing is a challenge as it depends on the ability to predict damage under severe loadings and the associated absorbed energies. In particular, modelling composite damage and their propagation under crushing is of great complexity. The crushing front is a particular zone where material can be completely damaged and this zone propagates continuously inside the structure in the case of a stable crushing, which is usually expected to obtain an efficient energy absorption.

For composite materials such as laminates, the crushing front reveals different mechanisms involved in the crushing process: delamination, bending of plies resulting in failure with big debris and local fragmentation initiated by kink bands, most often in the inner plies.

Israr [1] has shown that for 0° or 90° plies, this localised fragmentation is done at a constant level of stress, called mean crushing stress of the ply. He also calculated that the greater part of energy absorption in his crushing tests was linked to this localised fragmentation.

The DPM model (mesoscale finite element model developed at Institut Clément Ader for composite modelling) was then adapted to take into account both this mean crushing stress and the fact that the damage can continuously propagates [2].

It was then applied to different kinds of compression loadings:

- Compression after impact for laminates subjected to low velocity / low energy impacts [3]
- Composites tubes under crushing [4]
- Pin crushing in laminates

The results obtained with these numerical simulations demonstrate the relevance of using the mean crushing stress and the associated model to represent the localised fragmentation that rules the crushing front evolution.

A method for the experimental identification of the mean crushing test was also proposed by [1]. It is a quite laborious and tricky method, but it manages to give values for static crushing. The question is still opened today concerning the mean crushing stress under dynamic load.

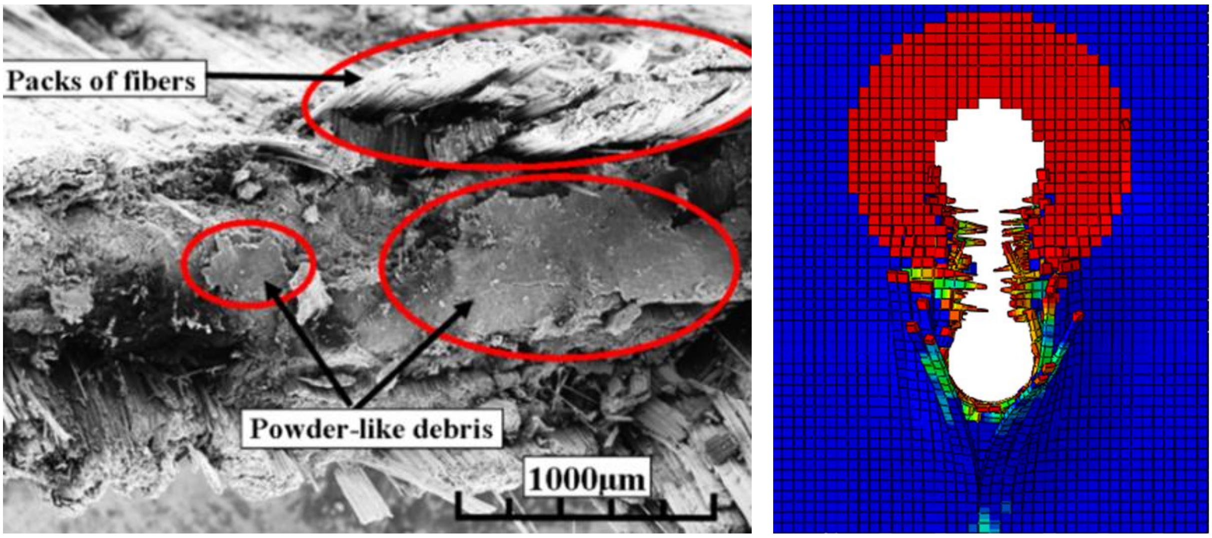

Figure 1: Localised fragmentation at crushing front (SEM picture) and pin crushing modelling

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RELEVANCE OF THE DOUBLE NOTCHED SHEAR TEST FOR MEASURING THE FRACTURE TOUGHNESS OF CARBON/FLAX HYBRID COMPOSITE LAMINATES IN MODE II

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Keywords: Fracture toughness, Mode II, Hybrid composites, Double Notched Shear test

ABSTRACT

Several experimental techniques are proposed in the literature and used for the identification of characteristic quantities of delamination resistance, and the values obtained by these different techniques are not always concordant, particularly for mode II failure mode. On the one hand, among the experimental techniques proposed, the DNS (Double Notched Shear) test allows a controlled and localized initiation of the crack without using an initial artificial crack. On the other hand, being relatively sensitive to the operating conditions, it is rather delicate to set up [1-3].

This work, carried out in collaboration between the GPM and CIMAP laboratories of Normandie University, aims to explore the potential of this DNS test and to propose technical solutions for its use.

In order to test the validity of the DNS test in material behavior configurations, the choice of reinforcement fabrics used in the composition of laminated composite materials was made on a carbon fibers fabric and a flax fibers fabric. These two fabrics are completely different from all points of view, the nature of the fibers, the intrinsic mechanical behavior of the fibers and the architecture of the reinforcements. The carbon fibers fabric is a 2/2 3K twill with a weight of 189 g/m2, with a density of 1.7 g/cm3 for the fibers. Its architecture makes it relatively deformable before impregnation to make it adapt to the shape of the part to be molded. The flax fibers fabric is completely different. Firstly, the flax fibers, with a density of 1.54 g/cm2, do not form parallel fiber strands but twisted threads. The architecture of the fabric made with these twisted threads is at first sight a canvas, with a weight of 240 g/m2. Closer observation shows that the weft and warp fiber bundles do not consist of a single twisted thread but of 5 parallel threads. The threads of the weft and warp fiber bundles are themselves interlaced in a 2/3 weave pattern. In the end, this twisted flax fibers fabric has a complex and highly interlaced architecture, which makes it very little deformable when dry, unlike carbon fiber fabric [4].

From these two reinforcement fabrics associated with an epoxy matrix, laminated composite sheets with different material configurations ([C$_8$]s, [F$_4$]s and hybrid [C$_6$F$_4$]) were fabricated by vacuum contact molding. The number of reinforcement plies is calculated according to the weight of the fabrics in order to obtain 4 mm thick specimens, as well as an interface between 2 plies in the center of the specimen. From the various laminated composite plates, DNS and tensile specimens were obtained by mechanical processing. Preliminary conventional tensile tests at 0° and 45° to the fiber direction showed that the [C$_8$]s and [F$_4$]s composites behave differently (Figure 1).

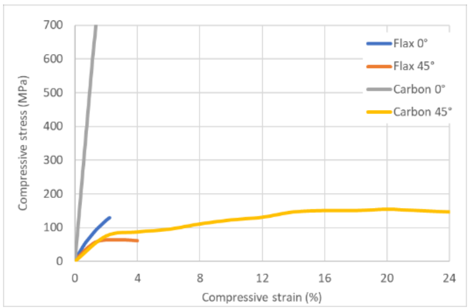

Figure 1: tensile mechanical responses of [0°] and [+/-45°] laminates

A parametric study of the Finite Element geometry minimized the generation of parasitic stresses normal to the plane of delamination crack propagation which could distort the identification of the material variables associated with mode II.

The mechanical loading system is mounted in a universal testing machine. Compared to tension, compression loading eliminates problems with specimen retention in the jaws and potential premature failure in the docking area. A guiding device limits the phenomena of buckling of the specimen and thus of parasitic stressing of the crack in mode I.

Figure 2a shows the results of the DNS tests for the three laminated composite materials tested ($[C_8]s$, $[F_4]s$ and $[C_6F^4]$). As suggested by the preliminary mechanical tests, the interface behavior of the C-C, F-F and C-F plies is strongly dependent on the nature of the plies. However, although the elongation at break under tensile stress of the $[F_4]s$ composite is higher than that of the $[C_8]s$ composite, the axial displacement at complete failure of the interface is lower. A parallel can be drawn with the shear behavior obtained from the 45° tension test (Figure 2), the strain at break of the $[F_4]s$ composite is significantly lower, micrographic observations show that the stiffer architecture of the flax fabric does not allow rotational movements of the fiber bundles and therefore limits its shear deformation capacity.

Figure 2b shows the evolution of the strain energy release rate (or fracture toughness) obtained by integrating the curves (force, displacement, crack length) with the area method.

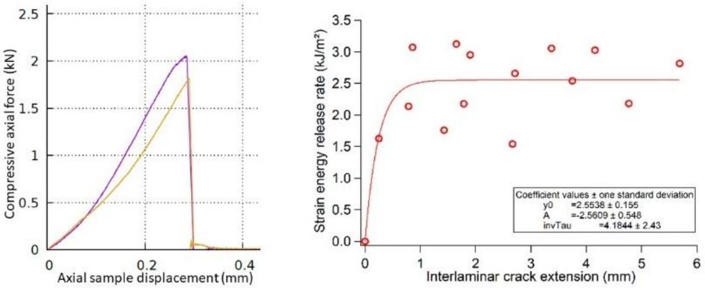

Figure 3: a – Example of force-displacement curve of the DNS tests. b – Example of fracture toughness estimation

In conclusion, the proposed method of test configuration and data reduction is relevant for the study of mode II cracking of laminated composites. However, there are points for improvement:

- The machining of the notches must be perfectly mastered (depth, symmetry between the 2 notches, surface condition) to control the initiation and propagation of the crack.
- The area method is not the most suitable for ductile fracture materials. In this case other methods, such as the compliance method, may be more suitable.
- Parasitic buckling phenomena can be reduced by a suitable specimen geometry and a specimen guidance system.

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