

Development and testing of hybrid composite coupons for crush applications

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*"O sucesso é ter quem fique feliz com o meu sucesso,
tão simples assim, e é mesmo assim.
Vale-me quem me abraça quando estou feliz, e no
final das contas é mais por isso que estou feliz.
De que vale ao campeão do mundo ser campeão do
mundo se não tiver quem o ame para ser campeão do
mundo consigo?,
Todas as vitórias são coletivas,
sobretudo as individuais."*

*Pedro Chagas Freitas, em
"Queres Casar Comigo Todos os Dias?"*

*Aos meus pais,
à minha irmã,
e à Beatriz.*

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Abstract

Crashworthiness can be defined as the ability of a material to absorb impact energy through controlled failure modes and mechanisms. Any structure that requires movement, such as cars and aircrafts, requires energy-absorbing structures to ensure the well-being and safety of vehicle occupants in the event of an accident. Motorsport teams have been manufacturing the impact-absorbing structures of their vehicles in composite materials, as these guarantee excellent specific mechanical properties, optimising performance and reducing fuel consumption.

However, physically testing large energy-absorbing composite structures is very expensive. As such, it is essential to numerically model these structures. Nevertheless, despite several studies in the literature evaluating the energy absorption capacity of composite materials subjected to crushing loads, there is still a lack of knowledge regarding the effect that possible geometric changes may have on the energy absorption properties. Such unawareness leads to a subjective assignment of these parameters and, consequently, to results that do not correctly translate the behaviour of composite systems.

The fibres that have been considered in the literature as being the most efficient for this type of application are the carbon fibres. However, these not only originate from petroleum products, but the transformation processes for obtaining them require very high temperatures, which result in excessive embedded energy values. These factors, combined with the high price of this raw material, have led the industry to seek more sustainable solutions that reduce its ecological footprint. In this context, fibres of natural origin, such as those made from *flax*, have been in demand.

Therefore, during this thesis, the geometric effect of carbon and *flax* fibre reinforced composites on the energy absorption parameters of specimens with different radii of curvature were evaluated. It was proved that there is a transitional decrease in the crush stress as the radius of curvature of coupons increases. However, it was not possible to obtain reliable results on flat coupons since the available testing methods proved to be ineffective. Even so, it was possible to perform preliminary tests with a different methodology, through industrial collaborations, which proved to be promising in obtaining more complete results. Besides, it was concluded that the geometry effect was more evident in the carbon fibre reinforced composite than in the *flax* one.

Furthermore, hybrid laminates were developed between the two composite materials evaluated. The compatibility of both resins was verified, but more importantly, it was concluded that by hybridising the synthetic fibre reinforced composite with the natural fibre one, interesting energy absorption levels were obtained, especially for less pronounced curvature radii. However, the drop in performance of the hybrid coupons relative to that of the carbon fibre reinforced composite was greater than that which could be expected. Even so, the specific energy absorption proved to be very promising.

Resumo

Crashworthiness pode ser definida como a capacidade de um material absorver energia de impacto através de modos e mecanismos de falha controlados. Qualquer estrutura que exija movimento, tal como automóveis e aeronaves, requer a existência de estruturas de absorção de energia, de forma a garantir o bem-estar e segurança dos seus ocupantes no caso de acidentes. As equipas de automobilismo têm vindo a fabricar as estruturas de absorção de impacto dos seus veículos em materiais compósitos, uma vez que estes garantem excelentes propriedades mecânicas específicas, otimizando a performance e reduzindo consumos de combustível.

No entanto, testar fisicamente estruturas compósitas de absorção de energia de grande dimensão é muito dispendioso. Como tal, é fundamental modelar numericamente estas estruturas. Contudo, apesar dos diversos estudos na literatura que avaliam a capacidade de absorção de energia de materiais compósitos sujeitos a cargas de esmagamento, existe ainda uma falta de conhecimento relativo ao efeito que possíveis alterações geométricas possam ter nas propriedades de absorção de energia. Tal desconhecimento leva a uma atribuição destes parâmetros de forma subjetiva e, como consequência, a resultados que não traduzem corretamente o comportamento dos sistemas compósitos.

As fibras que têm vindo a ser consideradas na literatura como sendo as mais eficientes para este tipo de aplicações são as de carbono. No entanto, estas não só têm origem em produtos petrolíferos, como também o seu fabrico exige processos de transformação a elevadas temperaturas, que resultam em consumos energéticos excessivos. Estes fatores, aliados ao elevado preço desta matéria-prima, têm levado a indústria a procurar soluções mais sustentáveis, que permitam reduzir a sua pegada ecológica. Neste âmbito, as fibras de origem natural, como as de linho, têm vindo a ser procuradas.

Posto isto, durante esta tese avaliou-se o efeito geométrico de compósitos reforçados com fibras de carbono e de linho nos parâmetros de absorção de energia de provetes com diversos raios de curvatura. Comprovou-se que existe uma transição decrescente na tensão de esmagamento à medida que se aumenta o raio de curvatura dos provetes. No entanto, não foi possível obter resultados fidedignos em provetes planos, uma vez que os métodos de testagem disponíveis se revelaram ineficazes. Mesmo assim, foi possível efetuar testes preliminares com uma metodologia diferente, através de colaborações industriais, que se mostraram promissores na obtenção de resultados mais completos. Para além disso, concluiu-se que o efeito da geometria foi mais vincado no compósito reforçado com fibras de carbono do que no de linho.

Por fim, desenvolveram-se laminados híbridos entre os dois materiais compósitos avaliados. Verificou-se a compatibilidade entre ambas as resinas, mas mais importante do que isso, concluiu-se que, ao hibridizar o compósito reforçado com fibras sintéticas com o de fibras naturais, se conseguiu obter níveis de absorção de energia interessantes, especialmente para raios de curvatura menos acentuados. No entanto, a queda na performance dos provetes híbridos relativamente ao do

compósito reforçado com fibras de carbono foi maior do que aquela que seria expectável. Mesmo assim, a absorção de energia específica revelou-se muito promissora.

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Chapter 1

Introduction

The world is currently facing environmental changes due to human luxuries and a lack of concern in previous years. Therefore, many measures are being implemented by the European Union (EU), and other institutions, to fight climate change and global warming. Most of these measures affect the transport sector. While before our quotidian, engineers could focus exclusively on extracting the maximum performance out of their manufactured structures, no matter the environmental cost it might have, that is no longer the case. Stringent emission and efficiency targets for fuel consumption allied with novel technologies, like electric mobility, are changing the paradigm of vehicle construction materials. As a consequence, fibre reinforced composite materials, such as carbon fibre reinforced polymers (CFRP) have been growing interest among the biggest manufacturers in the world as their low density, compared to conventional metal alloys, allows them to partially fulfil the EU requirements and improve their image in the eyes of their customers. However, this is no longer enough, as restrictions on oil-based materials usage and recyclability are also growing. Therefore, the carbon footprint must be lower, and that is why companies are pursuing alternative materials such as natural plant-based composites, to replace the polluting oil-based synthetic fibres. In this chapter, the background of this thesis is presented with a focus on the crashworthiness of composite materials. Then, the motivation for this work development is described as well as the objectives to be achieved at the end of the thesis. At last, the thesis structure is summarised.

1.1 Background

Composite material is a term referred to as any material consisting of two or more components with different properties, that when combined produce a material with properties that are superior to any of the singular constituent [1]. Usually, the two main constituents are the *reinforcement* and the *matrix*. While the latter binds, transfers the loads, and protects the reinforcement from the surrounding environment, giving the system its shape and appearance, the reinforcement carries most of the external loads and yields the composite material with high strength and stiffness, therefore performing the composite material main tasks. The use of composite materials for structural applications is growing every year in multiple application fields, such as automotive, aerospace, aircraft, marine, energy, infrastructural, and sports, among others [2]. The interest in the usage of composite materials is mainly due to their superior characteristics when compared to conventional isotropic materials. Among those, high stiffness and strength, and low density are the ones that stand out, enabling the potential for lightweight structures with high-quality mechanical

1.1. Background

properties. Furthermore, composites exhibit long fatigue life, corrosion resistance, acoustic, and conductivity insulation, justifying their applicability in multiple fields. Advanced composite materials are usually formed by multiple thin layers, the so-called plies, which when stacked together form the laminates. Depending on their orientation, the material properties change, and that is the main distinguishing property between composites and conventional metals, its possibility for anisotropy.

Composite materials are present in humanity for more than people imagine. The first forms of composite materials date back to ancient times, as Egyptians produced concrete as a composite material of mud or clay and straw. Later on, in 3400 BC in Mesopotamia, people strengthened wood materials by gluing wood strips at different angles, creating what is believed to be the first plywood. Elsewhere in the old world, different civilisations started to build their versions of composite materials to satisfy their necessities [3]. While on one side of the world the Chinese were combining paper pulp and adhesives to make paper structures and the Mongols were building bows made of wood, bone, and animal glue, on the other side the Romans were using concrete of various forms in 25 BC [4]. These landmarks in composite materials history prove that the desire and, most importantly, the necessity for its use is almost intrinsic in human life.

However, composite materials as we know them today, the so-called advanced composite materials began to emerge in the early 20th century with the creation of fibreglass by Owens Corning. Its first use was for electric insulation applications, and that is the reason why nowadays there is a fibre glass type called *E-glass*, as the *E* stands for electrical [5]. These advanced materials began to gain increasing importance during World War II, as military aircraft required lighter materials, and engineers began to realise the number of advantages fibre reinforced composites could offer when compared to conventional structural materials. After the war, the development of composites increased further, and after a few years, starting in 1970, the industry as a whole began to mature, with the introduction of improved resins and fibres, including aramid and carbon [4].

In the automotive industry, the use of composite materials began in 1981 when the Formula One (F1) McLaren team unveiled its title contender MP4/1, pioneering a monocoque made from CFRP. At first, the world was sceptical of this innovation, as despite its lightweight solution, the fragility of such materials remained a concern for many [6]. However, during the Monza Grand Prix, the car was involved in a serious accident, and the fact that the driver managed to walk away unharmed from his destroyed McLaren changed the paradigm of the sport forever. However, safety in the sport was still far from what was desired, as fatalities were still common during events. An effort made by the Federation International De L'Automobile (FIA) was instrumental in achieving the safety levels present in motorsport today, introducing strict rules to improve driver safety in the event of an accident [7].

Currently, F1 cars are implemented with crash structures made of CFRP. Its use increases the specific energy absorption of the structure when compared to previously used metals, which means that the driver's life is not as much at risk as it used to be in the event of an accident [8]. One of the biggest setbacks to the mass industrial implementation of CFRP in the automotive industry is the complexity of its crushing mechanisms and the fact that no safety factors can be considered. This fact is due to the fact that a high deceleration may be too much for humans to handle and too low energy absorption may be fatal. Despite this, some car models use CFRP and other composites in their structures, which need to be able to withstand high impact forces and pass mandatory crash tests before being released to the market.

However, there is one major issue that the automotive industry needs to address. Carbon fibres have huge amounts of embodied energy due to their manufacturing process, which requires

multiple high-temperature transformations. In addition, their predecessor products are generally petroleum-based, which, as is well known, is a very significant contributor to global warming and CO₂ emissions. Moreover, the recyclability of such fibres is yet to meet their demand. These factors call for eco-friendly composite materials, such as natural plant-based reinforced polymers, like flax fibre reinforced polymers (FFRP).

1.2 Motivation

The scientific community unanimously agrees on the need to use more sustainable materials, and composite materials are no exception. On one hand, the automotive industry needs to follow this trend and ensure better and more environmentally friendly materials. On the other hand, this industry is obliged to continue improving the safety levels of new vehicles. The balance between the increasing demand for improved safety and reduced emissions is very difficult to achieve and is driving car manufacturers around the world to develop new composite materials that can replace conventional metallic crash structures with lighter, improved and more cost-effective properties coupled with greater sustainability.

The understanding of the behaviour of composite materials in crushing applications is still far behind what is desired by the transport industry, thus limiting their application in mobile structures. Companies have difficulties in modelling their composite energy-absorbing structures as they have a lack of knowledge regarding what happens to the material during crushing and what are the factors that affect their behaviour, especially when considering the geometrical complexities of modern day structures. Furthermore, material characterisation provides another hurdle in the design process, as dynamic test setups for composite crush coupons are not yet standardised, and the mechanisms that control crushing are poorly understood. It is therefore necessary to further develop both test coupon geometries and dynamic experimental setups that enable a more accurate characterisation of the energy absorption parameters of composite materials, and to know how to interpret the obtained data, so that the gap between coupon testing and the modelling of complex crash structures can be bridged.

Furthermore, for greener crash structures to be used in the automotive industry, more knowledge must be acquired on the crushing performance of novel eco-friendly materials. Among these new materials are the natural plant-based fibre reinforced polymers (FRPs), such as those reinforced with flax, that have been attracting increasing interest in the scientific community, due to their sustainable origin and recyclability. However, there is still a significant gap in knowledge about the behaviour of flax fibre composites under crush loading, to an ever larger extent than that on CFRPs. Their energy absorption capacity is expected to be very limited and significantly lower than that of automotive and aerospace-grade CFRPs, which could make them unsuitable for use in structural applications in these industries. However, if a hybridisation process between stiff and strong fibres, like carbon fibres, and the mechanically-weaker flax fibres is carried out, there is the potential that the desired levels of energy absorption can be achieved without badly compromising the weight of the crash structures. This experimental study is yet to be carried out, and will first require an initial study on the monolithic behaviour of flax composite laminates under crush loading.

1.3 Thesis objectives

This thesis aims to shorten the gap between testing composite material coupons for crashworthiness applications and modelling impact absorption structures, with a focus on improving their

1.4. Thesis outline

sustainability. One of the milestones of this work is to carry out an extensive investigation of the state-of-art literature on crashworthiness and understand what the main gaps are. Based on that, it is an objective to understand how geometric parameters influence the energy absorption parameters on both monolithic CFRP and FFRP coupons. The hybridisation of both materials is also an object of study, as it is believed that this can substantially improve the degree of sustainability of impact structures without compromising too much on their specific energy absorption capacity.

As crash tests are destructive, the costs that arise from this mandatory step in the automotive industry are usually very high. Especially, when considering advanced materials for high-performance applications, like in motorsport, those costs grow in an even steeper manner. So, before testing the effective crash structure, coupon testing must be carried out, to characterise the properties and the crashworthiness parameters of composite materials. This necessity becomes even more important in hybrid composite materials, as the hybrid ratio plays a significant role in the overall stiffness of the composite and its other relevant mechanical properties. For that reason, coupon design, development, and testing are of vital importance for crushing applications and that comprises the main scope of this thesis. In this case, the testing of the specimens will be carried out exclusively in a quasi-static manner. Such a decision comes from the fact that it is necessary to understand, in the first stage, the behaviour of the materials under analysis when subjected to compressive loads. Such analysis becomes much easier and more reliable when tested statically. Furthermore, the test setup is much easier and more accessible when performed in a quasi-static manner, which allows for greater data collection and wider testing. Dynamic testing is still underdeveloped, requires more financial resources and labour.

1.4 Thesis outline

The themes covered in this thesis will be addressed in the order described in the previous section. This work divides its different chapters in the following way.

In Chapter 2 a detailed review of the state-of-art research performed on the crashworthiness field is covered. The evolution from metallic to hybrid sustainable composite materials is covered based on research that was made throughout the years. Crashworthiness parameters, failure modes and mechanisms are explained in detail, based especially in works carried out by researchers in the XX century, as these served as pillars for more modern studies in this field. Coupon testing is also covered throughout this chapter, which bridges this theme with crashworthiness numerical and analytical models that are mentioned at the end of the chapter.

In chapter 3 an assessment of the geometrical effects in coupon energy absorption is carried out. Firstly, the CFRP and FFRP materials used throughout the experimental test program are presented and are followed by the description of the manufacturing process of the coupons. The test setup used is explained and finally the results achieved are presented and discussed.

Chapter 4 covers the development and testing of hybrid composites made from FFRP and CFRP. Their potential to be employed as structural materials for modern-day composite structures is assessed based on the results achieved from the monolithic composite testing.

In chapter 5, the main outcomes of each chapter are presented, and several conclusions are drawn. Furthermore, this chapter raises a number of possible remaining gaps which need to be addressed in future work.

Chapter 2

State-of-art and literature review

In this chapter, an extensive literature review on the state-of-art of composite materials in crashworthiness applications is carried out. At the beginning, a short contextualisation is given, followed by a more specific theoretical explanation of composite materials in general and of materials used in crashworthiness structures, such as metals and composite materials. In addition, innovative solutions that can still be explored, namely through hybridisation with natural fibres, are briefly described. Much of the focus of this chapter is on explaining the crushing phenomenon, how it can be evaluated, and the main parameters that influence the energy absorption capacity of a given structure subjected to axial compression. A broad analysis of the fracture mechanics of composite materials is made, with a special focus on the behaviour observed during crushing loads. Finally, a review of the state-of-art of testing structures and coupons in crush applications is performed.

Furthermore, an analysis of the ecological impact of modern synthetic composite materials is performed. Currently existing alternatives, namely natural fibre reinforced composites, are explored, emphasising the strengths and weaknesses they may present in case of their industrial implementation as crash structures. Focusing on improving the sustainability of crash structures, a literature review on the topic of energy absorption of hybrid composites between flax and carbon fibres is carried out, despite the lack of research in this field.

2.1 Introduction

Composite material systems can be classified into different categories, namely *particulate composites*, *discontinuous or short-fibre composites* and *continuous fibre composites*. The latter are of particular interest for structural applications, as the reinforcement yields the composite with the best strength and stiffness, and general mechanical properties [9]. However, the use of fibres generates anisotropy on the laminates, which on one hand might be positive, as it provides the composite with many degrees of freedom for the material system, but on the other, it might weaken the composite if the load is applied in its most vulnerable direction, as it occurs, for instance, on the transverse loading of unidirectional laminates (UD) [10]. Generally, fibre reinforced materials have in their constitution either glass, carbon, or aramid (like KEVLAR®) fibres, bonded with a thermoplastic or thermoset resin, the so-called fibre reinforced polymers (FRP) [11]. Although

2.2. Crashworthiness

CFRP possesses great mechanical properties, such as high stiffness, due to their strong covalent bondings [5], the production of carbon fibres is highly polluting and a lot of energy is expended. Moreover, its organic precursors are overwhelmingly oil-based products, such as polyacrylonitrile (PAN) and pitch. The ever-growing concern over sustainability combined with the stricter european regulations has led the world to develop novel eco-friendlier materials, and composites are no exception.

Fibres from natural sources are emerging as a potential reinforcement for fibre reinforced composites (FRCs). Although natural fibre reinforced polymers (NFRP) are already being used in the automotive industry, their applications are mainly restricted to interior and exterior body parts without any structural function [12]. Mercedes-Benz pioneered the use of natural plant-based composites by combining an epoxy resin with jute fibres for the door panels of its E-class model in 1996 [13]. Many other car manufacturers soon followed this trend, using not only jute fibres but also flax, hemp and sisal as reinforcements [14, 15]. Currently, many efforts have been put in place so that NFRP can replace synthetic composite materials long used for structural applications. Shah et al. [16] conducted a comparative study between flax/polyester and E-glass/polyester for a wind turbine blade and concluded that although the mechanical behaviour of FFRP was inferior, its structural application is suitable for small wind turbine applications, which proves its potential for use in structural composites. Lately, further studies are being conducted to evaluate the possibility of replacing synthetic fibre reinforced polymers with NFRPs for crashworthiness applications [17–20]. Their potential for structural purposes, acting as monolithic or hybrid material has been corroborated. However, further studies in this field are required before this transition can be feasible.

2.2 Crashworthiness

Crashworthiness is defined as the ability of materials to absorb impact energy employing controlled failure mechanisms and modes [21]. For any automotive or aeronautical craft, the need for energy-absorbing structures or devices is mandatory, as crashworthiness has the function of (i) absorbing energy, (ii) keeping occupant compartments intact and (iii) supporting tolerable deceleration levels for drivers and passengers during a crash event [22]. For example, F1 teams are subjected to strict regulations imposed by the FIA regarding driver’s safety in the event of an accident. As shown in figure 2.1, four types of impact structures are required for the survival cell to remain unharmed: front, rear and side (top and bottom), which absorb a large amount of energy through a series of CFRP failure mechanisms [8]. These energy absorbing structures were originally made of steel or aluminium, in which the main energy absorption mechanism is based on controlled collapse by bending or folding, involving local plastic deformation [23].

However, not only in the heyday of motorsport, but also in the automotive industry, growing concern over environmental pollution, fuel consumption, government legislation and customer demand is driving the automotive industry to seek lightweight structures for crashworthiness applications [17, 22]. As a consequence, thin-walled composite structures have been widely used as energy absorption devices in many engineering fields, in order to replace thin-walled structures of steel, aluminium and magnesium alloys. Carbon fibre reinforced composites are of particular interest for energy absorption applications in vehicles as they have an excellent strength-to-weight ratio and design flexibility [18]. Such composite systems allow the weight of crash structures to be reduced, improving vehicle performance.

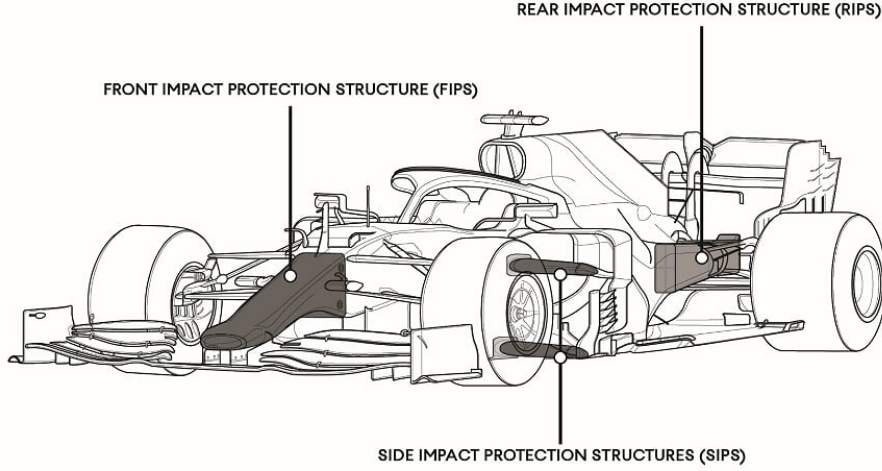


Figure 2.1: Front, side and rear impact protection structures of a modern F1 car (reproduced with permission from [24]).

2.3 Crashworthiness parameters

For the evaluation of the energy absorption capacity of a given material, it is necessary to define some parameters, so that its crushing quality can be better understood. These parameters are defined below.

2.3.1 Peak force

Peak force $F_{\max}$, also known as peak load, is the maximum force transmitted to the crash structure. It is important to avoid a very high peak force as this can be physically translated into too much deceleration for humans to survive. It can also lead to unstable failure of the crushing structure, as noted in Mamalis et al. [25]. In the case of impact structures, such as the side impact structure (SIS) of F1 cars, (figure 2.1) the value of the peak force can be reduced by a gradual increase in the cross-sectional area of the structure. However, when it comes to the testing of coupons this value is not of great relevance since it is highly dependent on the activation mechanism, which serves mostly to achieve progressive crushing.

Let $F(\delta)$ be the force at each point of the crushing section, a function of the displacement. The peak force can be given by Eq. 2.1:

$$F_{\max} = \max(F(\delta)) \quad (2.1)$$

where the displacement δ corresponds to the entire length of the crushed structure.

2.3.2 Average crush load

Average crush load F_{mean} , also known as the steady-state force, is the average force sustained during stable crushing progression. The post-crushing region of the load-displacement curve is

2.3. Crashworthiness parameters

characterised by high serrations, due to the crushing energy of the composite material being absorbed as a consequence of microfracture mechanisms [25]. Eq. 2.2 shows how to determine the average crush load.

$$F_{\text{mean}} = \frac{\int_{\delta_1}^{\delta_2} F(\delta) d\delta}{\delta_2 - \delta_1} \quad (2.2)$$

Note that δ_1 and δ_2 correspond to the inferior and superior limits of the post-crushing region.

2.3.3 Energy absorbed

The energy absorbed, EA, is given by the area below the force-displacement curve. It reflects the energy absorbed by the crushed part of the crash structure. Eq. 2.3 shows one way to calculate the EA.

$$\text{EA} = \int_{\delta_1}^{\delta_2} F(\delta) d\delta \quad (2.3)$$

There are a vast number of factors that affect the energy absorption capability of a material, such as fibre and matrix materials, laminate design, cross-section geometry, and the orientation of the loading, among others [25].

2.3.4 Specific energy absorbed

Energy absorption is a good measure to evaluate the capacity of a given structure to absorb energy. However, it does not quantify the energy absorption capacity of a given structure independently of its mass. Thus, it gives a better understanding of the structure performance, as it is independent of its geometry.

Specific energy absorbed SEA is the absorbed energy by the unit of mass of the crushed section of the structure. If the mass of the composite is known, it can be determined by Eq. 2.4:

$$\text{SEA} = \frac{\int_{\delta_1}^{\delta_2} F(\delta) d\delta}{m(\delta_2 - \delta_1)} \quad (2.4)$$

where m corresponds to the mass of the entire specimen or structure.

2.3.5 Crush efficiency

Crush efficiency, η_{eff} , is the ratio between the average crush force and the peak force. As Dalli et al. [26] stated, it assesses the progressiveness and stability of the crushing behavior. Low efficiency means that the structure is more prone to fail in an unstable manner. This value should be as close to the unity as possible. The equation that allows the calculation of the crushing efficiency is given below, by Eq. 2.5.

$$\eta_{\text{eff}} = \frac{F_{\text{mean}}}{F_{\text{max}}} * 100 \quad (2.5)$$

2.3.6 Crush stress

All the parameters presented above have some relevance and serve as a basis for some comparisons between materials. However, the crush stress is the most useful and distinctive parameter to relate the performance of different materials and component geometries [27]. Crush stress can be defined as the ability of a material to progressively absorb energy through destruction and disintegration [28], and it is therefore treated as a property of the material. In addition, crush stress can serve as an input parameter for numerical models. The average crush stress value can be easily calculated using the following equation:

$$\sigma = \frac{F_{\text{mean}}}{\text{Area}} \quad (2.6)$$

Figure 2.2 represents the typical response of a successful quasi-static crush test. It is possible to understand the previously mentioned zones, as well as the parameters that allow evaluating the energy absorption capacity of a composite when subjected to crush loads.

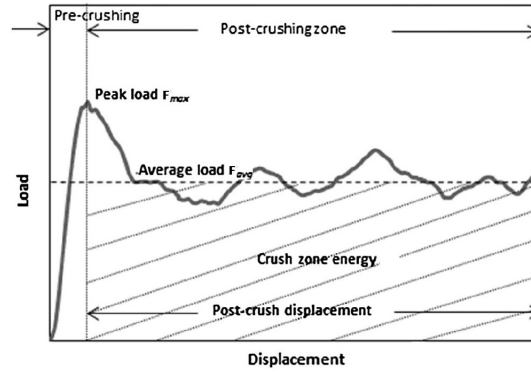


Figure 2.2: Typical load-displacement response of a crush test (adapted from [17]).

2.4 Materials for crush applications

2.4.1 Metallics

Traditionally, metallic materials have been used in previous years as energy absorption devices for moving structures. These energy absorption devices dissipate energy through different failure mechanisms such as friction, fracture, plastic bending, crushing, cyclic plastic deformation and metal shear [29]. As Salehghaffari et al. [30] concluded, metal structures for energy absorption resort to plastic deformation as a form of energy dissipation. Figure 2.3 shows the concertina mode effect in two axially crushed tube-shaped aluminium alloy specimens.

The use of metallic materials as energy absorbers, especially steel and its alloys, has some advantages. These include low material cost, good general ductility and recyclability. Other metal alloys, such as magnesium and aluminium, have lower density, better formability, and corrosion resistance. However, their lower strength and stiffness properties generally lead to larger deformations, as stated by Kaczyński et al. [31].

According to Mallick [32] some typical values of specific energy absorption of steel tubes are in the range of 30-60 kJ/kg. In the case of aluminium tubes, the value rises slightly to 70-85 kJ/kg. Compared with thin-walled carbon fibre reinforced composite structures, these values are much lower, as will be proven later in this thesis, in chapter 4.

2.4. Materials for crush applications



Figure 2.3: Two axially crushed tube-shaped aluminium alloy specimens (adapted from [30]).

2.4.2 Carbon fibre reinforced composites

The use of composite materials instead of metallic alloys is mainly based on their specific mechanical properties, such as high specific strength and high specific stiffness. In F1, their use in crash structures improves vehicle performance by providing considerably higher levels of specific energy absorption [25]. For example, tubes made of steel alloys can have up to 70% less specific energy absorption than CFRP tubes, while aluminium alloys can have only half the energy absorption capacity per unit of mass than a CFRP tube [33], making their use very attractive. However, a major disadvantage of using composite materials for crushing applications is the complexity of their failure modes and mechanisms. In fact this is one of the major differences between the use of composite materials and metallic materials in such applications. While the latter absorb energy mainly through plasticity, composite materials absorb energy through damage (fracture) mechanisms [27]. Furthermore, the behaviour of CFRPs when subjected to compressive loading depends on multiple factors, such as fibre and matrix type, fibre volume fraction [34], stacking sequence of the plies [27], and geometry [35, 36]. Several studies have been carried out so that these phenomena can be better understood and to improve the design and performance of such composite structures. Later in this work, the failure mechanisms and modes as well as their consequences on the crushing behaviour will be studied in more depth.

For energy absorption applications, carbon fibres are usually the type of reinforcement used. As mentioned previously, continuous fibres are the ones that, as a rule, produce the best mechanical properties, and are therefore usually desired for this type of application. CFRP represent a large share in the worldwide use of thin-walled structures for energy absorption structures. Carbon fibre is a synthetic fibre that can be obtained by different methods. About 90% of carbon fibres are obtained through the carbonisation process of polyacrylonitrile (PAN), which in turn is obtained from petroleum [18].

Two dimensional (2D) carbon fibre reinforced composites with continuous long fibres can be divided between UD and 2D woven fabrics. Although stiffness is usually higher in the fibre direction in UD composites, 2D woven fabrics ensure better balanced in-plane properties and higher interlaminar properties [37]. It is usually easier to shape complex geometries with 2D woven fabrics rather than UD. This characteristic leads to the fact that for the manufacture of complex composite structures the use of 2D woven fabrics is more suitable. For this reason F1 teams have used 5 Harness-Satin weaves to produce the side impact structures of their single seaters, as the ones shown in figure 2.4.

Although the use of synthetic fibres in crash structures presents numerous advantages, its manufacturing process requires high energy values, due to its various transformation processes at

high temperatures. For example, to produce glass fibres it is necessary, on average, to spend 54.7 MJ/kg. In the case of carbon fibres, on the other hand, this figure rises to 300 MJ/kg [38]. In an attempt to find materials that require less embodied energy, studies are being conducted to assess the potential for replacing synthetic fibres with natural fibres. Bio-fibres, such as jute, hemp and flax, are cost-effective, have low density and are biodegradable. For example, some of their specific mechanical properties may be comparable to those of glass fibres [39], as shown in table 2.1.

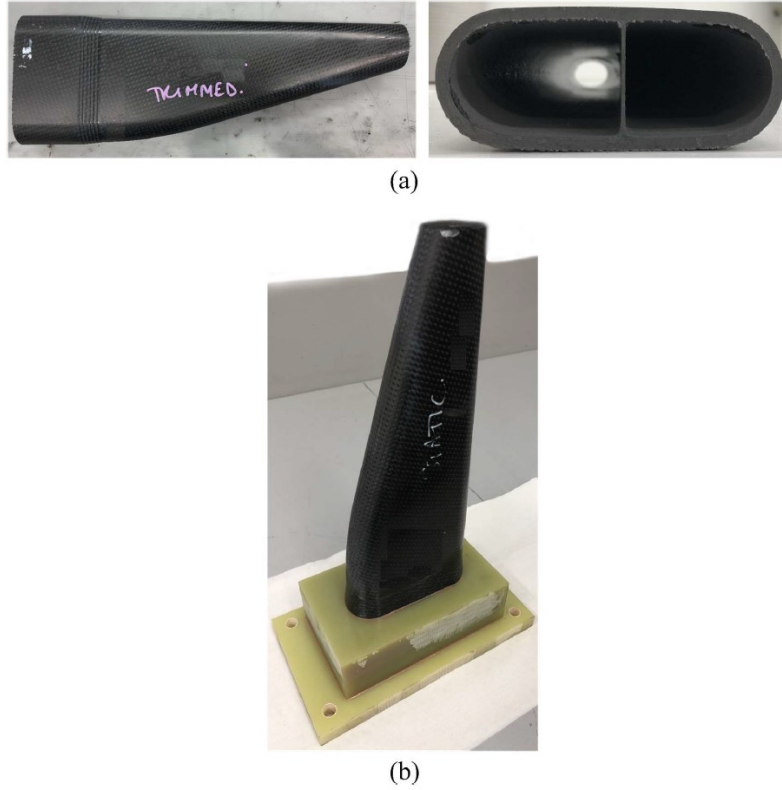


Figure 2.4: F1 side impact structure a) top and front views; b) mounted in a testing base [26].

2.4.3 Natural fibre reinforced composites - Flax

Flax fibre as reinforcement for composite materials has recently gained popularity as it shows a high potential to partially replace synthetic fibres with a very low embodied energy level. For example, the primary energy consumption for producing flax fibres is around 11.4 MJ/kg. This means that its processing requires much less energy compared to the synthetic fibres already analysed, showing potential to act as a more sustainable alternative [39]. In addition, flax fibres have a density comparable to carbon fibres, and the fact that it is a non-toxic material upon inhalation makes it appealing for some applications, including crushing.

Flax (*Linum usitatissimum*) fibres are a cellulose polymer produced in the stems of flax bast plant [39]. Such fibres have been used by humans for thousands of years, with early records of the use of this textile material back 7000 years ago in Egypt [40]. The constitution of flax fibre is extremely complex, with cellulose, hemicellulose and lignin determining its physical properties. The first mentioned is the strongest and the toughest, but it is also responsible for the hydrophilic nature of flax, which, when used to reinforce hydrophobic matrices, results in a poor interaction with the interface, absorbing a lot of moisture [41]. Indeed, the hydrophilic nature of natural fibres

2.4. Materials for crush applications

has proven to be one of the main drawbacks and challenges of plant-based fibres, leading them to produce composite materials that can result in even worse properties than their uncombined constituents [42]. This drawback can be solved by some fibre modifications, such as alkaline treatment that reduces the hydrogen-bonding capacity of cellulose, reducing its potential to absorb water molecules. Symington et al. [43] studied this effect on tensile properties, and although they were difficult to obtain, due to the variation of constituents in the cross-section, it was possible to reach some conclusions on the effect of alkaline treatment on natural fibres. Although these have increased fibre mechanics, as well as their ability to bond with hydrophobic resins, they have also introduced less desirable characteristics, such as higher pH values, polluted wastewater and the degradation of cellulose fibres, translating into a possible reduction in stiffness. Besides this method, there are also some other promising ways to reduce the moisture absorption potential, such as the Duralin steam process [44]. However, this treatment increases the amount of energy embodied in the fibres due to the steaming process. Such consequence limits the great advantage of using flax fibres in detriment of synthetic fibres, as their production becomes less sustainable.

Another challenge that studies have revealed concerns the long-term durability of natural fibres when exposed to various environments. Stamboulis et al. [45] revealed that the ability of ligno-cellulosic fibres to absorb moisture, their poor dimensional stability (swelling), and their susceptibility to rooting were the main restrictions for their use as reinforcement in composite materials, as they reduced their durability. In addition, moisture was found to be the main cause of fungal development experienced in flax fibre. The use of coatings and fibre modification treatments such as alkanisation, bleaching and silanes appear to delay the above effects [44].

Batch variability can be another disadvantage of using NFRP. Many factors can lead to variations in fibre quality, including crop variety, seed density, soil quality, fertilisation, field location, fibre location in the plant, climate, weather conditions, and harvest timing, as stated by Dittenber et al. [44]. Mohanty et al. [42] studied the effect of surface modifications on natural fibres. It was concluded that variation in cross-sectional area, extraction processing methods, damage incurred in handling and processing, and differences in the drying process can lead to variations in the final product. Such variations lead to a wide dispersion in the constitution of the fibre and, as such, a bigger scatter of its mechanical properties. Price fluctuations can also occur due to climatic variations, making the price of these fibres hard to predict or control.

During crushing of a composite laminate, the types of fracture that can be experienced are usually: (i) elastic and inelastic buckling, (ii) failure initiation away from the crush front, and (iii) normal progressive crushing. The latter is the mechanism that is intended to be promoted in order to obtain better energy absorption values. However, the behaviour of the composite laminate during crushing is highly dependent of its mechanical properties, and in specific, of its compressive strength. Therefore, to achieve progressive crushing, this property is of extreme importance, with the risk that if the stiffness of the material is too low, the material will suffer from buckling or failure away from the crush front. The cases previously described can be experienced, for example, in composites reinforced with flax fibres, which normally have much lower compressive strengths than carbon fibres. Bambach [46] carried out an experimental study on the compressive strength of composite laminates reinforced with flax, jute and hemp fibres with an epoxy matrix. The coupons exhibited linear elastic behaviour until buckling was initiated. Thereafter, a reduction in stiffness and an increase in out-of-plane deformations were observed, with no brittle rupture observed. His study showed the susceptibility of flax fibres to fail by fracture mechanisms other than those desirable for crushing applications.

Table 2.1 gives an overview of some mechanical properties of the previously mentioned materials,

as well as some additional data regarding their sustainability and manufacturing. Some direct comparisons can be made, such as between CFRPs and metallic materials. The density of carbon fibres is generally very low and their stiffness very high. As for their compressive strength, they also present high values, which is preponderant for crash structures. These factors make CFRPs ideal for energy absorbing structures, allowing a significant reduction in vehicle weight, a considerable reduction in fuel consumption and, consequently, a reduction in pollutant and greenhouse gas emissions. The same table shows the ecological and economic advantages of using flax fibres instead of the aforementioned synthetic fibres.

2.4.4 Hybrids

Hybridisation can be performed in several ways, namely intra-ply hybridisation, sandwich or shell hybridisation, and inter-ply or laminated hybridisation [47]. The latter is of particular interest for impact situations, as the stiffer material can improve the energy absorption capacity of the laminate if combined with lower modulus fibre plies [48]. Hybridising natural plant-based fibre laminates with synthetic fibre composite materials, such as carbon, can have very beneficial effects on crash structures. By hybridising natural fibres with synthetic fibres it is possible to ensure sufficient levels of compressive strength and stiffness so that the composite structure is progressively crushed without its weight being compromised. Moreover, as in any other case of hybridisation of composite materials, it is possible to highlight the best properties of each of its constituents. In the case of hybridisation of composite materials reinforced with natural and synthetic fibres, it is possible to highlight the high specific stiffness of the synthetic material with the high damping capacity and the low levels of embedded energy of the natural fibres [49]. It is of great interest to explore the full potential of this type of hybridisation since it allows for reducing the ecological footprint that composites reinforced with synthetic fibres present.

As demonstrated earlier, both carbon and flax fibres present some advantages so that they can be used as reinforcement phase in polymer matrix composites in energy absorbing structures. While carbon fibres have high specific stiffness, and superior tensile and compressive strength, flax fibres have stiffness comparable to E-glass fibres, density comparable to carbon fibres, and most importantly, show a high potential to make composite materials more sustainable. However, the so-called 'green' or 'semi-green' composites, such as FFRPs, have very low strength and stiffness, when compared to CFRP, which makes impossible its use as monolithic composites for structural applications. Having said that, the hybridisation between flax and carbon fibres can combine the best properties of both materials, and possibly maintain the requirements that guarantee the necessary levels of energy absorption.

When analysing non-hybrid CFRP, the energy absorption capacity depends on many factors such as material type, structural geometry, stacking configuration, strain rate, fibre stiffness, among others, as explained by Farley et al. [50]. However, when it comes to hybrid composites, additional variables must be taken into account, which increases the complexity of laminate design. Some of these variables include the hybridisation ratio, the stacking sequence of the plies, ply layup configurations, etc [18].

Hybridisation of composite laminates can be done by combining materials with the same fibre type. Ghasemnejad et al. [51] conducted a study on the effect of delamination failure of a hybrid composite box on its crushing behaviour. Its performance was compared with that of a non-hybrid box. A combination of twill weave composite and unidirectional CFRP was used to fabricate the hybrid composite box. Mode-I and mode-II delamination studies were performed with the same plies to investigate the effect of delamination crack growth on the energy absorption of the hybrid

2.4. Materials for crush applications

Table 2.1: Some qualitative and quantitative properties of the materials used or with the potential to be used in crashworthiness applications (after [20]).

	Properties		Mild steel		Aluminium alloy		Magnesium alloy		2D Woven Carbon		UD Carbon		E-Glass		Flax	
	Cost of raw material/fibre (€/kg)															
Economi- cal	Density (g/cm^3)		7.85		2.70		1.74		1.32-1.49		1.53-1.60		2.5		1.4	
	Tensile Modulus (GPa)		207-210		65-70		44.2		40-63		130-135		73		27-80	
	Compressive strength (MPa)		250		120		65-100		545-597		1000-1200		215-245		99	
Ecologi- cal	Primary energy consumption (MJ/kg)		22		211.5		310		300		54.7		11.7			
	Renewable Source		No		No		No		No		No		No		Yes	
	Recyclable		Yes		Yes		Yes		No		Partly		Yes			
	Biodegradable		No		No		Yes		No		No		Yes			
	Toxic upon inhalation		No		No		No		Yes		Yes		No			

composite structure. In this study, hybrid laminate designs showed enhanced fracture resistance in Mode-I and Mode-II delamination tests than monolithic laminates. As such, it was possible to predict that higher values of energy absorption in crushing can be achieved by hybridising two different types of fabrics.

Although there are some works that hybridise natural fibres with synthetic fibres, very few studies have been carried out hybridising FFRPs with CFRP. Strohrmann et al. [19] tested the crashworthiness of flax/carbon reinforced polymers by crushing circular tubes quasi-statically and dynamically. In this study four different types of tubes were manufactured. One of the tube types was composed exclusively of eight 2x2 twill plies of CFRP, another of eight 2x2 twill plies of FFRP, and the other two tubes were composed of hybrid forms of these two materials, both balanced and symmetrical, but with the difference that the carbon plies were on the outside in one of the tubes and the flax plies were on the outside in the other. The results obtained proved the worse energy absorption capacity of FFRP tubes compared to CFRP tubes. However, the hybrid tubes showed better crush stress and SEA values than their intermediate values. That is, the crush stress and SEA values in the hybrid forms were higher than the arithmetic mean of the crush stress and SEA values of the CFRP and the FFRP crushed tubes. For example, the SEA value obtained in the quasi-static tests was 103.9 J/g for the CFRP and 19.3 J/g for FFRP tubes, i.e., the average of these values was 61.45 J/g. However, the hybrid tube, with CFRP on the outside of the laminate, was 71.2 J/g. These values, prove the hybridisation potential between these two different materials in crushing applications.

In general, hybridisation of flax and carbon fibre reinforced composites seems to be promising in crushing applications, as it can make these types of structures more sustainable, without compromising too much their energy absorption capacity and weight. However, it is important to highlight that the sustainability-related benefits of flax fibre reinforced composites may be overshadowed by the use of non-green materials in the composite matrix. That is, the matrix of a composite can be a thermoset resin, a thermoplastic polymer or a bio-resin. Although the use of a bio-resin is more beneficial in terms of sustainability, its mechanical properties are much lower than the other alternatives. Thermoplastics, despite being recyclable and having mechanical properties much better than bio-resins, and even slightly better than thermosets, have great limitations in terms of handling the melt, which limits their use in complex shapes, and require high temperatures to be processed, which becomes impractical when the reinforcement material is flax. One must recognise such a limitation, i.e., FFRP are not fully sustainable as the matrix is generally made up of thermoset resin. In the future, more studies of the hybridisation between flax and carbon fibre reinforced composites should be conducted, in order to better understand the behaviour of such structures and to exploit the potential of these hybrid structures.

Throughout these sections, it was pointed out which are the benefits in terms of performance and energy absorption that composite materials can assure to detriment of, for example, metallic materials. From now on, more emphasis will be given to the crashworthiness of composite materials, since when well designed and modelled, they can provide the best energy absorption properties.

2.5 Fracture mechanisms in composite materials

While in metallic materials, the energy absorption by the structures when subjected to crushing loads is mainly due to the plasticity of the material, in composite materials energy absorption is achieved through complex fracture and damage mechanisms.

2.5. Fracture mechanisms in composite materials

Figure 2.5 schematically represents the typical behaviour during progressive crushing of a composite laminate, experienced by Savona et al. [52]. As can be observed, there is an enormous variety of interactions between the plies and fracture phenomena occurring at the crush front. For instance, interlaminar crack growth and shear forces between plies, friction between moving plies and crush plate, fibre breakage, matrix cracking, delamination, etc.

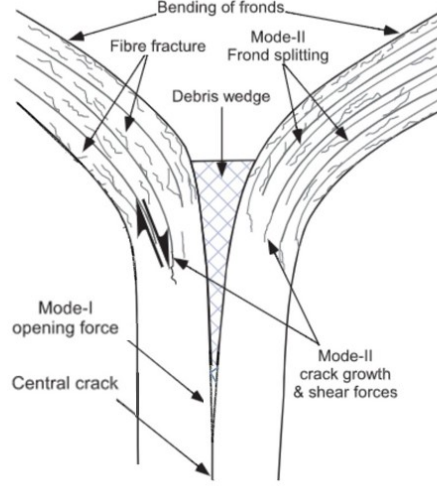


Figure 2.5: Schematic representation of the different effects occurring at the crush front of a flat coupon. Figure inspired in the work carried out by Hull [27] and adapted from [52].

If all the factors contributing to energy absorption are added together it is possible to calculate the total energy absorbed by a composite when subjected to crushing loads. Equation 2.7 allows this value to be obtained by adding up all the components contributing to energy absorption [52].

$$U_{\text{total}} = U_{1c} + U_{2c} + U_{\sigma} + U_{\text{ff}} + U_{\text{fr}} + U_{\text{others}} \quad (2.7)$$

where U_{1c} describes the Mode-I fracture energy, U_{2c} the Mode-II fracture energy (which comprises the frond splitting, crack growth and shear forces), U_{σ} the bending of the fronds energy, U_{ff} the fibre fracture energy, U_{fr} the friction energy at and within the crushed fronds and U_{others} other energies that include the Mode-III effects. Hussein et al. [53] studied the crushing of square-shaped tubes, concluding that crack propagation in the laminate accounted for about 35% of the energy absorbed and that about 60% of that same energy was caused by shear effects. In addition, they found that failure modes are highly dependent on fibre orientation and laminate geometry, as Farley [35] had previously found. Having said this, it can be seen that composite materials when crushed experience several damage modes and that each one has a different contribution to the energy absorption capacity of the laminate. To have a better understanding of the crushing behaviour of composite materials and how their energy absorption is achieved, some of these fracture mechanisms will be described as follows.

2.5.1 Matrix cracking

Matrix cracking can be defined by the formation of cracks in the bonding component of the laminate, i.e. the thermoset or thermoplastic matrix. Matrix cracking can also lead to other types

of damage, such as localised clustering¹, fibre fractures or delamination [55]. These matrix cracks typically occur at stresses lower than the failure stress of the entire laminate. Whether under static or fatigue loading, the damage at initiation is usually the result of the nucleation, propagation and multiplication of transverse cracks. As this failure mechanism is a non-catastrophic damage mechanism, the number of cracks increases while external loads are applied. The presence of cracks degrades material properties and changes the way loads are transferred [56].

2.5.2 Fibre breakage

Also known as fibre splitting, fibre break consists of the rupture of the fibres. In the case of compressive loads, this failure mechanism is more likely to occur if large in-plane shear stresses are combined with compression. This fracture mechanism is one of the steps towards the final failure of composites. In the fibre bundle theory, the final tensile failure of the composite occurs when a certain number of fibre breaks occur. This failure can occur as a result of high stresses, (which is what happens in crush loads), a sudden temperature rise during experimental work or as an indentation effect [57]. In addition, in compressive loading local kink-band² may appear in regions of fibre misalignment, leading to a premature failure of the fibre in the longitudinal direction [58].

2.5.3 Delamination

Also known as interlaminar cracking, delamination is one of the most frequent types of damage in composite laminates [59]. It is a failure mode in which the material fragments in layers, i.e., it is a form of matrix crack that propagates between layers [47]. Delamination can affect several properties of the composite material, such as the compressive strength, which can lead the composite to fail by buckling [57], which is unacceptable for composite materials designed for energy absorption purposes. It is also known that woven fabric composites offer higher damage tolerance compared to UD composites due to their non-planar interply structure. This property intrinsic to this type of fabric allows better interaction between the delamination crack, matrix regions and weft structure during propagation, resulting in crack growth [60]. It is important to distinguish delamination from debonding, as the latter occurs due to the low adhesion between plies, for various reasons. There are three different modes of interlaminar fracture by which a load can operate a crack. Some of these interlaminar cracking modes play an important role in crashworthiness applications, so a brief description of them is made as follows.

2.5.3.1 Mode-I interlaminar fracture toughness

Mode-I (or opening) delamination is the interlaminar fracture of a composite by inducing a tensile load, normal to the plane of the crack, on both sides of the laminate as it is described by figure 2.6. In this case, a double cantilever beam (DCB) test is represented and performed by the ASTM D 5528 standard. Mode-I interlaminar fracture toughness, G_{Ic} , measures the critical value of delamination growth as a result of the opening load P .

DCB tests have visual similarities with various coupon crush tests, so this property appears to be very important in composite laminates designed to act as energy absorbers. The determination of the fracture toughness of a composite material for crushing applications can be very useful to make crush stress predictions, as in the studies carried out by Hussein et al. [53] and Mamalis et

¹Clustering in composite materials refers to the aggregation of the constituents such that the composite does not exhibit uniform micro-structural distribution [54].

²Kink bands are bands of material where the fibres inside the band have rotated relative to the fibres outside. This failure mechanism is prone to appear during the compressive loading of the composite material.

2.5. Fracture mechanisms in composite materials

al. [61–63]. Studies conducted by Savona et al. [52], Hull [27] and Mamalis [25] reveal that the fact that the composite splits its mid-plane at the initial stage of crushing is related to the mode-I fracture toughness properties.

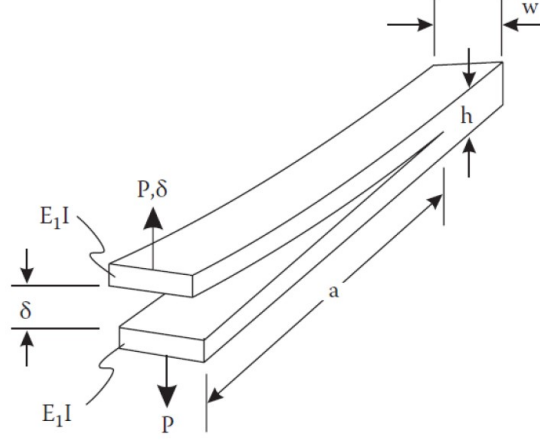


Figure 2.6: Schematic representation of a mode-I fracture toughness DCB test (after [64]).

In the study performed by Farley [35] several tubes were crushed axially. On the tube walls an annular wedge of strongly compacted crushing debris forced the tube wall to separate symmetrically, causing a long mode-I crack to propagate axially along the centreline of the tube wall. Dalli et al. [26] also achieved a similar result by axially crushing flat plate coupons, where a central wedge of debris caused the creation of two symmetrical fronds, generating mode-I delamination.

2.5.3.2 Mode-II interlaminar fracture toughness

Mode-II fracture toughness comprises the delamination of composite materials when subjected to shear stress acting parallel to the crack plane and perpendicular to the crack front. The end-notched flexure test (ENF) is one of the tests to determine the mode-II fracture toughness, G_{IIc} . Is a test described by the ASTM D 7905 standard and it is represented in figure 2.7. Similarly to mode-I, shear fracture toughness is also believed to play an important role in the energy absorption of a crushed composite laminate. Savona et al. [52] concluded that during progressive crushing the splayed fronds split and delaminate through mode-II shearing. That is, mode-II properties show a strong correlation with the energy absorption capacity of a composite laminate, indicating that shear cracking is an important factor that influences the energy absorption of a given composite structure.

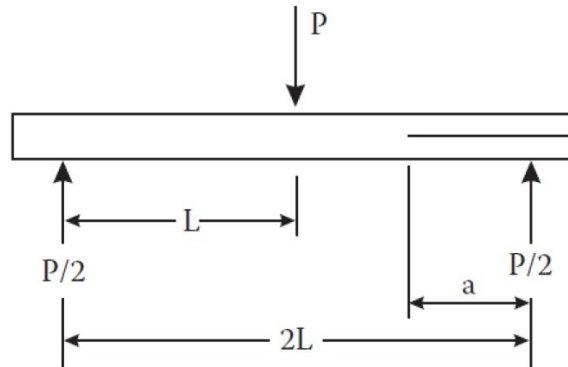


Figure 2.7: Schematic representation of an ENF test according to the ASTM D 7905 standard (after [65]).

2.6 Composite failure modes at the crush front

Hull [27] wrote an extensive work where the phenomena behind progressive crushing are explained based on experimental studies carried out. He explicitly divides the failure modes of composite materials subject to crushing into 'splaying' and 'fragmentation'. These modes are related to the primary micro-mechanisms of fracture in the composite material described before. The following sections describe these two failure modes experienced at the crush front.

2.6.1 Splaying mode

Splaying is a failure mode that usually occurs during axial crushing of structures or coupons, in which out-of-plane failure is predominant. In the study done by Hull [27] the mode of failure by splaying was described by subjecting a cross-ply glass fibre/polyester composite tube to crushing. The layup of the tube was $[0,90]_s$, with the plies in the 0° direction corresponding to the hoop direction and the plies at 90° to the axial. In this kind of layup, the fibres in the axial direction carry the majority of the load and the so-called hoop fibres support them, mitigating premature buckling. Thus, the compressive strength is dominated by the axial plies. The axial fibres spread in a series of fronds to the outside and inside of the tube, and a crack was formed along the centre of the tube wall. A wedge of debris, consisting of crushed fibres and resin, was formed on the surface of the crush plate at an early stage of the crushing process. Then, as the crush plate moved forward the axial fibres moved outwards, and the outer fibres of the hoop were subjected to tension and eventually fracture. Similarly, the axial fibres moved inwards, the inner fibres of the hoop were compressed and the plies failed by buckling and intralaminar shear normal to the fibres [27]. Figure 2.8 represents the stages of splaying mode in the laminate tested by Hull.

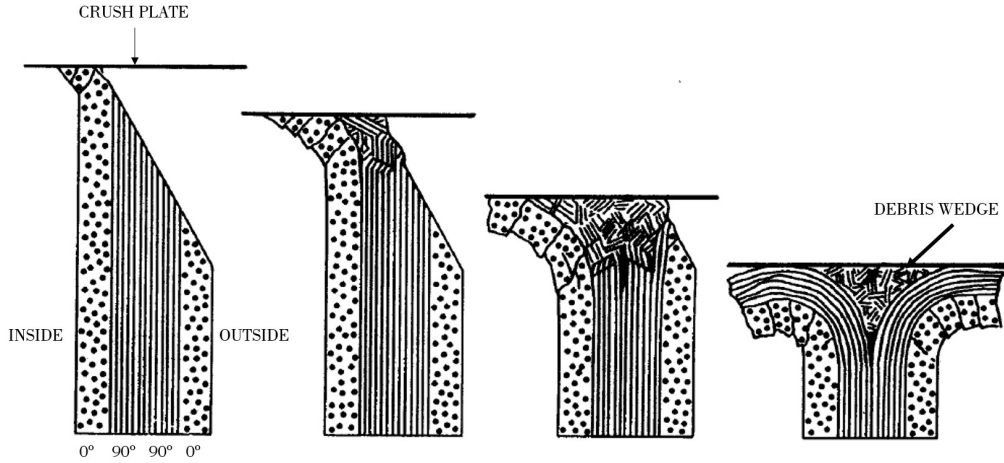


Figure 2.8: Schematic representation of the formation of the splaying mode in the wall of a tube being crushed (adapted from [27]).

In the study carried out by Dalli et al. [26] CFRP tubes with eight woven plies were axially crushed statically and dynamically. The predominant damage mode was found to be splaying, while some fragmentation of the central plies of the coupons was also observed. The transition from the initial mode of fragmentation to the predominant mode of splaying was possible to observe through the stress vs strain plots, since as this transition occurred the crushing load decreased. Comparing the type of plies used in this study with the ones used by Hull [27], it is possible to realize that this type of failure mode can occur not only in UD cross-ply laminates but also in laminates composed by woven fabric plies.

2.6. Composite failure modes at the crush front

In some studies conducted with flat coupons splaying was also the most predominant failure mode. Dalli et al. [26] also tested flat coupons under static and dynamic conditions. When the flat coupons did not buckle, a dominant symmetric splaying effect was observed, as shown in figure 2.9. Crushing debris from the inner plies forced the outer plies to be folded outwards. Delamination fronts were created between the two outermost layers on either side of the coupons. As the amount of debris in the central region increased, the outermost layers offered less support, and as such the inner layers began to fold outwards in a similar way to the outermost layers. After significant progress on the crush front, all the plies eventually folded outwards, with a central wedge of debris being progressively forced to delaminate the layers beneath it. Another example where splaying is predominant in flat coupons was in the work carried out by Vigna et al. [66] where the in-plane compression of flat coupons under quasi-static and dynamic conditions was studied. Symmetric splaying was also the predominant failure mode, which basically consisted of delamination along the mid-plane of the laminate, forming two fronds.

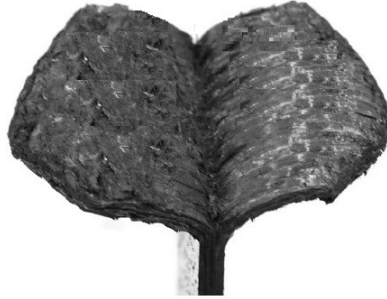


Figure 2.9: Symmetric splaying of the fronds on a woven fabric flat coupon, with the debris wedge removed (adapted from [26]).

To sum up, splaying is a failure mode that occurs in several composite laminate geometries when subjected to crushing loads. The failure micro-mechanisms that lead to this behaviour of the laminates are diverse and are originated by different forces acting at the crush front. Among them the following groups stand out: compressive forces acting between the crush plate and the debris wedge, friction between the fronds and the crush plate as the sliding occurs, friction between the debris wedge and the fronds, friction between the various plies as the sliding and delamination between the adjacent plies occur, and the constraints that the outer layers cause by resisting the crack formation in the inner wall of the tube [25, 27, 36, 61, 62].

2.6.2 Fragmentation mode

Fragmentation is a type of failure mode that occurs during crushing in which in-plane failure modes are promoted. In Hull review [27], the mode of fragmentation was illustrated by referencing crushing tests of tubes manufactured from woven fabric of E-glass fibre-reinforced epoxy. As the progressive crush zone in the tube was reached fragments were formed on the tube walls before these were completely separated from the tube wall. The layup of the tubes was the same as that used to explain the splaying mode, i.e. $[0,90]_s$, thus implying fibres in the axial and hoop directions. However, their distribution along the tube wall was distinct since the plies were a woven structure and not UD as before, as can be seen in the first image of figure 2.10. The trigger zone was crushed in a manner very similar to that previously experienced in the tubes of section 2.6.1, through a combination of shear splitting and compressive buckling, and matrix cracking was also evident in the resin-rich areas. After that, the compressive forces generated very high shear forces resulting in shear failure, as shown in the second image of figure 2.10. Fragments were broken and as they were forced outwards, the hoop restraints resulting from the tubular shape produced

additional tensile and compressive forces that tended to break the fragments into short segments by compressive buckling inside the tube and tensile fracture on the outside, as shown in figure 2.10. The shear stress failure involved several failure mechanisms previously mentioned, such as fibre fracture, interlaminar fracture and matrix cracking.

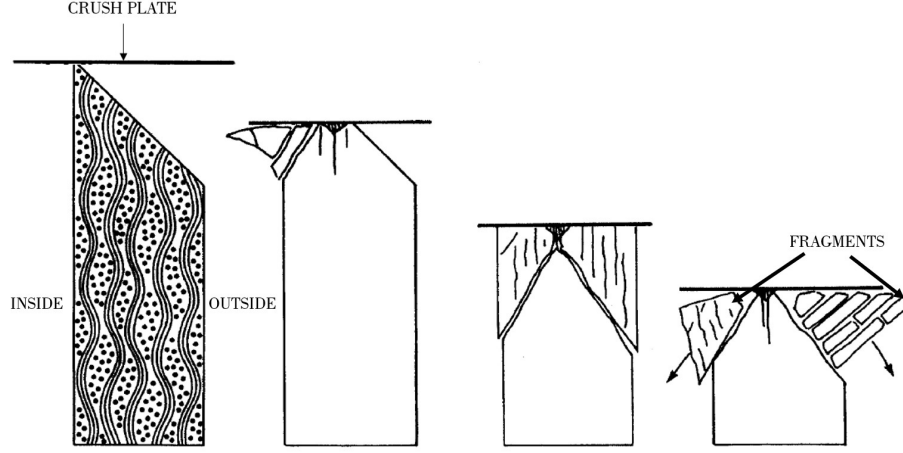


Figure 2.10: Schematic representation of the formation of the fragmentation mode in the wall tube being crushed. Adapted from [27]

Xu et al. [22] studied the effects of strain rate, hybrid ratio, fibre orientation and tube wall thickness on composite tubes. One of the fabricated specimens consisted of a CFRP tube manufactured by filament winding with a heat treatment. The tube configuration consisted of an inner wall with 0.15 mm thickness of fibres at 88° to the tube axis, a 2 mm thick intermediate wall with the fibres at 17.6° , and a 0.5 mm thick outer wall with the fibres again aligned at 88° . These tubes were crushed statically and dynamically. After crushing, the tube wall split into internal and external fronds typical of splaying mode crushing. A well defined debris wedge was observed. Below the debris, a wedge of short crack was observed in the longitudinal direction of the tube wall. Fibre fracture and interlaminar delaminations were observed in both fronds, especially in the external fronds with small bending curvature. Figure 2.11 shows a photographic capture of a post-mortem analysis of the composite tube described above. On the outer side of the tube it is possible to clearly observe that a greater failure by fragmentation occurred than on the inner side of the tube, where the splaying mode was predominant. This may be related to the ratio between the fibres in the axial direction and the hoop direction, A:H ratio.

Berry [67] studied the effect of different hoop and axial fibre ratios. Tubes with a thickness of 2 mm (10 plies) were fabricated from a series of pre-preg glass-polyester fabric materials with different warp to weft ratios, which are described in table 2.2. The tubes that presented higher number of fibres in the hoop direction were crushed essentially by fragmentation. Similarly to Hull [27], the formation of shear cracks caused compressive and tensile stresses in the hoop, causing fracture in segments of varying lengths. As for the remaining tubes, with H:A ratios equal or less than 1, splaying was the predominant failure mode. Table 2.2 synthesizes the microfracture mechanisms experienced for the different H:A ratios tested.

By varying the fibre distribution of a laminate, it is possible to alter the micromechanisms of crushing, which are the main factors for composites to fail by splaying or fragmentation. The transition between these two modes can be explained through the constraint that fibres in the hoop direction impose, mitigating or reducing the splaying mode in fibres oriented in the axial direction.

2.7. Crush testing

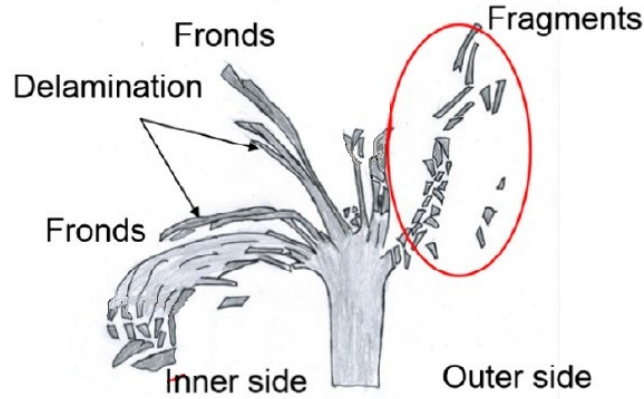


Figure 2.11: Filament wound CFRP tube wall crushed statically. The inner wall fails by splaying and the outer wall fails by fragmentation (adapted from [22]).

In other words, as the constraints imposed by the fibres in the hoop direction increase, there is a tendency to reduce the probability of failure by splaying mode, and in turn a higher probability that the applied load generates an increase of shear fracture across the tube wall leading the laminate to fail by fragmentation. That said, for example if splaying does not occur, the stresses in the crush zone will increase significantly until a shear fracture saturation point is reached, generating fragmentation [27].

Table 2.2: Failure mode variation during crushing of glass cloth-polyester resin tubes for different hoop-to-axial fibre ratios (after [67]).

H/A ratio	Comments
8.5:1	The rings in the hoop direction suffered shear stress and failed in compression on the inside and in tension on the outside. Fragmentation was the predominant failure mode.
7:1	
4:1	
1:1	A large wedge of debris. The fibres in the axial direction were broken in very short lengths, and splaying was predominant.
1:4	Large wedge of crushed debris. More intact splaying, i.e., fewer fibre breaks
1:7	Very pronounced splaying with complete delamination and very isolated axial fibre fracture
1:8.5	

2.7 Crush testing

Some years ago, a group represented by entities from aerospace, automotive, academia and government laboratories was formed to study crashworthiness. It was agreed that it was vitally important to develop suitable test methods so that researchers could compare candidate materials and structural designs with which to build a suitable database. To this end, two test methods were identified for development and standardisation, namely laminated flat coupons and thin-walled tubular specimens [68]. One of the methods used to assess the crashworthiness capability of a determined structure is to subject them to axial crushing loads. During crushing, it is possible to collect enough data to calculate the parameters described in chapter 2.3 and to analyse the failure modes and fracture mechanisms of the structure during and after the experimental procedures. As already mentioned, the crush stress parameter is of utmost importance in the characterisation of

structures for crashworthiness applications. Several factors can influence the value of this parameter, among which the geometry of the component stands out, i.e., whether it is flat or curved, the strain rate and the angles of orientation of the laminate plies, as seen in the previous section. Thus, coupons for crush applications can vary in terms of geometry and material (including ply orientation) and the tests themselves can be performed quasi-statically or dynamically. As for crash structures, since they are normally subjected to dynamic conditions, the dynamic crushing test becomes practically imperative, as it is the case of F1 crash structures [8]. The following section comprises a short literature review of some crush tests performed, focusing on the test strain rates, and the geometry and material of the specimens.

2.7.1 Crash structures

As seen earlier, impact-absorbing structures are fundamental in moving structures to ensure the well-being of their occupants during impact situations. The crash structure must be neither over-dimensioned nor under-dimensioned, since in the case of the first condition, passengers may be subjected to too abrupt decelerations, and in the case of the second condition, the structure may not absorb the amount of energy required to ensure physical integrity.

F1 impact structures are subjected to dynamic tests that require at least 15 m/s deformation rates to be applied [69]. Dynamic testing of impact absorbing structures can be carried out using, for example, drop tower tests, more suitable for coupon testing, or sled impactor tests, for structures, as done by Dalli et al [26]. These types of tests require complex setups and the data reduction itself is complicated, as it requires the application of noise-reducing filters due to oscillatory responses obtained during testing. In addition, these are tests that require greater financial capacity from companies, since they are more expensive than testing quasi-statically. In addition, they are very limiting tests in terms of the conclusions that can be drawn after they have been carried out. That is, it is more complicated to characterise material behaviour dynamically than statically, and as a consequence, it becomes much more challenging to determine consistent and reliable energy absorption parameters.

Therefore, it is imperative to test coupons, statically, so that it is possible to perform a correct evaluation and understanding of what effectively happens with composite materials when subjected to crushing loads.

2.7.2 Open section coupons

Open section tubes have been tested in the literature, in various geometries. C-channels were tested by Waimer et al. [70] for aeronautical applications, and by Feraboli [71]. Corrugated and semi-circular were also assessed by Feraboli in the same study [71]. Flat coupon testing studies were also carried out in several other occasions [23, 26, 66, 68, 72, 73]. Flat coupons are easier to manufacture when compared to closed section coupons, but their testing is way more complex and hard to carry out, due to the higher potential for elastic instabilities caused by long unsupported lengths, as experienced by Dalli et al. [26] and Feraboli [23].

One of the main challenges of flat coupon testing is that there is the need to use a dedicated fixture. Feraboli [68] has conducted a comprehensive review on some of the supports used in some flat coupon testing. It was concluded that the attachment of flat coupons to the test support has a major influence on the crush response and failure modes. At the same time, it is really challenging to achieve a plateau of crush stress like the one observed in tubular coupon testing, which is self-supported. Vigna et al. [66] studied the effect of friction between the flat specimen and the fixtures and concluded that there is a considerable difference between some test setups in the

2.7. Crush testing

energy absorption values. For example, the use of lubricant at the interface of the sheathing with the fixture helps to reduce the clamping friction by 5.6%, influencing the crush stress. Furthermore, Vigna et al. [66] developed a solution to dynamically crushing of flat coupons avoiding their buckling. However, such an alternative requires the use of a very complex fixing structure which makes not only testing more difficult but also the results obtained. For example, this structure that promotes in-plane failure essentially leads to delamination fracture neglecting other failure modes, such as fragmentation or tearing.

The trigger choice influences the response of the specimen crushing behaviour. A study carried out by Ueda et al. [72] proved this point by using a V-shaped trigger, which promoted splaying and lamina bending and a central pillar on the crushed plate. A study was carried out by Bru et al. [73] in which a triangular through-thickness (TTT) trigger was used, in order to promote the type of fragmentation crush failure. Israr et al. [74] proposed a bevel trigger, which promoted out-of-plane shear, thus splaying. Also, Feraboli [23] studied the difference between saw-tooth and steeple triggers, with steeple trigger seemingly demonstrating worse energy absorption capacity, but showing similar failure modes as the saw-tooth trigger plates. That said, the choice of trigger, despite being only a way to initiate progressive crushing, can have a substantial effect on material behaviour when subjected to crush loads.

In addition, the unsupported crushing distance is of vital importance, as the longer it is, the more prone to buckling the specimens are, and as such its energy absorption capacity tends to decrease. This behaviour was experienced in the study carried out by Dalli et al. [26], in which CFRP coupons with $[45^\circ/0^\circ/-45^\circ/90^\circ]_s$ and $[+45^\circ/-45^\circ]_{2s}$ ply configurations buckled at an early stage, before progressive crushing was even achieved. To tackle that issue, a pre-crushing of the trigger was performed, to allow a stable progressive crushing of the flat plate. However, such a solution is not ideal. In other words, there must be a balance in the choice of unsupported length. That is, if the length is too long, elastic instability phenomena may occur leading to low levels of energy absorption. If the length is too short, a plateau of crush stress crushing may not be achieved and the correct evaluation of the energy absorption parameters is not possible. Vigna et al. [66] and Barnes [75] found a way to tackle the issue of the unsupported length by using a setup that allows the formation of a crush stress plateau by assuring a constant unsupported length throughout the entire testing. These solutions will be explored in more detail in section 3.6.3.

Overall, flat plate coupon testing has the inconvenience of depending of all the aforementioned factors, like trigger shape, unsupported length and fixture, which will always yield a measure of structural property and not of a material property [68]. Thus, there is still a need to define a specific crushing test standard that allows for material characterisation and development of laminate designs.

2.7.3 Closed section coupons

Several closed section composites have been tested in the last few years, such as round tubes [19, 26, 27, 76], square tubes [53, 77–79], double hat-shaped geometries [80] and cones [81]. These are the so-called tubular geometries. Tubular coupons are one of the most typical cross-section geometry for the assessment of energy absorption of a determined specimen, as this geometry assures higher levels of energy absorption when compared to flatter geometries [25, 26].

Fairfull et al. [82] evaluated the effects of tube dimensions on the energy absorption of glass fibre reinforced composite tubes. Different thickness to diameter ratios were tested in quasi-static

conditions. Each tube contained a chamfer³ that acted as a trigger for progressive crushing. The results obtained originated three very distinct zones in the crush stress vs t/D curve. The first zone was composed by the tubes with smaller thickness to diameter ratio, which failed essentially by elastic instability. When reaching the peak load, irregular buckling patterns were formed, which caused a low crush stress value when compared to the other tubes. The third zone was characterised by the tubes with higher thickness to diameter ratio, and the failure of the laminates occurred by brittle fracture, which comprises the micromechanisms of failure already discussed. The intermediate zone consisted of a mixture of tubes which failed by elastic instability and brittle fracture. The crush stress values (which relate proportionally to the absorbed energy) were much higher in the third zone than in the first one. It can thus be concluded that to obtain better levels of energy absorption in tubular sections one should promote brittle fracture.

Oskovr et al. [83] and Dalli et al. [26] also experienced phenomena of elastic instability in their investigations. In both cases, it is possible that this phenomenon occurred essentially due to a lack of stiffness in the axial direction. In the study carried out by Oskovr et al. [83] composite tubes reinforced with silk fibres and an epoxy matrix were crushed axially. As the silk fibres have very low compressive properties, the material started to undergo ductile deformation without the formation of debris or fronds, resembling its behaviour to that of a metallic structure.

On the other hand, in the study conducted by Dalli et al. [26], three types of CFRP tubes were manufactured, all with eight plies, but with different orientations of the plies. While the $[0^\circ/90^\circ]_{2s}$ and the $[45^\circ/0^\circ/-45^\circ/90^\circ]_s$ tubes were progressively crushed, the same did not happen with the $[+45^\circ/-45^\circ]_{2s}$ layup. In the latter, a shear dominated failure far from the crushing front was experienced, generating an unstable failure. As a consequence, the stress values were very low when compared to the results obtained in the successful tests. Mamalis et al. [25] had already stated that specific energy absorbed tends to vary according to ply orientation. An angle of $[+45^\circ/-45^\circ]_n$ appears to be a critical ply orientation in the construction of a laminate with respect to energy absorption capacity.

The fact that the tubular structures described above were not progressively crushed may be related to the statement made by Barnes [28] that a good material for an energy absorbing structure should have high compressive strength when compared to its static crush stress. Otherwise, it becomes complex to design structures that are efficient. The ratio described above is called Compressive Crush Ratio (CCR) and can be calculated by the following expression:

$$CCR = \frac{X_c}{\sigma_{crush}} \quad (2.8)$$

where X_c is the static compressive strength of the material and σ_{crush} is the static crush stress. For a material to cope with geometric stress concentration and out-of-plane loading the CCR value should be greater than 3. Otherwise, the design will rely on idealised structures with constant sections and axial loading [28].

Although most of the research on crashworthiness has been carried out using composites reinforced with synthetic fibres, such as CFRP and glass fibre reinforced composites (GFRC), some studies with natural fibres have also been carried out. In the work done by Strohrmann et al. [19] already presented in section 2.4.4, the absorbed energy was higher in the hybrid tubes when the carbon fibre plies were placed on the outside of the tube. This may be related to the fact that

³The use of a 45° chamfer on tubular coupons is very often used in order to initiate progressive crushing of crush structures. Most authors who have performed this type of experiment have chosen this type of trigger mechanism [19, 23, 25, 26, 72, 76].

2.8. Crashworthiness models

the compressive and shear properties of carbon are higher than those of flax. As such, during the progressive crushing the flax fibres in the core of the tube wall were being constrained by the carbon fibres which were failing by tension and compression on the outside and inside, respectively, with higher values than the flax fibres.

Yan et al. [17] also tested woven fabric flax fibre tubes with 3 different diameters, different numbers of plies and length-to-diameter ratios. Most tubes failed in a mixed mode combining splaying and fragmentation. However, the tubes with lower thicknesses failed due to elastic instability, namely localised buckling. The optimal tube in terms of energy absorption reached a SEA value of 41 J/g for the tube with three plies and a length-to-diameter ratio equal to two. Compared with the study performed by Strohrmann et al. [19], this value is much higher, since the value achieved in that study for composite tubes reinforced with flax fibres was 19.3 J/g [19]. However, the thickness of the laminate was greater in the study of Yan et al. [17]. The authors reveal that this value of SEA is superior to conventional metal energy absorbers and close to that of GFRCS reported in literature.

2.8 Crashworthiness models

2.8.1 Numerical models

High performance materials can be extremely expensive to test. For example, an F1 front crash structure can cost up to £20,000 in material and labour. Therefore, testing such a structure so repeatedly is impractical [84]. For this reason, several approaches using numerical methods have been undertaken in an effort to recreate the behaviour of composite materials under crush loading and to help engineers build more efficient crash structures without excessive costs.

Numerical modelling approaches include composite laminates using either single layer or multiple layers of shell elements, i.e., models at the macro- and meso-scale, respectively. In the single-layer models, the laminate is modelled using a single layer of shell elements, with each layer represented by an integration point in the thickness direction. In the multi-layer approach the laminate is modelled using multiple layers of shell elements, representing a group of layers that are connected together using a tiebreak contact definition [85], offering better accuracy than the aforementioned models and assuring less computational effort than if three-dimensional (3D) elements were to be used.

In the scope of the multi-layer model approach, McGregor et al. [86] studied the progressive crushing of woven composite tubes under axial impact, employing the finite element method (FEM) with multiple layers of linear elements. In this particular case, the delamination capabilities between the layers resulted in major improvements over past attempts to model axial crushing of woven composite tubes. Although the SEA and crush loads from both the simulation and experimental results were indeed very close (4% mean variation), the reproduction of effects such as the formation of the debris wedge was not possible to reproduce. Siromani et al. [85] achieved similar results on their simulations when compared with the experimental results, the simulation predicted essentially identical sustained crush load and SEA values, but initial peak loads within 8–20% of the experimental values. The authors believed that this scatter on the peak load might be explained by the lack of detailed representation of the triggered region on the model. This issue could be solved, for instance, by modelling the plies in the trigger zone separately. Bisagni et al. [8] faced the same issue when studying unidirectional and woven fabric tubes. Although the average load and the energy absorption obtained by the crushing simulation results were very close to the experimental ones, the description of the failure modes, load-displacement curve and peak load

had a large scatter of values. In the study carried out by Mamalis et al. [87] progressive crushing of thin-walled CFRP tubes were simulated also by a multi-layer approach. However, differing phenomena from the ones experienced by McGregor et al. [86] and Sironami et al. [85] were achieved. In this case, the FE model was able to accurately predict the peak load, but the overall SEA was underestimated by 33%. While in the experimental study the debris wedge between the fronds of the tube wall contributed to energy absorption, in the simulations, instead of forming debris, the crushed elements were deleted and did not contribute to energy absorption. In addition, this model was not able to predict correctly the progressive failure process but was capable of predicting the unstable collapse and local buckling.

In a study developed by Reitner et al. [88] axial crushing of quasi-isotropic composite crush tubes was analysed using three different continuum damage mechanics models in Abaqus/Explicit and LS-DYNA. In that study, excellent predictions of the force-deflection and SEA were recorded. However, as only one shell element was used through the thickness to model the composite layup, delamination could not be captured. Deleo et al. [89] used the single-layer approach to simulate composite tubes crushing and were able to achieve a good correlation between the force-displacement curves of crushed coupons by taking into account the interaction between the specimen and the test fixture. However, as stated by Sironami et al. [85], the single-layer model is not ideal for describing the failure and crushing behaviour of coupons and crash structures as they are not able to capture interlaminar and intralaminar fracture phenomena. The leverage of this approach is the fact that it requires a very low computational cost when compared to multi-layer approaches.

To implement numerical models in commercial software, such as Abaqus[®], Engenuity Ltd. developed an add-on called CZone to allow robust simulations of composite materials for crashworthiness applications with the same level of predictability that can be obtained in metallic structures [28]. CZone requires an input of crush stress, which is considered a structural property influenced by ply orientation, specimen geometry and the test strain rate [26]. Dalli et al. [26] carried out an extensive set of experimental coupon crash tests. By combining the results achieved in the experimental test program with the ply-level material parameters it was possible to model a crash structure, namely a SIS from an F1 car, using the CZone add-on. The authors assigned the crush stress parameters manually based on the results achieved in the crush tests of the tubular and flat coupons, following the methodology shown in figure 2.12. In this case, the crush stress parameters were assigned to what the authors considered to be curved regions, and vice-versa for what they assumed to be flat. This approach is not immune from subjective interpretation because the crash structure has a very complex geometry, which comprises several different radii of curvature. It was concluded that a better understanding of the effect of varying curvatures on the crush stress parameters is needed. This way, a more precise assignment of these parameters can be done, improving the compliance between the results of simulations and the real behaviour of large composite structures.

To sum up, despite the current crashworthiness models being able to yield quantitative predictions of crash structures at a very reasonable computational cost, the qualitative results still show deviations between these numerical models and physical behaviour. Part of the reason comes from the fact that the macro-scale models are heavily simplified and thus are not able to capture key energy dissipation mechanisms, such as shear nonlinearity, matrix crack propagation, contact friction and fibre breakage. Even so, simplifications of this type are often necessary for the evaluation of large composite structures in a computational cost-effective way [90]. However, even in the macro-scale approaches, the methodologies used still need further development. The lack of knowledge that exists regarding the behaviour of different geometries in crushing applications

2.8. Crashworthiness models

makes it difficult to extrapolate data from coupon-level tests to models of large composite structures. Therefore, it is necessary to better assign curvature-dependent properties to the models so that the behaviour of these structures can be better captured.

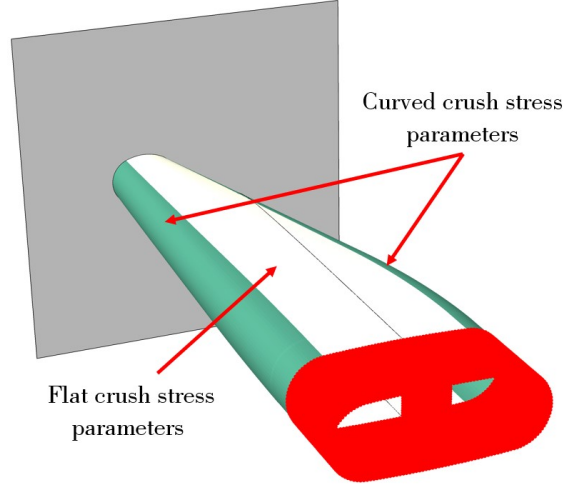


Figure 2.12: Subjective assignment of geometry-dependent energy absorption parameters in a crash structure model (adapted from [26]).

2.8.2 Analytical models

In addition to the numerical studies performed, some analytical methods have also been developed to obtain energy absorption predictions of a given structure, through much simpler ways that require considerably reduced computational effort. However, these methods only allow the prediction of some crashworthiness parameters, such as peak force, mean force and energy absorption, while numerical models can also predict the force-displacement curves of more complex geometries.

Hussein et al. [53] developed an analytical model for square CFRP tubes subjected to axial compression. In this research, a section of a CFRP laminate was subjected to a detailed analysis. Figure 2.13 shows an illustration of the crushed specimen.

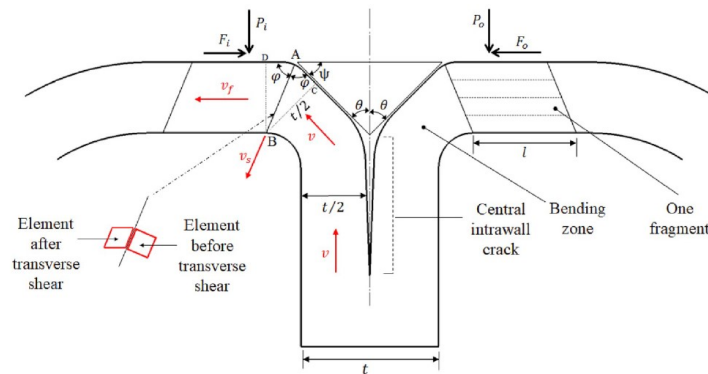


Figure 2.13: Illustration of inward and outward fronds experienced in the study carried out by Hussein et al. [53].

For the considered model, some assumptions were made and equations were derived to obtain the energy absorption predictions by calculating the mean force and the partial energy absorption

of each influencing parameter in the process. Finally, it was clear that to predict the energy absorbed by the specimen, geometrical factors had to be taken into account, as well as the out-of-plane shear strength of the laminate, the coefficient of friction between the fronds and the crush platen, the ultimate tensile stress and fracture strain of the laminate, and the Mode-I interlaminar fracture toughness. The discrepancy of values between the predictive models and the experiments was not high, and, in the worst case, the mean force measured had a scatter of only 7%.

Several other studies were carried out with different geometries and materials [61–63] and it was found that, despite the failure mechanisms being very complex, the mean force and the energy absorbed can be accurately predicted. The theoretical approach in all cases (including Hussein et al. [53]) can be simplified by only considering some of the most relevant phenomena that occur during crushing, namely, i) friction between debris wedge, between the fronds and between the fronds and the platen, ii) fronds bending, iii) crack propagation, and iv) axial splitting between fronds (central intrawall crack). Despite these simplifications, decent predictions can be analytically done.

However, analytical models are very limited, as they can only predict crashworthiness parameters of simple geometries from which the behaviour is already known. Furthermore, large crash composite structures are very complex and their crushing behaviour can be very unpredictable, as experienced by Dalli et al. [26].

2.9 Concluding remarks

After an insight into the current state-of-art of composite materials for crush applications, it became clear that experimental testing in this field still needs substantial progress and innovation. Not only is it necessary to improve the setups used, for example in testing flat plates or dynamic testing, but also to better understand the influence that coupon design has on material characterisation for energy absorption applications, without forgetting the issue of sustainability. Therefore, three major gaps were identified in the research of composite materials for crashworthiness applications. Firstly, there is a lack of knowledge on how the coupon geometry affects the energy absorption parameters. For example, nowadays models are very restrictive, as they require subjective manual assignment of energy absorption parameters based on curvature. However, modern crash structures are very complex geometries with several different curvatures and inclinations, and thus the manual assignment of parameters becomes more prone to error. Therefore, it is necessary to bridge this gap by understanding better the effect of geometry on coupon energy absorption, so that models can have a strong physical basis.

Secondly, modern-day CFRP crash structures embody considerable amounts of energy that make them non-sustainable structures. Thus, it is important to start searching for more sustainable materials that can partially replace CFRP. Natural fibre reinforced composites, such as FFRPs, are one of the alternative materials that can play an important role in the replacement of the long-used synthetic fibre reinforced composites. However, there is still little information regarding the behaviour of such materials in crushing applications. Therefore, there is a need to understand how these materials behave in energy absorption situations, so that their sustainable leverage can be exploited for novel crash structures.

Finally, dynamic testing of coupons was found to be underdeveloped, which generates a large dispersion of results and misinterpretation of the data collected.

Chapter 3

Assessing geometry effects on monolithic coupon energy absorption

Coupon testing in crashworthiness applications is of utmost importance, as it allows an understanding of the behaviour of composite materials when subjected to crush loads. However, there is still a lack of awareness regarding the effect of 2D curvature in composite material's coupon energy absorption parameters. The following chapter undertakes a comprehensive study on the assessment of coupon geometry in the energy absorption capacity of composites as monolithic materials. The outcome of such a study should be able to bridge the existing gap in knowledge concerning the effects of curvature and other geometrical parameters on composite structures for crush applications.

3.1 Introduction

Testing crash structures can be very costly since the manufacturing of its complex geometries requires long labour hours and high-temperature curing cycles. Furthermore, these tests are destructive, which enlarges the necessity of repeating this process over and over if these tests were to be carried out several times. That said, models are required to aid engineers to build more efficient large composite crash structures without the excessive costs that their testing compels. However, modern-day composite structures for crashworthiness applications still lack a detailed representation of physical models, especially due to the approach that is usually used. Fairfull [82] and Farley et al.[50] highlighted that thin-walled composite structures seem to be highly dependent on their geometry, with Feraboli [91] corroborating that hypothesis by stating that curved geometries assure better levels of energy absorption than flat surfaces. That is part of the reason why testing at the coupon level is of extreme importance to characterise the energy absorption parameters of composite materials. Dalli et al. [26] concluded that there is still the need to better understand the geometrical effects of coupons on the energy absorption parameters, as complex crash structures have several different curvatures and geometries, and as such, their numerical models require geometry-dependent crush stress inputs to better represent their behaviour in crushing applications.

In this work, it was possible to have access to the CFRP material used in the study carried

3.2. Material selection

out by Dalli et al. [26]. Since the authors recognised the necessity to study in more depth the effect that geometry has on the crashworthiness parameters of crash structures, an extensive study on that field will be carried out. For comparison's sake, the same approach taken in that study will be adopted, i.e., similar coupon geometry and testing setups will be implemented. To limit the number of influencing factors on the results achieved, some considerations will be taken into account. Namely, each laminate will be limited to eight plies, which was the number of plies used in that study, making the comparison with that study easier, stacked in the 0° direction. Such assumptions keep the number of plies and layup constant, restricting the number of study variables.

Modern-day natural fibre reinforced composites are evolving sharply. Such progression requires an in-depth evaluation regarding their capacity to act as materials for structural applications. Through the collaboration with an industrial partner, a study on the energy absorption capacity of a novel FFRP was carried out. To compare its behaviour with the CFRP similar coupon geometry was adopted, likewise the layup configuration and number of plies. The assessment of FFRP laminates in crushing applications allows understanding if such material has the minimum requirements to be used in energy-absorbing structures, and if that is the case, it can help provide a starting point for hybridisation strategies.

3.2 Material selection

3.2.1 Carbon fibre reinforced composite

Toray supplied the CFRP material used in the coupons designed. The material was a *pre-preg* of a carbon fibre reinforced polymer with an epoxy matrix (IM7/E745). This *pre-preg* consisted of a weave with a 5 Harness-Satin (5HS) fabric with 280 g/m^2 . This material is the same as the one used in the side impact structures of the McLaren Racing F1 cars [26]. The fact that it is balanced, makes its properties very similar in the 0° and 90° directions. Table 3.1 shows the elastic and strength properties of the previously described Toray 5HS 280 g/m^2 ply. Note that the resin E745 is a toughened epoxy, consisting of a mixture of epoxy with a thermoplastic to add extra toughness to the more brittle epoxy. Remember that the resin is crucial in crushing because, unlike in tension, where the strength mostly depends on the fibres, compressive failure and delamination are highly dependent on the mechanical properties of the matrix.

Table 3.1: Ply properties of the 5HS Toray carbon weave [92].

E_1	62.54	GPa	$\bar{\sigma}_{11}$	1046	MPa	$\bar{\tau}_{12}$	125	MPa
E_2	62	GPa	$\bar{\sigma}_{22}$	1008	MPa	V_f	49	%
G_{12}	3.69	GPa	$\bar{\sigma}_{11}^c$	595	MPa	ρ	1.5	g/cm^3
ν_{12}	0.03		$\bar{\sigma}_{22}^c$	547	MPa	t_p	0.30	mm

E_1 and E_2 are the longitudinal and transverse Young's moduli, respectively, G_{12} is the shear modulus, ν_{12} is the Poisson's ratio, $\bar{\sigma}_{11}$ and $\bar{\sigma}_{22}$ are the tensile strengths in the longitudinal and transverse directions, respectively, $\bar{\sigma}_{11}^c$ and $\bar{\sigma}_{22}^c$ are the compressive strengths in the longitudinal and transverse directions, respectively, $\bar{\tau}_{12}$ is the shear strength, V_f is the fibre volume content, ρ is the density and t_p is the cured ply thickness. As can be observed, the material properties in the longitudinal and transverse directions are very similar, which is an effect of the balanced weave.

3.2.2 Flax fibre reinforced composite

The company Bcomp was the supplier of the flax fibre reinforced plastic *pre-preg*, also with an epoxy resin matrix phase. The material was the ampliTex™ 300, twill 2/2, which is a 2x2 twill flax weave with 300 g/m². The elastic and strength properties of the FFRP provided by the manufacturer are defined in table 3.2. As with any composite material, whenever a different batch is used, it is recommended to carry out some material characterisation experiments to confirm that the elastic and strength properties still match those of the previous batches. It is normal for properties to vary slightly between batches, as the raw material is not always the same and manufacturers themselves may make changes to their production processes and stock material. This aspect is even more important in bio-composites or natural fibre-reinforced plastics. In the case of flax, as mentioned in chapter 2, crops vary with numerous factors, and even between the same batch of flax, each plant can vary its elastic and strength properties. Consequently, higher dispersion of results is expected when testing such materials.

Table 3.2: Ply properties of the ampliTex™ 300, twill 2/2 [93].

E_1	17.10	GPa	$\bar{\sigma}_{11}$	126.60	MPa	$\bar{\tau}_{12}$	34	MPa
E_2	17.10	GPa	$\bar{\sigma}_{22}$	126.60	MPa	V_f	46	%
G_{12}	2.00	GPa	$\bar{\sigma}_{11}^c$	99.7	MPa	ρ	-	g/cm ³
ν_{12}	0.12		E_1^c	14.33	GPa	t_p	0.4125	mm

E_1^c is the compressive stiffness, and the rest of the properties have been already defined. As can be seen, the material properties in the longitudinal and transverse directions are very similar, which is an effect of the balanced 2x2 twill weave. As expected, the properties of FFRP are very low compared to CFRP. The density of the material was not specified, so it is not shown in the table.

3.3 Manufacturing of the CFRP tubes

To assess the effect of geometry on coupon energy absorption, several tubes with different radii of curvature were designed and produced. Manufacturing composite structures can be very laborious as it is not an easy process to automate, thus being highly dependent on the experience of laminators. Furthermore, the high complexity of certain structures can add an exponential level of difficulty to their production. Although tubular thin-walled composite structures are not considered complex geometries, their manufacturing process is very time-consuming and requires some particularities. Therefore, its manufacturing process will be briefly described as follows.

3.3.1 Geometry

The chosen geometry for the tubular coupons was based on the work carried out by Dalli et al. [26], where a CFRP tube with 32 mm of internal diameter and 60 mm length was tested with several layups. The tube with the $[0^\circ]_8$ layup was reproduced in this work. Since the material used in that study was the same as the one used in this work, the first tested tube hereby (TC-2) had the exact same geometry as that one. As one of the main objectives of this work is to assess the effect of geometry on the energy absorption parameters of composite coupons, several other tubes with different diameters were manufactured. To keep the assessment of the 2D curvature as consistent as possible the same L/D ratio was used for the remaining coupons.

3.3. Manufacturing of the CFRP tubes

Figure 3.1 shows the geometry of the manufactured and tested circular cross-section tubes. A 45° chamfer was included in the tubes to act as a trigger for progressive crushing. Deviations from the nominal values were observed, as the tubes were cured in the autoclave under high-pressure conditions and were machined and finished. Furthermore, several external wrinkles were formed after the curing process, which also influenced the measured geometrical values. It should be noted that the nominal dimensions were used to perform the data reduction, enabling for a more concise comparison of the crush stress values with other published experimental data, and, more importantly, to provide input values for modelling, where the ply thickness must match the nominal one. Table 3.3 presents the nominal dimensions of the tubular coupons and the average weight of the specimens after being manufactured.

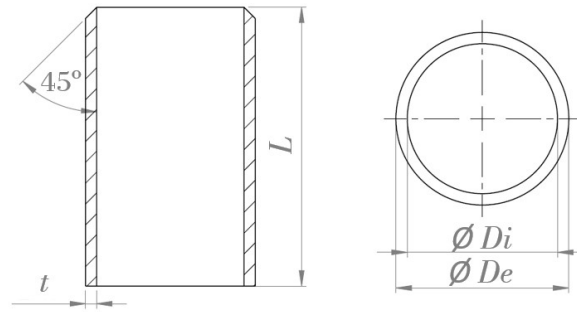


Figure 3.1: Geometry of the CFRP and FFRP tubular coupons.

Figure 3.2. shows the nomenclature adopted for the coupons that are going to be used throughout this chapter.

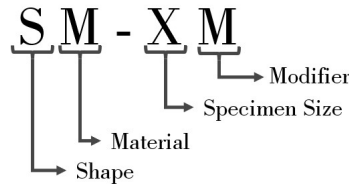


Figure 3.2: Designation of the coupons used throughout this chapter.

The possibilities are described below:

1. Shape

- (a) T - Tubular coupon;
- (b) F - Flat coupon;
- (c) H - Hybrid coupon;

2. Fibre material

- (a) C - Carbon;
- (b) F - Flax;

3. Specimen Size

- (a) 1 - internal diameter of 19 mm;
- (b) 2 - internal diameter of 32 mm;

- (c) 3 - internal diameter of 44.45 mm;
- (d) 4 - internal diameter of 57.15 mm;
- (e) 5 - internal diameter of 76.20 mm;

4. Modifier

- (a) HL - Half-length tube;
- (b) HS - Half-section tube;
- (c) QS - Quarter-section tube;

For example, if a coupon has a tubular shape, is composed exclusively of carbon fibre composite plies and has an internal diameter of 44.45 mm, it will have the designation TC-3.

Table 3.3: Geometrical parameters and mass of the CFRP circular tested tubes.

Coupon	t [mm]	L [mm]	Di [mm]	De [mm]	Mass [g]
TC-1	2.40	36	19	23.80	9.14
TC-2	2.40	60	32	36.80	23.30
TC-3	2.40	84	44.45	49.05	46.70
TC-4	2.40	107	57.15	61.75	76.10
TC-5	2.40	142	76.20	80.80	132.40

3.3.2 Manufacturing process

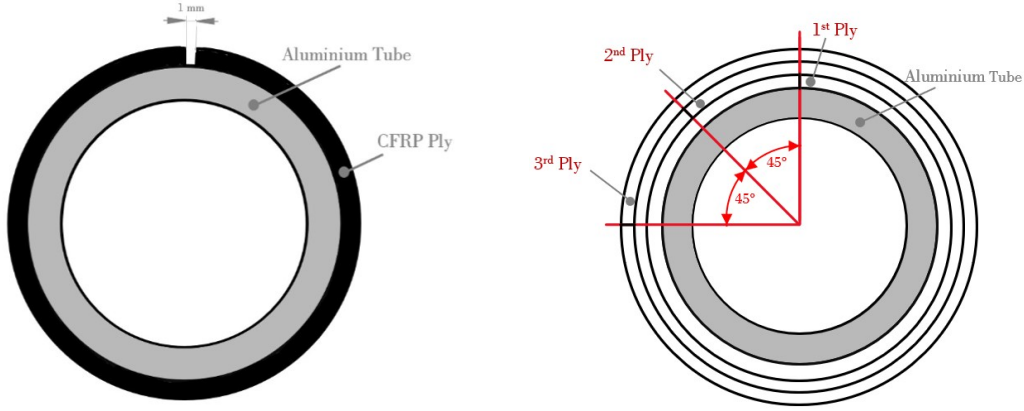
The CFRP tubes were manufactured with the help of the company Dragon Equation in Leça da Palmeira. The manufacturing process began by cutting the *pre-preg* according to the dimensions of the tubular coupon planned. The mandrel that shaped the tubes was made from aluminium, due to its good thermal conductivity, which allows rapid and homogeneous heating and cooling of the composite coupons during the curing cycle. In addition, the thermal expansion coefficient of this material could help demoulding the CFRP tubes by their contraction capacity during the cooling phase.

After the tubes and plies were cut and prepared, these were wrapped around the aluminium mandrel. Note that the plies were cut with a width that allowed the tube not to have an overlap of material in each layer, i.e., the joint area at the ends of the plies was a butt joint. During the rolling of the TC-1 tube plies (using the same designation described in table 3.3), there was a gap of 1 mm between the beginning of the plies and its end, which means that there were areas with less material. Figure 3.3a represents the gap described.

After applying the first layer, a vacuum debulk was done, to guarantee that the composite was evenly consolidated and to remove air from the laminate. This process consisted of submitting the tubes under vacuum for about 30 minutes. After the first debulking some wrinkles appeared on the outer surface of the tubes, that could not be removed and remained until the end of their manufacturing process. Layers two and three were wrapped, with a 45° offset from the beginning of the wrapping of the previous layer, as represented in figure 3.3b. Note that the plies were applied in a way to avoid warping during curing, i.e. the side in contact with the previous plies was reversed between each layer application. This had to be performed since the weave is a 5HS, and unlike a plain or twill weave, its top and bottom surfaces are not perfectly symmetric, leading to through-thickness cure-induced warping unless the plies are laid up with alternating top and bottom surfaces. After these layers had been added, another debulk was made. The process was

3.4. Manufacturing of the FFRP tubes

repeated until all eight layers were stacked, with another thirty minutes of debulk between the fifth and sixth layer, and a final debulk of 12 hours after the eighth ply was applied.



(a) Gap between the beginning and the end of the CFRP ply on the TC-1 tube.

(b) Example of the offset technique used to avoid the overlap between plies.

Figure 3.3: Example of challenges faced and approaches taken during the manufacturing.

After the 12 hour debulk, the tubes were bagged in a vacuum bag with an internal bag passing through the inside of the tube mandrels, avoiding the application of a large pressure on the hollow inner section that could lead the bag to collapse inwards. Figure 3.4a shows the tubes inside the bag right before entering the autoclave for curing.

In the first phase, the curing cycle consisted in increasing the temperature with a rate of $2^{\circ}/\text{min}$ until reaching 140°C , which corresponds to 5°C higher than recommended by the manufacturer, to compensate for possible leaks during the process. Simultaneously, the pressure inside the autoclave was adjusted to 5 bar, while the vacuum inside the bag was kept. Then, the samples were left at constant temperature and pressure for one hour. Finally, the cooling stage was done with the same rate used in the heating phase, and the pressure was reduced to atmospheric pressure near the end of the cycle. In total, this process lasted about 3 hours.

When the curing cycle was over, the tubes were removed from the autoclave and some very significant wrinkles were observed. The demoulding of the tubes was also very challenging, and to remove them from the aluminium mandrel an external turning operation was required. Each tubular geometry was cut into 6 different smaller tubes as shown in figure 3.1 and with the dimensions presented in table 3.3. Figure 3.4b shows the tubes before the turning operation. As can be seen, several wrinkles were originated during the curing cycle.

3.4 Manufacturing of the FFRP tubes

The FFRP tubes were manufactured at the McLaren Technology Centre in Woking, in the UK through collaboration within the scope of this work. The tubes were manufactured by their workers, and the time and resources available there were bigger than if they were to be manufactured locally. In general, the manufacturing steps were very similar to those followed in the manufacture of CFRP tubular specimens. However, some adjustments had to be made, due to the peculiarities involving the handling of such material, such as its stretching characteristic. The methodology followed will be briefly described in the following section.



Figure 3.4: Curing of the tubular coupons.

3.4.1 Geometry

The geometry of the FFRP tubes was slightly different from the CFRP ones, because the length of the moulds were different. In terms of internal diameter the dimensions were very similar, however, the height was different, with its value set to 70 mm. The difference in height was related to the need to extract as many specimens as possible from the larger tubes, and as the mandrel had different length, these change had to be done. Furthermore, the less stiff flax could lead to premature buckling of the large diameter tubes if they were kept long. The geometric dimensions of the tubes are presented in table 3.4, and their nomenclature is organised in the same way as it was done for the CFRP tubes in table 3.3. Furthermore, only four different coupon sizes could be manufactured, as the 19 mm inner diameter tube proved too difficult to be manufactured because flax fibres are more elastic than carbon, so they contract during manual layup, causing significant wrinkles when wrapped around a very tight curvature.

Table 3.4: Geometrical parameters and mass of the FFRP circular tested tubes.

Specimen	t [mm]	L [mm]	Di [mm]	De [mm]	Mass [g]
TF-2	3.30	70	32.00	38.60	32.61
TF-3	3.30	70	44.45	51.05	44.32
TF-4	3.30	70	57.15	63.75	55.05
TF-5	3.30	70	76.20	82.80	69.31

3.4.2 Manufacturing process

The process began by wrapping a thin layer of polytetrafluoroethylene (PTFE) tape around the aluminium tube, which is a tape suitable for high-temperature applications. Then non-perforated release film was wrapped around the mandrel. The purpose of such a step was to create two smooth surfaces, which would allow the demoulding of the tubes more easily, avoiding what happened previously with the CFRP tubes that got stuck to the mandrel. After the mandrel was prepared, the first ply of flax was wound around it, and to avoid the gap described in figure 3.3a the plies were cut with an extra 10 mm margin, which was then cut with a scalpel. The flax plies proved to be very elastic, making it difficult to apply the plies to the mandrel. After each ply application, the

3.5. Flat plates manufacturing

tubes were wrapped in a perforated release film and were bagged for a 15-20 minute debulk. After the first three and the sixth ply, a pressure debulk was made in the autoclave for 30 minutes at 6 bar and 65°C. After this pressure debulk, many wrinkles started to appear, so the ply edges were unpeeled, and the excess trimmed. After the 8th ply, a 3 mm thick pre-cured rubber sheet was cut to size and tightly wrapped around the tubes, after having applied a non-perforated release film. The rubber was meant to distribute the external pressure onto the tube surface in a more even manner and try to limit the development of wrinkles during curing. Finally, the tubes were cured in the autoclave with a similar cycle as the CFRP tubes. Figure 3.5 shows the tubes after being demoulded and before being cut.



Figure 3.5: FFRP tubes before being cut into specimens.

3.5 Flat plates manufacturing

For the manufacture of the CFRP and FFRP composite plates two 300x300 mm plates of hybrid and non-hybrid composite laminates were made. As the manufacturing process of both plates was carried out in the same way for all of them and their process is very simple, only a brief description of their process will be made. First of all eight plies were cut and then these were all stacked in the same 0° direction. After this process, which was repeated for all the laminates manufactured, the laminates were placed in the autoclave with a curing cycle equal to that of the tubes. The plates were then placed on a DECKEL MAHO DMU 60 eVo CNC machine to be cut to the desired coupon geometry. Figure 3.6 shows the FFRP plate clamped to the machine support after cutting 3 flat coupons for crushing.

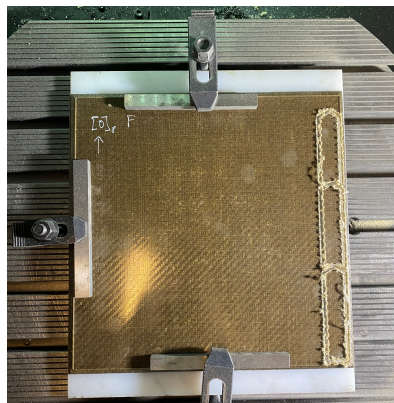


Figure 3.6: Cutting of the FFRP flat crush coupons (on the right side of the plate) still attached to the CNC machine.

3.6 Experimental setup

3.6.1 Compressive strength

Barnes et al. [28] highlighted the importance of a material's compressive strength in crushing applications. Although there are several more properties of a material, such as the elastic modulus, that are important to characterise a composite material, the compressive strength is the most pre-eminent property regarding crush applications. Therefore, compressive strength characterisation tests of both monolithic FFRP and CFRP were carried out. Further in this work, the CCR for the FFRP and CFRP coupons will be calculated, based on the compressive results achieved in this test.

The compressive strength was determined by subjecting the cut specimens, clamped in a CLC (combined loading compression) test fixture, to a compressive load, as shown in figure 3.7b. The test was performed according to the ASTM D 6641 standard [94]. The materials were only tested in the 0° direction, because this was also the configuration of the laminates being used in crushing. Figure 3.7a shows the geometry of the specimens, where the 20 mm along the length of the specimen correspond to the gauge section.

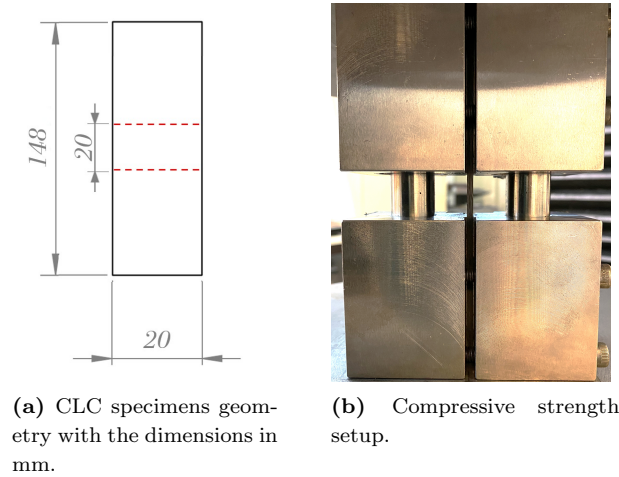


Figure 3.7: Geometry of the CLC coupons and setup of the compressive strength test.

Usually, this type of testing also determines the compressive elastic properties. However, as the repetition unit cells of the weave are 8 mm long, and the strain gauges available only had 2 mm, the characterisation of the compressive elastic moduli of the material would not be possible to capture correctly, and thus, this property was not determined. For each material, three coupons were tested, as can be seen in the compressive test matrix in table 3.5, where t corresponds to the nominal thickness of the specimens.

Table 3.5: Compressive strength test matrix

Sample	# specimens	# plies	Layup	t [mm]
CLC-C	3	8	$[0^\circ]_8$	2.40
CLC-F	3	8	$[0^\circ]_8$	3.30

3.6. Experimental setup

3.6.2 Closed section coupons

CFRP tubes

As crush tests of composite tubes are not standardised, the testing of the tubular coupons was not performed according to any standard. The tests were carried out quasi-statically using an Instron 5900R machine with a load cell of 100 kN for tubes TC-1 to TC-3 and 200 kN for tubes TC-4 and TC-5. The change to a 200kN load cell had to be done after the initial tests on smaller tubes highlighted the possibility of exceeding the 100 kN limit. Three specimens of each coupon were tested, as this was sufficient to obtain consistent data from which a scatter measure could be obtained. This decision was supported by the low scatter results reported in [26]. Because some sections of the uncut tubes had much smaller wrinkle defects, it was decided to test three specimens per tube size with varying degrees of wrinkling to evaluate the potential effects of such defects. Figure 3.8 shows 5 of the carbon tested tubes.



Figure 3.8: The 5 different tube sizes tested. From left to right: TC-5, TC-4, TC-3, TC-2 and TC-1.

The bottom surface of the tubes was ground with P300 ultra-fine-grit sandpaper to ensure axial crushing of the specimens. If the bottom surface is not planar, defect free, and perpendicular to the crushing axis, the tube could start to buckle. The crushing of the tubes did not require any special support or fixture, i.e., the tubes were self-supported on the bottom plate. A top plate was then moved downwards until it was in contact with the coupon, and the force and displacement were zeroed. After that, the top plate started to move in the downward direction with a displacement of 10 mm/min¹, pressing the sample down and crushing it. Figure 3.9 shows the setup for the TC-3 CFRP coupon testing.

In the study carried out by Yan et al. [17], there were differences in the crush stress of tubes when they were crushed with different L/D ratios, as stated in chapter 2. There was no pattern discovered, because when the L/D ratio was 1 and 2, the crush stress barely changed, but when that value was 1.5, the crush stress decreased. To evaluate this effect on the CFRP tested tubes, a fourth TC-5 tube was cut in the middle point of its length, obtaining two half-length tubes out of one original specimen (TC-5HL), thus an L/D ratio of approximately 0.9. These tubes were tested with the same setup used in the testing of the TC-5 tubes. Table 3.6 represents the matrix of tests performed on the CFRP tubes, where D_i corresponds to the inner diameter of the coupon, t corresponds to the nominal coupon thickness and L to the length.

¹For crushing applications, any crushing velocity under 1 m/s is considered to be quasi-static [26].

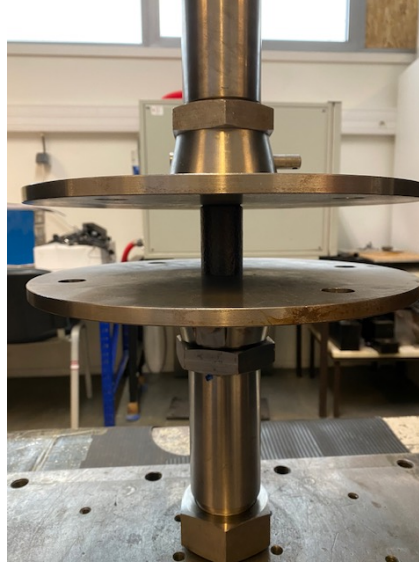


Figure 3.9: Test setup for the CFRP TC-3 tubular coupon. This moment corresponds to the leveled upper plate touching the specimen before starting to apply any force on the coupon.

Table 3.6: Crushing of CFRP tubes test matrix.

Sample	# specimens	# plies	Layup	D_i [mm]	t [mm]	L [mm]	Speed [mm/min]
TC-1	3	8	$[0^\circ]_8$	19	2.40	36	10
TC-2	3	8	$[0^\circ]_8$	32	2.40	60	10
TC-3	3	8	$[0^\circ]_8$	45.45	2.40	84	10
TC-4	3	8	$[0^\circ]_8$	57.15	2.40	107	10
TC-5	3	8	$[0^\circ]_8$	76.20	2.40	142	10
TC-5HL	2	8	$[0^\circ]_8$	76.20	2.40	70	10

FFRP

The tests of the FFRP tubes were performed using the same testing machine and the same setup used in the CFRP tubes. The major difference in the FFRP was the length of the specimens, which was the same for all coupons. Figure 3.10 shows the FFRP tested tubes. This test aimed to evaluate the behaviour of FFRP tubular coupons, as well as to characterise the energy absorption capacity of such composite materials.



Figure 3.10: The 4 different FFRP tube sizes tested. In order from left to right: TF-5, TF-4, TF-3 and TF-2

The test matrix of the tests performed on the FFRP circular section tubes is described in table

3.6. Experimental setup

3.7. The tests of the first two TF-2 FFRP tubes revealed some different results from what would be expected in crush tests, as will be addressed in section 3.7. To understand what was causing such behaviour, a third coupon was tested at 5 mm intervals allowing to capture images between these time intervals and thus have a better understanding of the failure mechanisms that were taking place on the specimen. Then, a fourth coupons was tested.

Table 3.7: Crushing of FFRP tubes test matrix.

Sample	# specimens	# plies	Layup	$D_{internal}$ [mm]	t [mm]	L [mm]	Speed [mm/min]
TF-2	4	8	$[0^\circ]_8$	32	3.30	70	10
TF-3	3	8	$[0^\circ]_8$	45.45	3.30	70	10
TF-4	3	8	$[0^\circ]_8$	57.15	3.30	70	10
TF-5	3	8	$[0^\circ]_8$	76.20	3.30	70	10

3.6.3 Open section coupons

Sectioned coupons

To assess the free edge effect of coupons on the crush stress, one specimen each of TC-3 and TC-4 were cut in sections. That is, the tube TC-3 was cut in half, resulting in two coupons TC-3HS, and the tube TC-4 was cut in 4 quarters resulting in four coupons TC-4QS. This experience aimed to understand whether there was an effect on the crush test of a curved coupon if it was not fully closed. There is the hypothesis that as the fibres in the direction of the tow no longer form a closed section, the constraints that the hoop fibres provoke on the coupon are not as high as in closed tubular geometries. Such difference might be translated into a reduction of crush stress. Furthermore, this is especially important to compare with the results of crush stress parameters obtained in Barne's [75] study for Engenuity, where the curvature effect was defined as a simple delamination suppression mechanism, when in fact, curvature has additional ways of improving energy absorption. Thus, their use of a flat coupons with suppressed delamination using metallic restraint bars at the crush front, might be providing an inaccurate measure, since it does not possess any actual curvature and it is an open-section coupon. But there is also the possibility that the crashworthiness parameters of such geometries do not change compared to their respective closed coupons, and if that could be proved, several manufacturing hurdles could be avoided, since it would be easier to manufacture open section curves, ironing out the wrinkles during the lay up process, and enabling a much simpler demoulding procedure.

The geometry of these coupons is described in figure 3.11. Note that the dimension presented with a D on this figure represents the diameter of the tube TC-4, which is 57.15 mm. As the cutting tool had a certain thickness, the angle of the coupons was not perfect. That is, on the half-sectioned tubes the angle between the two free axial edges was not 180° , but a little bit lower. As for the quarter-sectioned tubes, the same tool effect was observed, but with some axial edges forming angles of more than 90° degrees and others less. Table 3.8 presents the nominal configurations TC-3HS and TC4QS and the real the values of the angles α that were tested with success. Note that t corresponds to the nominal thickness of the coupons.

The most challenging part of the testing was the support of the partial sectioned tubes. The TC-3HS coupons were self supported on top of the bottom crush plate, while the TC-4QS coupons were clamped in a CLC fixture, which was the only way of supporting them to avoid the risk of the coupon being projected from the testing machine.

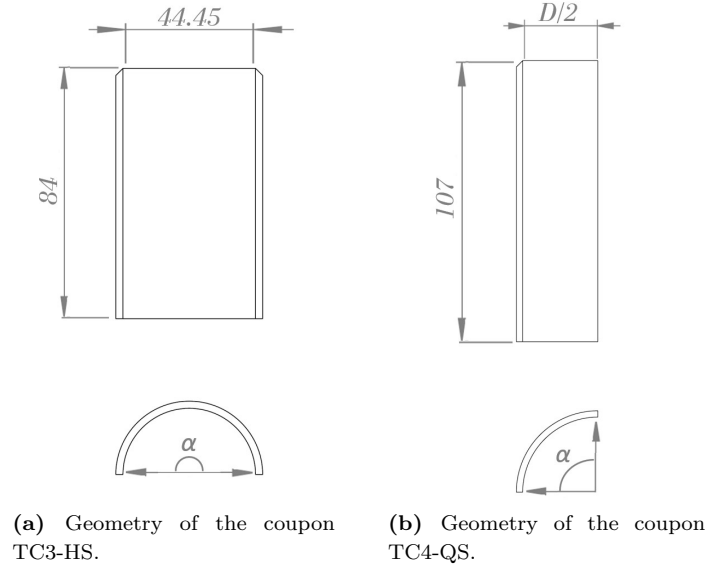


Figure 3.11: Geometry of the sectioned CFRP open section curved coupons.

Table 3.8: Test matrix of the partial cross-sectioned tubes.

Sample	# specimens	# plies	Layup	t [mm]	α [°]
TC-3HS	2	8	[0°]	2.40	180°
1					173°
2					177°
TC-4QS	1	8	[0°]	2.40	90°
1					92°

CLC flat coupon crush testing

As mentioned before, there is a high probability of failure by elastic instability in flat coupons, as experienced by several authors [23, 26, 66]. This is a major drawback of using flat coupons to obtain crush stress parameters, although their manufacturing is much easier when compared with tubular coupons. To assess the best geometric parameters of the flat coupons, 3 coupons were cut with the design shown in figure 3.12c. Three different unsupported heights were chosen, to assess their sensitivity to elastic instabilities. The flat coupons were designed based on the crush coupon geometry proposed by Bru et al. [73] with a 30°TTT (triangular through-thickness) trigger. Dalli et al. [26] also used a very similar geometry for both the trigger and the crush zone of the coupons.

In figure 3.12, w represents the width, L the total length of the coupon, l the unsupported length and t the coupon thickness. The choice of length comes from the fact that the CLC fixture used was 64 mm high and had a 20 mm wide clamping zone. Table 3.9 shows the dimensions of the flat coupons tested with this setup. Note that in the case of flat coupons the designation of the specimen after the specification of shape and material (FC or FF) corresponds to the unsupported length, l . For example, FC-15 corresponds to a flat carbon coupon with an unsupported length of 15 mm.

The flat coupons were clamped during the test using a fixture of the sort used for CLC testing, as shown in figure 3.13. Such test setup was also used in the study carried out by Dalli et al. [26].

3.6. Experimental setup

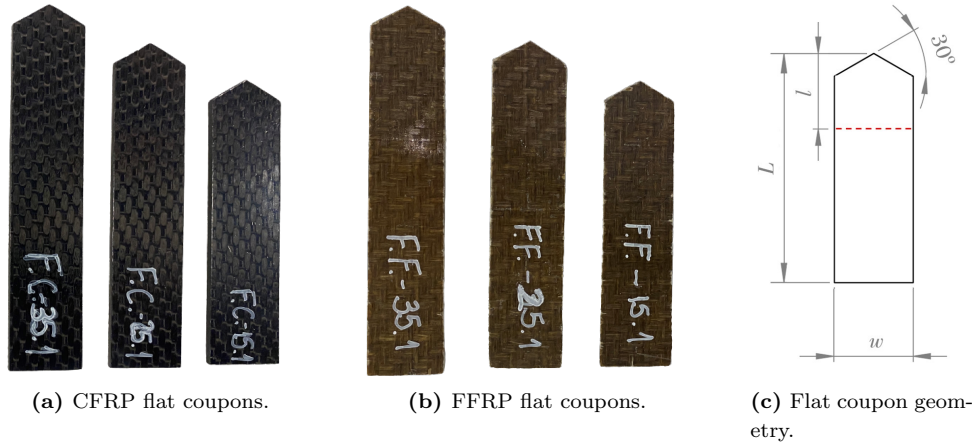


Figure 3.12: Geometry of the FFRP and CFRP flat coupons for crushing with the CLC fixture.

Table 3.9: Geometric parameters of the flat coupons.

Specimen	Geometric parameters			
	w [mm]	L [mm]	l [mm]	t [mm]
FC-15	20	99	35	2.40
FC-25	20	89	25	2.40
FC-35	20	79	15	2.40
FF-15	20	99	35	3.30
FF-25	20	89	25	3.30
FF-35	20	79	15	3.30

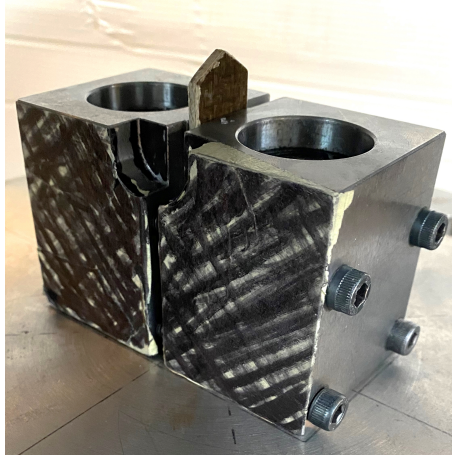


Figure 3.13: Quasi-static setup for the flat coupons of FFRP and CFRP. Here the FF-15 clamped on the CLC fixture before the upper plate being in touch with the specimen.

INSTRON flat coupons crush testing

A small set of CFRP flat coupons were also tested through a different quasi-static setup by means of an industrial collaboration with INSTRON, but unfortunately, the number of coupons able to be tested was limited to a few. The flat coupons were sent to Italy to be tested in the fixture

Chapter 3. Assessing geometry effects on monolithic coupon energy absorption

developed by Vigna et al. [66], which can be seen in figure 3.14. The specimens were clamped to the support with a given unsupported length that was kept constant throughout the entire testing. The upper plate pushed the flat coupon downwards forcing it to slide between the anti-buckling fixture and crushing it onto the bottom plate.

Two flat coupons with different unsupported lengths were tested. A first one with 10 mm of unsupported length and a second with 20 mm. The geometry was similar to the ones of the CLC, in figure 3.12c, but having slightly different parameters, presented in table 3.10.

In a work developed by Barnes [75] in cooperation with Engenuity Ltd., a novel fixture for crushing flat coupon specimens was also developed. Similarly to the fixture developed by INSTRON this fixture and setup make it possible to reproduce load-stroke curves similar to the ones obtained in tubular coupons, which allows for a plateau of crush stress to be reached. This is possible due to the so-called spacer height, i.e., a defined height of the gap between the steel frame and the base plate which remains constant throughout the entire testing.

Another major advantage of using the fixtures developed by these two companies is the fact that dynamic testing is also possible to be performed. However, they use different concepts. While INSTRON's dynamic setup is the one of the drop tower, where a mass is dropped impacting the specimens, the one used by Engenuity Ltd. is performed by a high-speed servo-hydraulic machine. The latter has the advantage of carrying a quasi-constant speed throughout the entire test. On the other hand, the setup used by INSTRON decelerates the mass as the test progresses. Consequently, the speed decreases as the test advances affecting the dynamic energy absorption parameters.

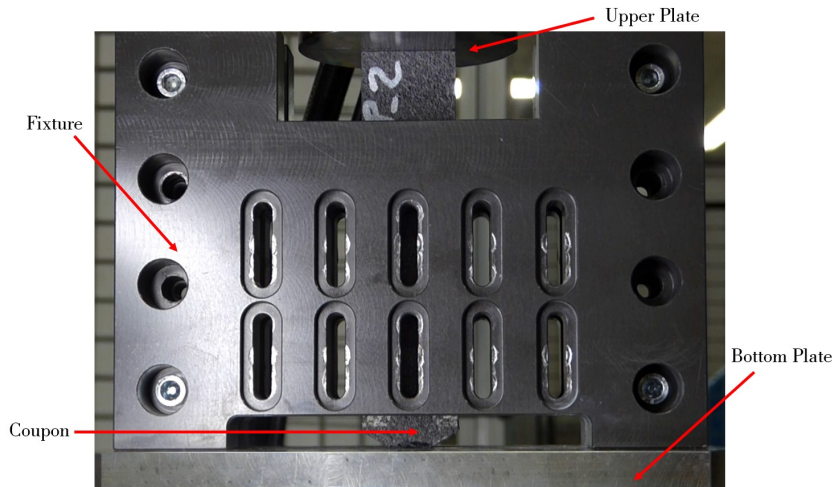


Figure 3.14: Setup of the flat coupon crushing with the INSTRON setup.

Table 3.10: Geometrical parameters of the flat coupons tested with INSTRON setup.

Specimen	w [mm]	L [mm]	l [mm]	t [mm]
FC-10-Instron	30	135	10	2.4
FC-20-Instron	30	135	20	2.4

3.7. Experimental results

3.7 Experimental results

The following section presents and discusses the results obtained during the experimental testing program of the developed CFRP and FFRP coupons in their monolithic forms. A MATLAB[®] script was developed to perform the data reduction, to draw the plots presented in this section and to calculate some of the crashworthiness parameters described in section 2.3.

3.7.1 Compressive strength tests

Figure 3.15b shows that, according to the standard ASTM D 6641, the specimens failed by transverse shearing at the ideal acceptable section, which is located in the middle of the gauge section.

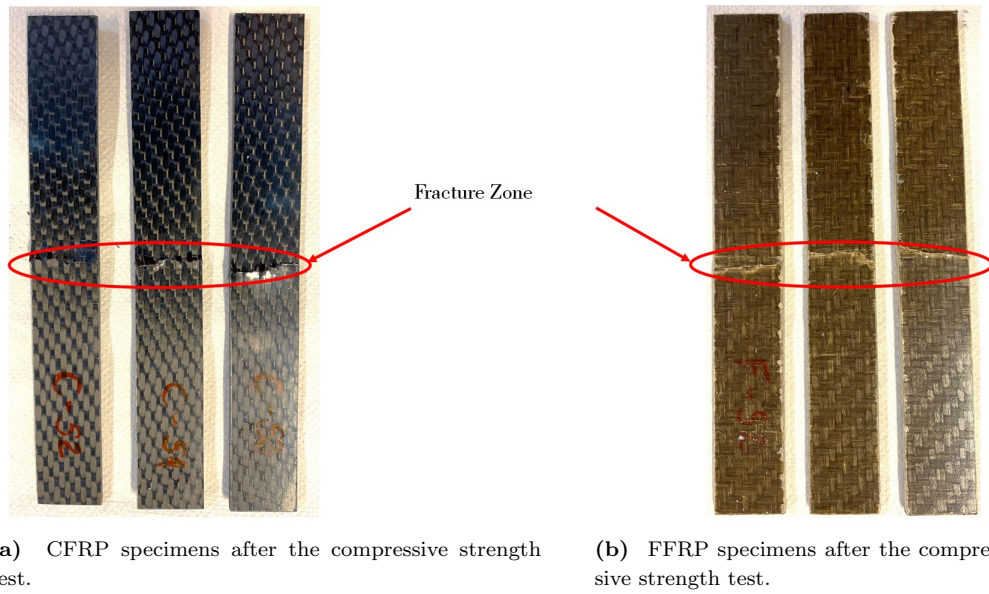


Figure 3.15: CFRP and FFRP specimens after the compressive strength test.

In order to calculate the compressive strength according to the standard followed, equation 3.1 was used:

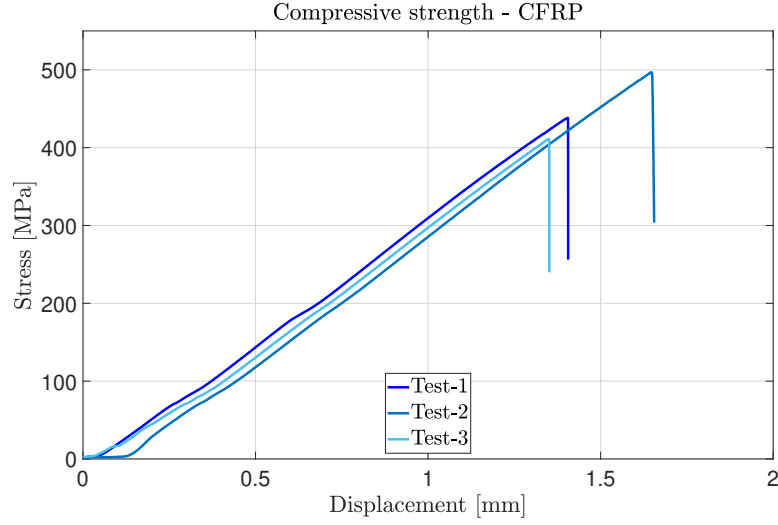
$$F^{cu} = \frac{P_f}{wt} \quad (3.1)$$

where F^{cu} is the laminate compressive strength in MPa, P_f is the maximum load to failure, in N, w is the specimen gauge width in mm, and h is the specimen gauge thickness in mm.

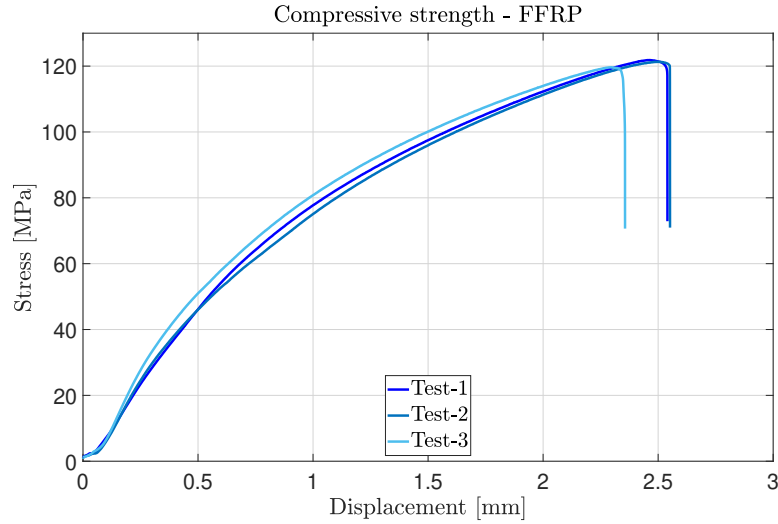
From table 3.11 one can observe the compressive strength results achieved from the CFRP and FFRP laminates. In figures 3.16a and 3.16b the stress-displacement curves obtained from the testing of the specimens is presented.

Table 3.11: Average compressive strength from the CFRP and the FFRP.

Material	Compressive strength, F^{cu}	Standard deviation
	[MPa]	[MPa]
CFRP	448.8	43.9
FFRP	120.9	1.1



(a) Stress-displacement curve from the compressive strength test of the CFRP.



(b) Stress-displacement curve from the compressive strength test of the FFRP.

Figure 3.16: Stress-displacement curves from the CFRP and FFRP compressive strength tests.

3.7.2 Carbon fibre reinforced composites

Flat coupons - CLC setup

Flat coupon crush testing is quite challenging, especially due to the influence that the unsupported length of the specimens and the fixture have on the crushing of the coupons [23]. As aforementioned, flat coupons with different unsupported heights were tested, so that the maximum unsupported height could be properly evaluated. The CFRP flat coupons tested with CLC test support are shown in figure 3.17. The coupon FC-15 was crushed in a stable manner with a wedge of crushed debris at the crush front creating a longitudinal crack in the mid-plane of the laminate causing delamination between the inner plies. This interlaminar fracture forced the plies to splay symmetrically in fronds that were bent outwards. The plies in the splayed fronds also suffered from delamination, as can be seen in figure 3.18.

3.7. Experimental results

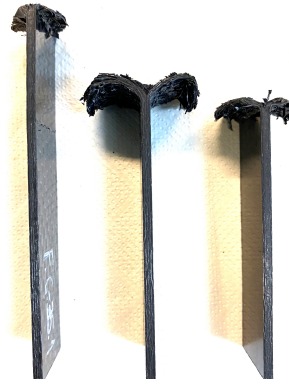


Figure 3.17: Crushed CFRP flat coupons. From left to right: FC-35, FC-25, FC-15.

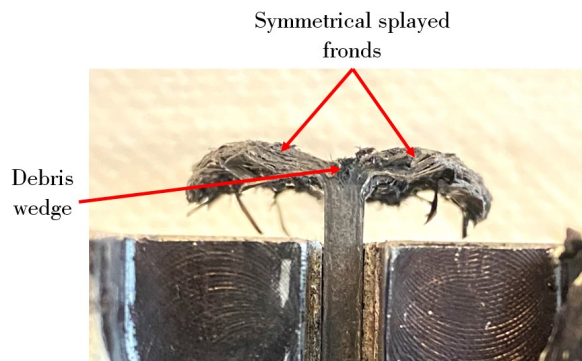


Figure 3.18: Flat coupon FC-15 crushed on CLC support, with the failure modes highlighted.

From figure 3.17 one can realise that the coupon FC-25 was crushed predominantly by splaying. At first glance it appears to behave similarly to the FC-15 coupon, however, after a more detailed examination of this coupon, this was not quite the case. During the test of this coupon, it was possible to observe some instability after the crushing of the trigger zone that resembled a buckling failure. However, shortly afterwards the coupon straightened again and was crushed. After the end of the test, it was observed that the coupon failed by asymmetric splaying, probably due to its initial elastic instability that caused the coupon to bend to one side. This effect resulted in a splaying with five plies to one side and three to the other, as can be seen in figure 3.19.

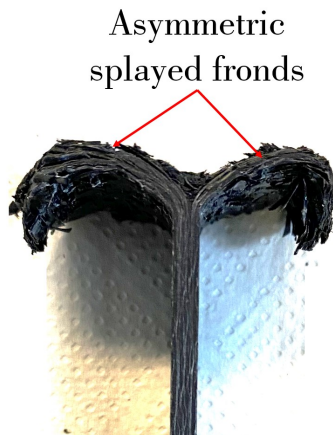


Figure 3.19: Flat coupon FC-25 crushed, with an emphasis given to its unsymmetrical splaying. On the left frond 5 plies and on the right frond three plies.

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Regarding the FC-35 coupon test, buckling was observed immediately after the trigger crushing was finished (as shown in the figure 3.20), so the test was stopped. This phenomenon was already expected to occur in this coupon since in the FC-25 coupon test this instability had already been observed.



Figure 3.20: A frame from the FC-35 coupon crush test in which buckling can be observed.

The crush stress-displacement curves are shown in figure 3.21. Figure 3.21a shows the stress-displacement curve of the FC-15 coupon, where it can be seen that no plateau of crush stress was achieved. This was a result of the crush front being too close to the CLC fixture, which translated into artificial crush stress. Therefore, the data obtained is not feasible to calculate the average crush stress. The experienced phenomena highlight the shortcoming of testing flat coupons with a short unsupported length, which is the fact that a plateau of crush stress is not achievable since the length is very small once the trigger is crushed. Using Vigna's fixture, even with an unsupported height of 10mm, good crushing was achieved, because the height was kept constant and the crush front was far enough from the clamping fixture.

Figure 3.21b describes the stress-displacement curve of the FC-25 coupon. After the trigger was crushed the specimen showed the unstable behaviour already described, which caused the sudden drop observed in this figure. Although a plateau was reached, the elastic instability of the test proved that the unsupported length was too big to achieve decent levels of crush stress.

Overall, the testing of CFRP flat coupons with the CLC support proved to be very ineffective and unsuitable for crush applications, as either too much elastic instability was observed, as in the case of FC-25 and FC-35 coupons, or an unsupported length was too short for conclusions to be drawn, as in the case of the FC-15. This was highlighted by Feraboli [23, 91] and Dalli et al. [26], and was verified again in this study, since it was the easiest flat coupon test that could be conducted in-house, and which could provide a first-hand understanding of the crushing/buckling phenomena at play.

3.7. Experimental results

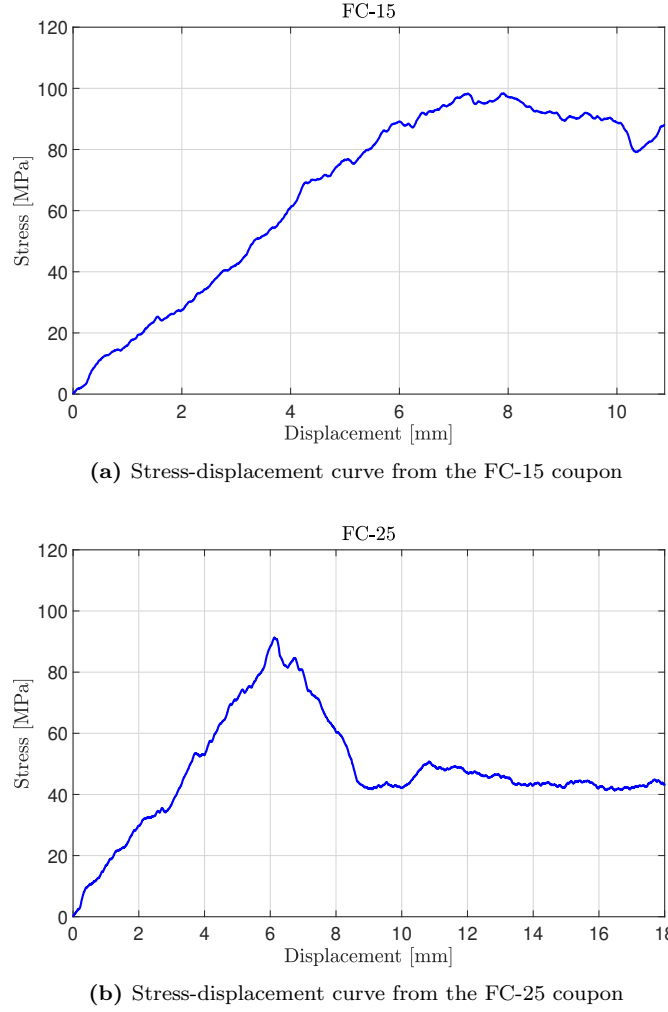


Figure 3.21: Stress-displacement curves from the CFRP flat coupons FC-15 and FC-25

Flat coupons - INSTRON setup

One of the biggest advantages of crushing flat coupons with the INSTRON fixture is that it is possible to reach a plateau of crush stress with a fixed unsupported length without the fronds touching neither the fixture nor the crush plate.

The coupon TC-10-INSTRON crushed progressively predominantly by symmetrical splaying (figure 3.22) as it happened in the coupon TC-15. The average crush stress of the coupon was calculated between the two orange dashed vertical lines in figure 3.18, i.e., between 15 and 23 mm. Its average value is specified in table 3.12. Figure 3.23 shows the stress-displacement curve of the two tested flat coupons, FC-10-INSTRON and FC-20-INSTRON. As one can observe, even though the unsupported lengths of the crush specimens were 10 mm and 20 mm, respectively, it was possible to obtain almost 23 mm crushing of the specimen. This happened because the unsupported length was kept constant and the specimen slid between the clamping fixture, as was already explained in section 3.6.3.

The coupon FC-20-INSTRON failed by buckling, due to the unsupported height being too long. This resulted in a sudden drop in crush stress after the trigger was crushed (which corresponds to the moment where the coupon started to buckle). The curve obtained by testing this coupon was very similar to the FC-25 coupon, which corroborates the theory that the latter failed due to

elastic instability. It can be concluded that flat coupon testing is complex, unstable and depends on several parameters. However, efforts are being put into practice to tackle the shortcomings arising from flat coupon testing, as shown by the setups developed by Vigna et al. [66] and Barnes [28]. It is very important to keep developing alternative setups for flat coupon testing because crash structures usually have several geometries, among which are flat sections. Thus, is of paramount relevance to understand the behaviour of these types of geometry under crushing loads, and most importantly to estimate the crushing stress of such geometries correctly.

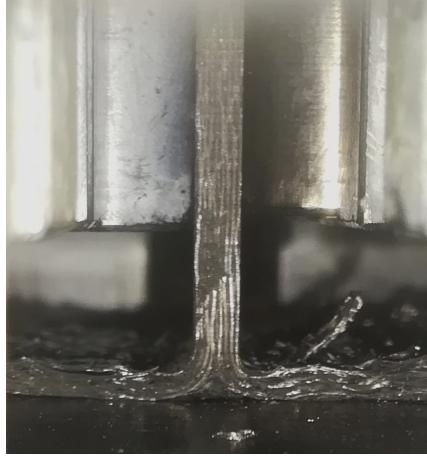


Figure 3.22: Crushing of the coupon FC-10-INSTRON tested with INSTRON setup.

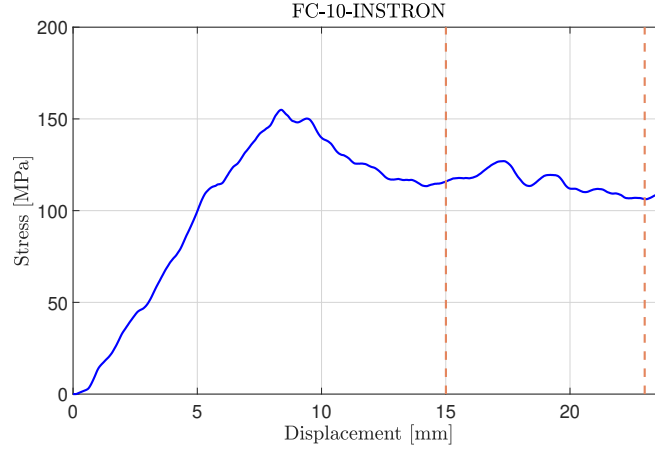
Table 3.12: Average crush stress from the FC-10-INSTRON coupon tested with the fixture from INSTRON

Specimen	Average Crush stress
	[MPa]
FC-10-INSTRON	115.4

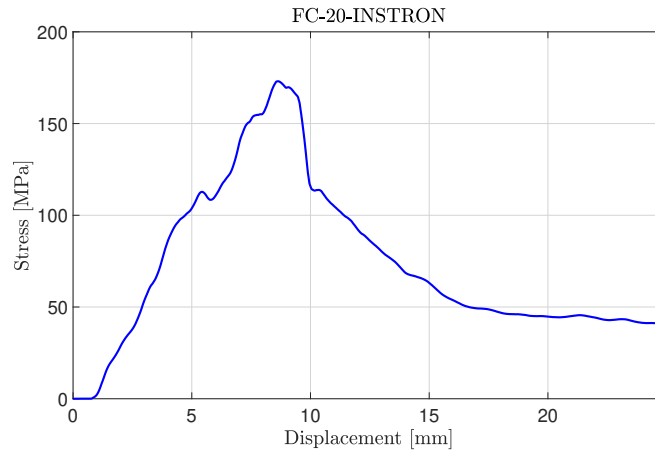
Note that the tests performed by this setup were preliminary. That is, in the future the objective is to test wider and longer flat coupons, to capture their behaviour in a better way. Furthermore, the contact area with the top plate is still too unstable, and sometimes the failure of the coupon can occur in this region, which is undesired. Therefore, development still needs to be carried out on this fixture, so that these side effects can be avoided.

Another limitation of testing open section coupons is the fact that they are not very representative of an authentic large crash structure, as this type of coupon falls within the group of open section coupons. On the other hand, closed section coupons have circumferential stress arising from the fact that the fibres in the circumferential direction form a closed hoop. Thus, when crushed, tearing lines are formed, developing the so-called fronds. To better replicate this effect in flatter sections it would be interesting to develop and test tubular coupons with square cross-sections, as in the study carried out by Mamalis et al. [77]. This way, it would be possible to achieve at least four tearing lines, corresponding to the corners of the square, and thus reproduce more trustworthy results. Furthermore, the tubes could be self-supported, simplifying the test-setup of the flatter geometry.

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(a) Stress-displacement curve from the FC-10-INSTRON coupon.



(b) Stress-displacement curve from the FC-20-INSTRON coupon.

Figure 3.23: Stress-displacement curves from the CFRP flat coupons FC-10 and FC-20 tested at INSTRON.

Tubular coupons

As already stated, Dalli et al. [26] tested round tubular coupons with the same material and geometry as the TC-2 coupons tested in this work. Using the raw data of the crush test from Dalli et al. [26], the crush stress was calculated, and it was compared to the one achieved by the TC-2 coupons in the current study. The baseline comparison of those tests is described in figure 3.24. One can observe that the peak stress was lower in the current study than in the one carried out by Dalli et al. [26]. That happened because the trigger was produced in two different ways. In that study, the triggers were manufactured manually using sandpaper. In the current work, the manufacturing of the triggers was done by machining one of the tube ends in a lathe with the angle specified in figure 3.1.

The average crush stress values are presented in table 3.13, where one can observe the proximity of the results achieved in both studies. This baseline comparison proves that the material used in this work, manufacturing and test setup match the same experimental procedures used by Dalli et al. [26]. Note that the interval used to calculate the average crush stress is defined in figure 3.24 between the vertical orange dashed lines (10-20 mm) and was chosen because Dalli et al. [26] also used that same interval. However, different intervals were used in this work to perform the data

reduction of the tested specimens, as it was possible to achieve a more extensive range of plateaued crushed stress.

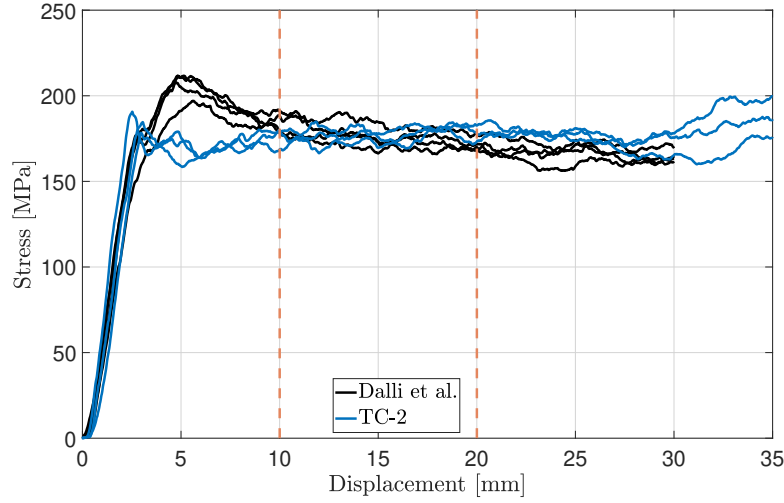


Figure 3.24: Comparison between the stress-displacement curves from the tested tubes in Dalli et al. [26] and the TC-2 coupons tested in this work.

Table 3.13: Comparison of the average crush stress between the TC-2 coupon and the study performed by Dalli et al. [26].

Specimen	Average Crush stress [MPa]
TC-2	177.6
Dalli et al.[26]	176.5

In the current work, all the CFRP tubes were crushed progressively, and no elastic instabilities were observed, contrarily to what happened in the study from Fairfull et al. [82]. The tubes failed in combined splaying and fragmentation modes, with the first being more predominant. After the trigger was crushed, the constant cross-sectional area started to be progressively crushed with a wedge of debris created on the crush front forcing the adjacent plies to delaminate. As the crushing front progressed and delamination occurred, the hoop stress in the circumferential fibres increased significantly. Consequently, the circumferential tows failed on the outside in tension, while the hoop fibres on the inner circumferential tows of the plies failed in compression. Their failure led to the tearing of the laminate resulting in the formation of several fronds, as explained by Hull [27] and experienced in studies by Dalli et al. [26] and Strohrmann et al. [19]. Figure 3.25 shows the TC-3 coupon after being crushed, where these described phenomena can be observed. Furthermore, the inner fronds started touching each other soon after the progressive crush started, which caused additional inner friction contributing to the energy absorption.

All the CFRP tubes with a circular cross-sectional area failed in very similar manner, as can be seen in figure 3.26, that shows the qualitative results of the five crushed tubular coupons. Analysing the specimens in a qualitative way it is possible to observe that the smaller coupons were the less tended to be the number of splayed outer fronds. Another interesting aspect observed was the behaviour of the tubes in the axial wrinkled regions. These zones corresponded to tearing lines on the outside of the composite since these were also zones richer in resin and consequently mechanically more fragile. However, the fronds created in the zone of the existence of wrinkles

3.7. Experimental results

presented in general a much stiffer behaviour than that observed in the remaining fronds. This phenomenon may be related to an increase in the second-order moment of inertia in the section of the geometric imperfection of the tube. Figure 3.27 demonstrates this effect in one of the tested specimens.

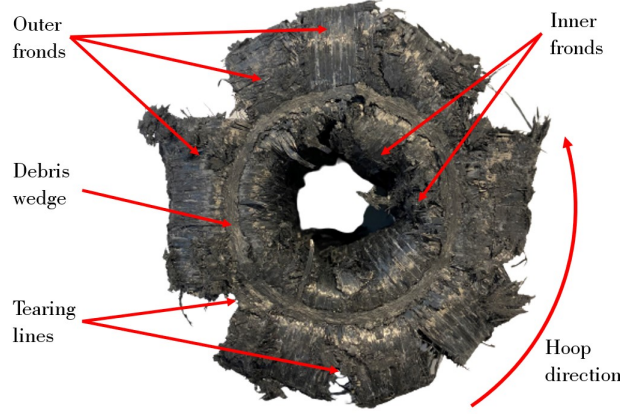


Figure 3.25: Top view of one of the TC-3 crushed coupons describing a typical behaviour of the CFRP tubular coupons, highlighting the fronds, debris wedge and tearing lines.

The crush stress was calculated dividing the load by the cross-sectional area of the tube, which was calculated by Eq. 3.2. The plots in figure 3.28 show the stress-displacement curves of these five sets crushed coupons. These curves are characterized by several serrations due to the crush energy of the composite material being absorbed by a sequence of different microcracking processes characterising each case of collapse [25].

$$A = \frac{\pi}{4} \times [(D_i + 2t)^2 - D_i^2] \quad (3.2)$$

In Eq. 3.2 D_i corresponds to the nominal internal diameter and t to the nominal thickness of the laminate.

The energy absorbed (EA) was calculated using the trapezoidal rule² which is presented hereafter:

$$\int_a^b EA(x)dx \approx \sum_{k=1}^N \frac{f(x_{k-1}) + f(x_k)}{2} \Delta x_k \quad (3.3)$$

where $EA(x)$ represents the energy absorbed between the two points of integration a and b , $f(x_{k-1})$ and $f(x_k)$ are the load values in two immediately adjacent points. To calculate the specific energy absorption the EA was divided by the crushed mass of the specimen. Another possible way to calculate the SEA would be to divide the crush stress by the density of the coupon, but as this method is not as accurate, due to the challenges of calculating a precise density of the coupons, the specific energy absorption was calculated by the equation 3.3.

²Trapezoidal Rule is a rule that evaluates the area under the curves by dividing the total area into smaller trapezoids.



(a) All TC-1 crushed tubes.



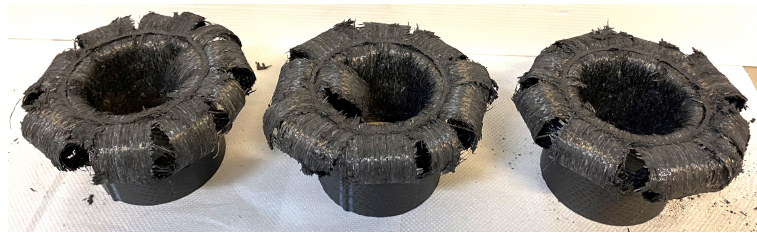
(b) All TC-2 crushed tubes.



(c) All TC-3 all crushed tubes.



(d) All TC-4 crushed tubes.



(e) All TC-5 crushed tubes.

Figure 3.26: Crushed CFRP tubular coupons.

The crashworthiness parameters were calculated, for each coupon, between the values marked in figure 3.28 with two orange vertical lines. That is, for TC-1 the calculation was performed between 7.5-17.5 mm, for TC-2 between 10-25 mm, for TC-3 between 10-45 mm, for TC-4 between 10-50 mm and TC-5 between 10-60 mm. This choice was because this was the zone in which an energy absorption plateau was achieved, while the other zones were affected by other factors. Note that the repetitive unit cell of the CFRP woven is 8 mm, thus this is the minimum crush length required to achieve a decent representation of the progressive crushing [26]. That said, the calculation interval of the parameters of interest also took this factor into account, i.e., it was

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guaranteed that at least 8 mm of the plateau was considered, and the longer the interval the better.

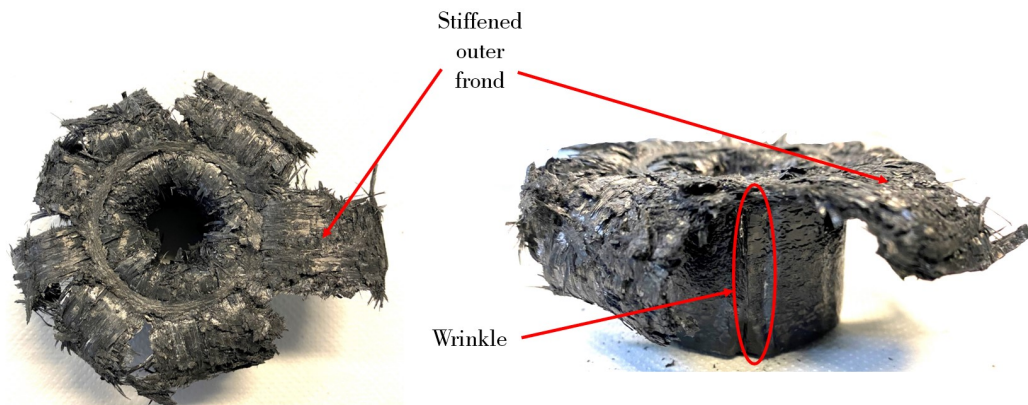


Figure 3.27: Top and front views of the qualitative wrinkle effect on the tubular coupons.

For example, the pre-crush zone corresponds to the crush of the trigger that serves only to initiate the progressive crushing of the coupon, not being interesting for the calculation of crash-worthiness parameters (except for peak load and crushing efficiency, which are highly dependent on the material and geometry of the trigger). Figure 3.28b, which corresponds to the crush stress-curve displacement of TC-2, shows that there was a sudden rise in the crush stress value after 25 mm of crushing. This increase in stress happened because the internal fronds of the tube started to touch the bottom plate where the tube was supported. This effect was reflected in an increase in the resistance of the material in the interior zone of the tube and as consequence led to an increase in the crushing stress. So, the regions out of the plateau in the load-displacement curve cannot be considered during the crush stress calculations.

In figure 3.28c one can observe an increase in crush stress from the coupon TC-3 from roughly 12.5 mm to 32 mm, followed by a sudden drop until the end of its crushing length. To better understand what caused such behaviour, the specimens were analysed in more depth. It was observed that 10-15 mm from the end of the test two of the wider fronds separated into three smaller ones due to excessive hoop stresses in those two fronds. Note that cracks will take a path of least resistance, and in this case it was slightly less energy consuming to create another tear-line rather than to maintain the very high hoop stresses in the particular fronds.

Table 3.14 presents the average values of crush stress and specific energy absorption obtained from the CFRP tubular coupons testing.

Firstly, it can be observed that between each type of specimen the standard deviation of both parameters was quite low, which confirms a low level of dispersion of results in the tested tubes³. Another deduction that can be drawn is that the wrinkles had no evident adverse effects on the crush stress and SEA values. It is interesting to observe that there is no pattern related to the existence of wrinkles that could justify their influence on the crush stress of the composite material. For example, in the TC-2 coupon the average crush stress was the lowest in the tube with more geometric defects. However, in most of the remaining cases, the most wrinkled tube was the one with higher levels of energy absorption, which can even lead to wonder if this geometric defect

³Note that the values for each test are specified with more detail in appendix A.

Chapter 3. Assessing geometry effects on monolithic coupon energy absorption

is acting as a stiffener, which ends up increasing the resistant area of the tube and influencing the crush stress in a positive way. However, as no in-depth study was carried out on this type of effect, no conclusion can be drawn on the increase or decrease of crush stress due to the existence of geometric defects. In this case, they were considered to have little influence on the crush stress results obtained. Further research should be done to analyse the effect of wrinkles on crush tests, through numerical models, for example.

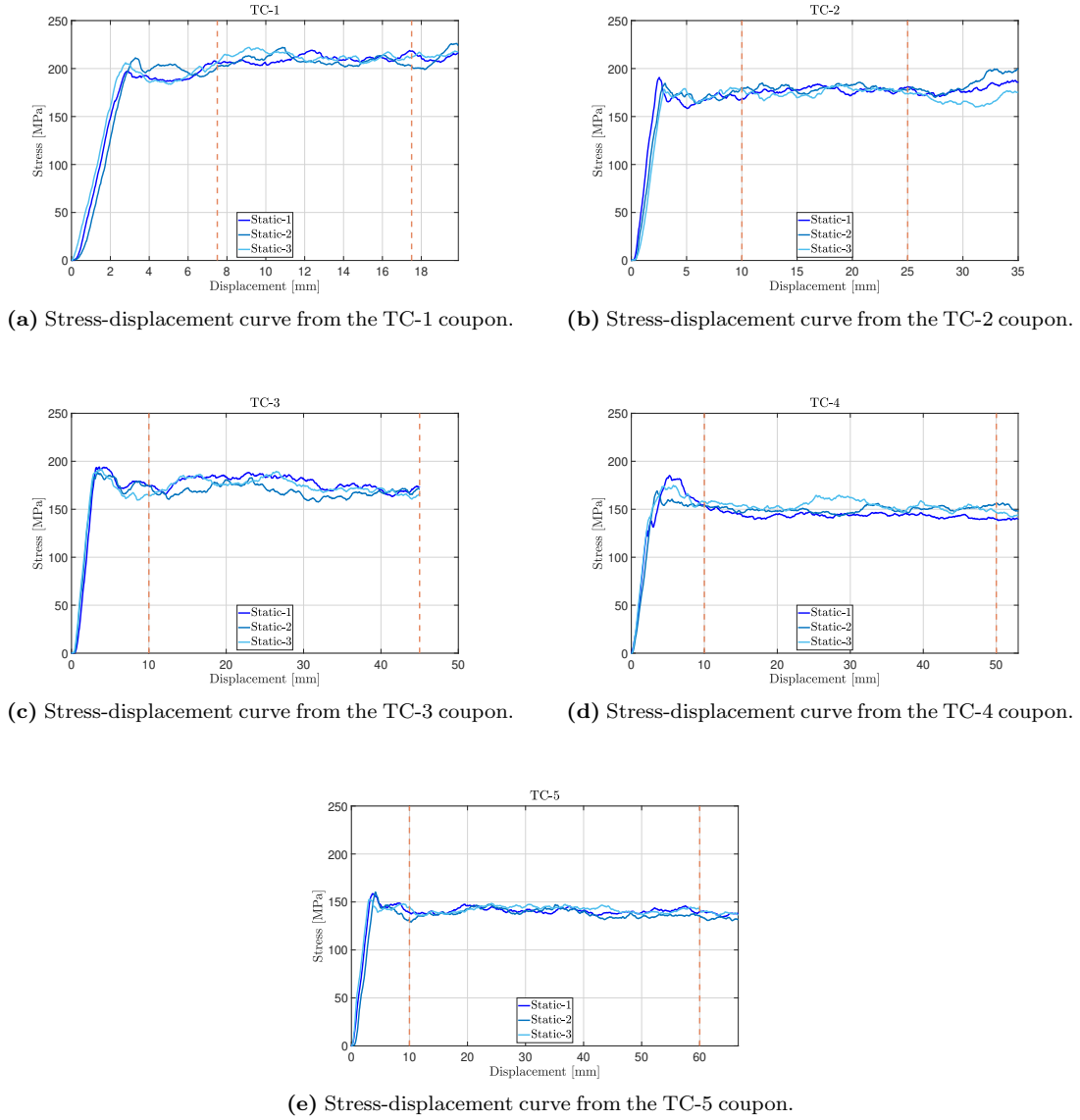


Figure 3.28: Crushing stress-displacement curves from the tested tubular coupons.

From table 3.14 it can be seen that the crush stress value decreases as the curvature decreases. When comparing the crush stress of the tube of 19 mm of internal diameter with the tube of 76.20 mm a drop of about 33% is observed from the value from the smallest diameter to the largest. Such a factor leads to believe that there is an effect of curvature in the value of the crush stress of the CFRP tubes.

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Table 3.14: Average crush stress and SEA values for the five CFRP tubular coupons

Specimen	Average Crush stress [MPa]	Standard deviation [MPa]	SEA [J/g]	Standard deviation [J/g]
TC-1	210.4	2.1	133.7	1.4
TC-2	177.6	2.0	118.6	1.4
TC-3	173.6	4.2	110.4	3.0
TC-4	149.3	4.8	96.8	3.3
TC-5	140.5	1.8	89.3	1.2

Effect of the 2D curvature on the crush stress of CFRP coupons

As aforementioned, the average crush stresses presented in table 3.14 show a clear decreasing trend as the radius of the tubes increases. Figure 3.29 shows this tendency in a more intuitive way, with the vertical axis showing the crush stress, the horizontal axis showing the radius of curvature, and the points marked in the plot corresponding to the average crush stress values of the tubular coupons TC-1 to TC-5. Although a polynomial fit cannot be plotted yet, it can be seen that there is a transitional reduction of crush stress with increasing radius of curvature, possibly tending towards some asymptotic value. Furthermore, the preliminary result achieved through the testing of the TC-10-INSTRON flat coupon is drawn as a blue dashed horizontal line.

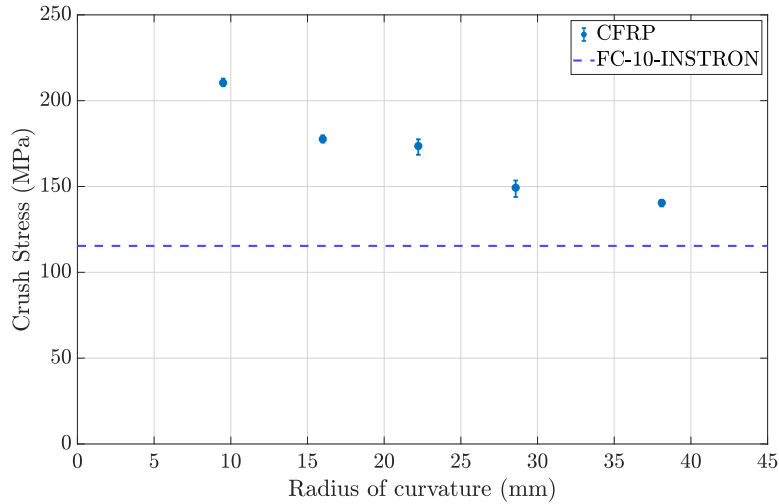


Figure 3.29: Effect of curvature on the CFRP tubular coupons on the crush stress. Markers: curved coupons vs line: flat coupons.

This decreasing trend corroborates the observations that flatter surfaces absorb lower energy levels [23]. There are several reasons that could explain this drop in average crush stress as the radius of curvature increases, which will be addressed in more detail at the end of this chapter. In the study carried out by Fairfull et al. [82], the crush stress also increased slightly with increasing t/D ratio, although a glass fibre weave was used over a carbon weave. That trend also seems to be observed in CFRP composites.

If square tubular coupons were to be developed, it would be expected that they would fit somewhere in figure 3.29 between the value of crush stress from TC-5 and the flat coupon TC-10-INSTRON. Such prediction would be related to the fact that flat coupons can be approximated as having a massive radius of curvature. In the future, it would be convenient to develop and test this tubular geometry in order to assess its behaviour and corroborate the hypothesis outlined.

Effects of other geometrical parameters

After testing the CFRP tubes, an evaluation was made regarding the possible effect of the length of the tube compared to its diameter. This study was performed on the tube most susceptible to elastic instability, that is, the TC-5 tube whose thickness/diameter (t/D) ratio is the smallest of the 5 tube sizes. As already explained, a specimen of diameter TC-5 was cut in half giving origin to two tubes TC-5HL with 70 mm length. Figure 3.30 shows the crushed TC-5HL tubes, through which it can be observed that their fracture modes were very similar to the closed sectioned tubes, in which predominantly splaying, and fragmentation were observed. Both splayed in internal and external fronds with tearing lines separating them in the areas where the fibres of the hoop direction fractured.

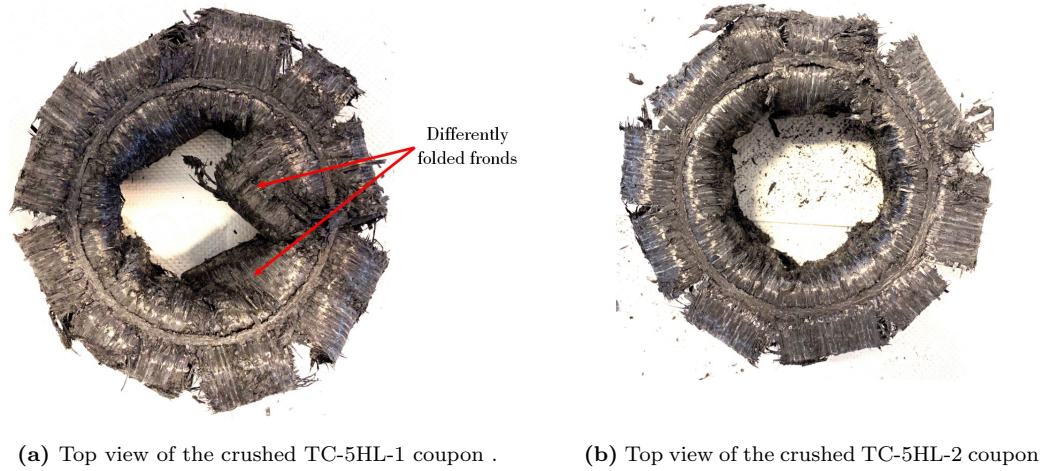


Figure 3.30: Top view of the crushed CFRP tubular coupons TC-5HL.

Table 3.15 presents the average crush stress and the SEA values of these specimens, calculated between the 10-35 mm of the crushed length (the dashed orange vertical lines in the stress-displacement plot). Although the inner fronds of the specimen TC-5HL-1 marked in figure 3.30a were crushed, the manner in which they folded could have allowed for lower frictional energy absorption, which might be the reason why the crush stress of this specimen was lower than the TC-5HL-2, as can be seen in figure 3.31. As already explained, the crushing of the inner fronds between each other causes extra energy absorption from the material by fracture micromechanisms and friction. However, no definitive conclusions on the differences observed between the two specimens will be drawn.

Table 3.15: Average crush stress and SEA values for CFRP tubular coupons TC-5HL and TC-5.

Specimen	Average Crush stress [MPa]	Standard deviation [MPa]	SEA [J/g]	Standard deviation [J/g]
TC-5HL	129.7	7.7	91.1	2.4
TC-5	131.4	1.7	88.9	1.2

As one can see, there was not much difference in the average crush stress when the L/D changed, with one of the coupons TC-5HL presenting higher crush stress than the average value presented in table 3.14 for TC-5 (all values are presented in appendix A). It can be concluded that there is no effect on the crush stress value when altering the L/D ratio.

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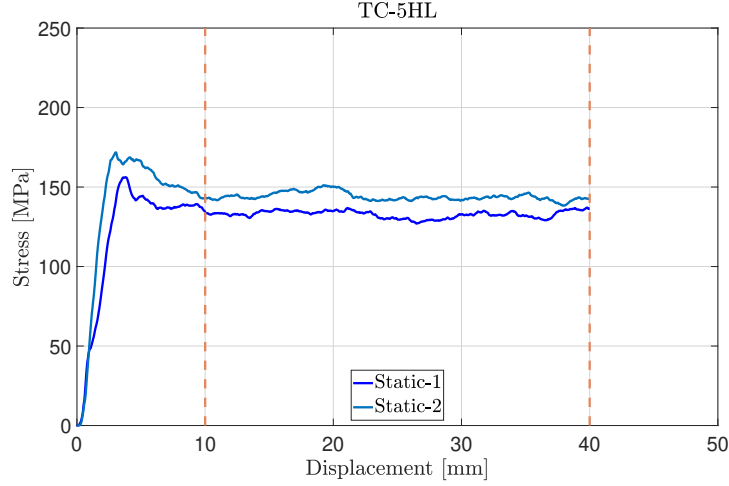


Figure 3.31: Stress-displacement curves from the TC-5HL coupons.

As aforementioned, the free-edge effect was also studied. The TC-3HS and the TC-4QS coupons were tested to understand if the breakage of fibres in the tow direction would have any influence on the crush stress of the specimens. As previously stated, the angles of the cross-section were not perfect, due to the width of the cutting tool and, defects (non straight edges) induced by manual cutting. To determine the cross-sectional area to calculate the crush stress the following equation was used:

$$A = \frac{\alpha}{360} \times \frac{\pi}{4} \times [(D_i + 2t)^2 - D_i^2] \quad (3.4)$$

where α is the angle measured between the two free edges of the coupons. This allows keeping the area as precise as possible, instead of only dividing the cross-sectional area by two or four.

The crushing of the sectioned tubes looked promising at first, as the half-sectioned tube TC-3HS-1 crushed progressively with no issues. The coupons started to delaminate in the mid-plane of the laminate, similarly to what happened to the closed coupons. As the crush front progressed the outer plies separated into four fronds. The inner-most plies bent inwards, but tearing did not occur, thus fronds were not originated. Instead, the inner plies kept deforming plastically until the end of the crush length. Figure 3.32 shows this coupon after testing.

The TC-3HS-2 coupon, on the other hand, started to crush progressively similarly to the one described above. However, after about 23 mm of the test had started, it was observed that the coupon began to bend to one side. The test was then stopped, and after analysing the coupon, it was possible to see that it had catastrophically failed by folding, as shown in figure 3.33. This observed phenomenon highlights one of the major limitations of testing sectioned coupons. The most likely cause for this failure could have been caused by a misalignment between the centre of the coupon and the centre of the test plates which is very hard to achieve manually, and would necessitate a custom fixture for reliable centering. Compared to circular coupons it is much more complicated to align these sectioned coupons correctly, which can cause a bending moment in the coupon caused by the off-axis load. Furthermore, the free edges are much more susceptible to buckling due to the reduced constraints when compared to closed-section axisymmetric tubes.

Figure 3.34 shows the crush stress-displacement plots of the half tubes. As already explained, the test of the second coupon was stopped after its catastrophic failure was observed, and as such

its stress-displacement curve was shortened. Fortunately, it was still possible to obtain a plateau that allowed the calculation of the average crush stress. The range of 10 to 40 mm was considered for the TC-3HS-1 coupon (orange vertical lines in the graph) and for TC-3HS-2 from 10 to 23 mm (first orange vertical line and red vertical line). There was a greater dispersion of results obtained, with the second coupon obtaining higher crush stress values than the first. Table 3.16 shows the average crush stress and SEA value for these coupons.



Figure 3.32: Crushed TC-3HS-1 coupon with the debris wedge removed post mortem.

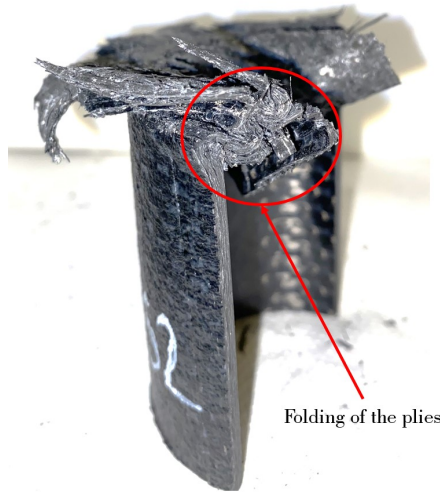


Figure 3.33: Crushed TC-3HS-2 coupon highlighting the folding of the plies.

Although the average crush stress was much lower than that of the full tube (173.6 MPa), only two tests were performed, and the dispersion of results was quite high. More tests would be necessary to draw more concise conclusions. However, for instance, the TC-3HS-2 coupon obtained higher crush stress (170.0 MPa) than the TC-3-2 coupon (168.5 MPa). This observation leads to the conclusion that the half tubes should not have a great influence on the crush stress. However, their testing seems to be more unstable and unpredictable, if the method used for the testing is the same as the one used in this work.

Initially, the four prepared TC-4QS coupons were supposed to be tested. However, although the first coupon was crushed, the second and third coupons failed catastrophically by buckling.

3.7. Experimental results

This was observed as no effective way to fix these coupons was found and therefore, they either slipped in the fixture or started to crush at the base. In other words, the testing of quarter sections became practically impossible. The lack of alignment with the testing axis of the machine might have also been the reason for such behaviour of these coupons.

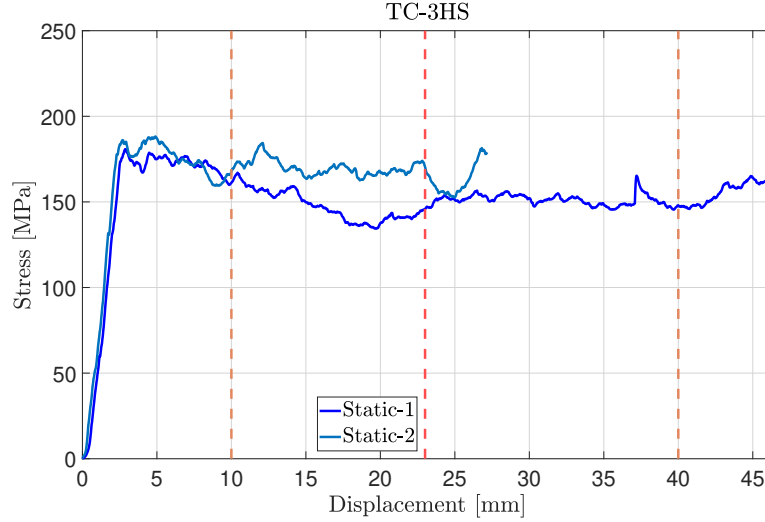


Figure 3.34: Stress-displacement curve of the TC-3HS.

Table 3.16: average crush stress from coupons TC-3HS

Specimen	Average Crush stress [MPa]	Standard deviation [MPa]	SEA [J/g]	Standard deviation [J/g]
TC-3HS	159.8	14.4	98.5	10.8

Even so, the first quarter section was successfully tested. The crushing behaviour was very similar to that observed in the TC-3HS coupons. That is, fronds formed on the outside and splayed outwards, while on the inside the delaminated plies bent without suffering from tearing. Figure 3.35 shows this coupon after testing. The delamination did not look to be symmetric, as it seems that three plies were bent to the outside, while the remaining five were bent to the inside. This indicates that the smaller the angle of the open-section coupons, the more likely it is to observe some amount of asymmetry, buckling, and other possible undesired failures.

Figure 3.36 shows the stress-displacement plot of the coupon that was successfully crushed. The crush stress was calculated between 10 and 35 mm and its value is shown in table 3.17. As can be observed, the crush stress is also lower than the one of the tubular coupon TC-4 (149.3 MPa). However, the number of specimens tested was too low to draw any strong conclusion on the effect of this type of specimen on the crush stress regarding the effect of free edges on curved coupons. Although there seems to be a reduction of crush stress the tests performed were very limiting, as only three successful tests were performed in total. One of the great advantages of using this type of coupon to characterise composite materials in crush applications would be the fact that less material is used than in closed section tubes, and the manufacturing process itself is much more simplified. However, the testing of such coupons would require further development. It shown that, if the sectioned tubes are self supported, they may become too unstable. On the other hand, a fixture would have to be developed, which not only entails development and manufacturing costs but also makes testing more complex. Furthermore, the alignment of the tubes with the loading

axis is also more complex and, if not appropriate, the material can fail catastrophically, as has been observed.

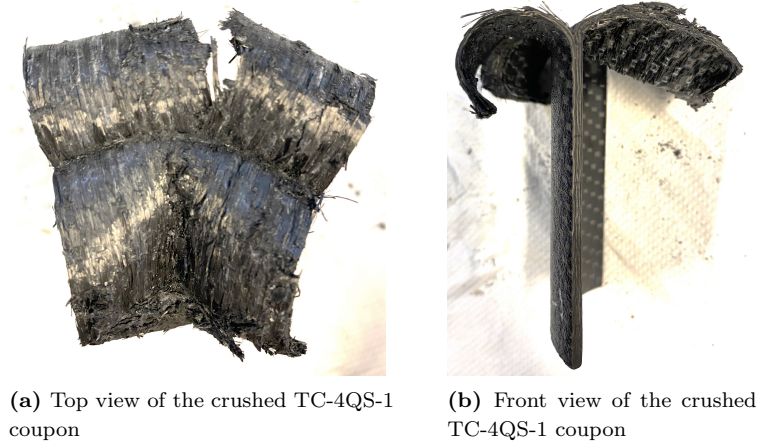


Figure 3.35: Different views of the crushed TC-4QS coupon

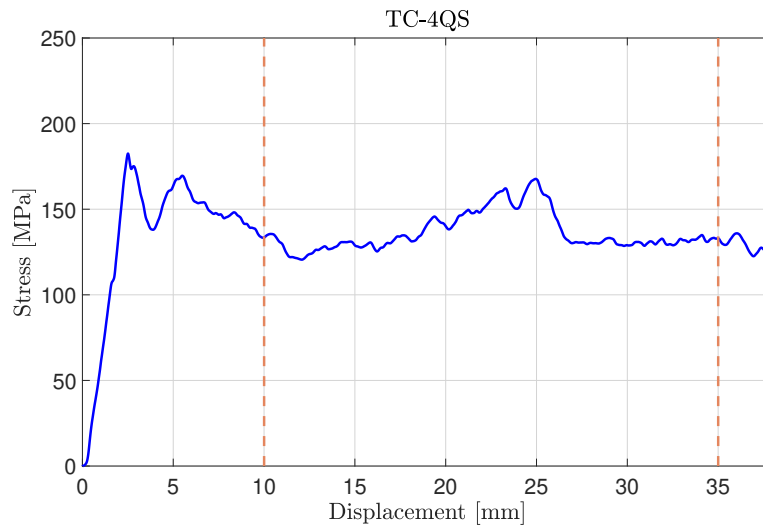


Figure 3.36: Crush stress-displacement curves from the TC-4QS coupon.

Table 3.17: Crush stress and SEA from the TC-4QS coupon

Specimen	Average Crush stress [MPa]	SEA [J/g]
TC-4QS	139.5	89.8

Although it is apparent that there is some influence on the testing setup of the coupons, geometric effects such as the L/D ratio and free edge effects do not appear to lead to a large change in crush stress. Figure 3.37 shows the crush stress of all curved sections tested considering the effects of coupon geometry.

By analysing the crush stress of the several CFRP geometries tested throughout this section, it can be observed that the 2D curvature effect, i.e., the radius of curvature of the tubes, is the most important effect on this crashworthiness parameter. It is visible that there is a transitional drop in the crush stress as the radius of curvature of coupons increases. This results can change how

3.7. Experimental results

material crushing parameters are applied to complex geometries. Until now, only the distinction between curved or flat sections in crash structures would be considered, which meant that the energy absorption parameters were assigned to these regions based on whether those conditions were verified or not. If the effect of different curvatures can be corroborated, modern composite large structures can be modelled using different crush stress parameters in different curved regions. Such enhancement might lead to more precise numerical predictions.

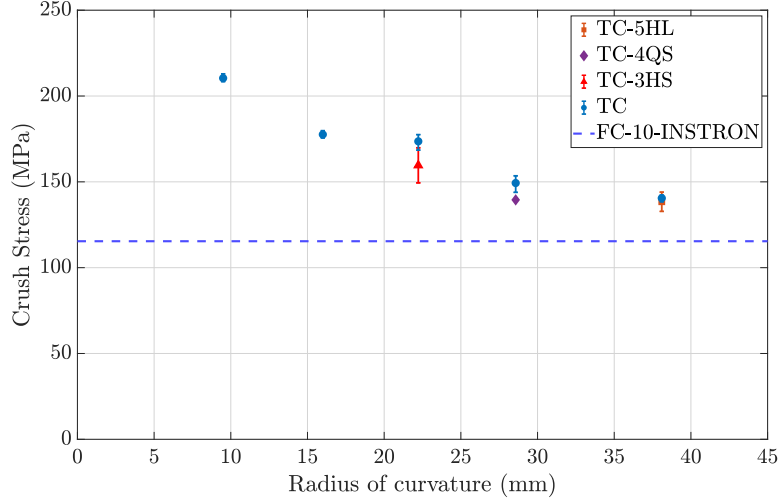


Figure 3.37: Effect of curvature on CFRP tubular coupons (TC), their respective geometrical variations (TC-3HS, TC4-QS and TC-5HL) and flat coupon (TC-10-INSTRON).

3.7.3 Flax fibre reinforced composites

Flat coupons

As in the case of the CFRP flat coupons tested with the CLC test fixture setup, the FFRP flat coupon testing was also challenging. The unsupported length from FF-15 revealed to be too short for a decent plateau of crush stress to be obtained. In the case of FF-25 the unsupported length was too long, leading the coupon to buckle. Because the stiffness of the CFRP is higher than that of the FFRP, it was expected that the FFRP coupons would buckle with smaller unsupported lengths. That prediction was verified, as the coupon FF-25 buckled. The coupon FF-15 was crushed with no elastic instabilities being observed. However, as had happened to the CFRP FC-15 coupon, it was not possible to achieve a plateau of crush stress due to the proximity of the crush front to the CLC fixture, which translated into an artificially high crush stress. In figure 3.38a the coupon FF-15 can be observed after testing. In the core of the laminate, it was observed that some plies started folding in what seemed to be a compressive failure of the plies in that area.

The data in figure 3.39 proves that the data collected is insufficient for a plateau to be reached. Furthermore, the failure mode majorly by splaying was asymmetric, which can indicate that the coupon with this unsupported length was already suffering from certain instability, bending slightly more to one side.

As aforementioned, the size FF-25 buckled, as can be seen in figure 3.38b, meaning that the unsupported height of the coupon was excessive for this specific material, thickness and test setup. Once again, this proves the necessity to improve flat coupon testing, especially when dealing with composites that have lower compressive strength, as is the case of the FFRP. Unfortunately, it was

not possible to test the FFRP flat coupons using the INSTRON or the Engenuity setups, could be more appropriate to determine the crush stress of flat FFRP coupons.

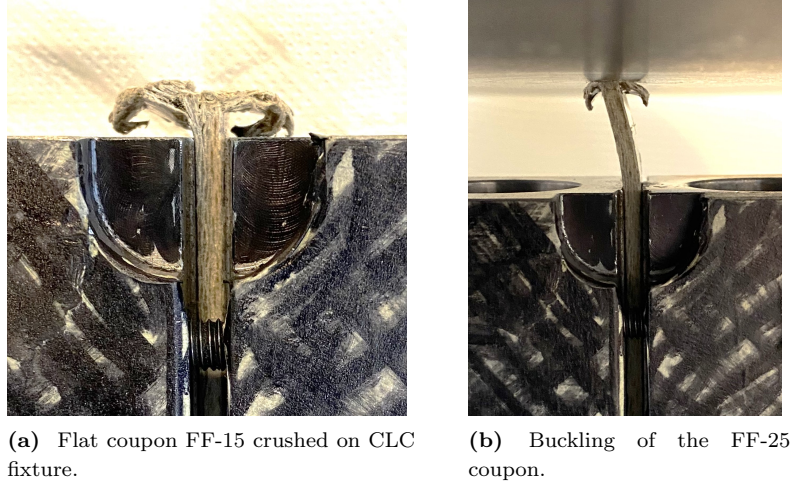


Figure 3.38: FF-15 and FF-25 coupons after testing.

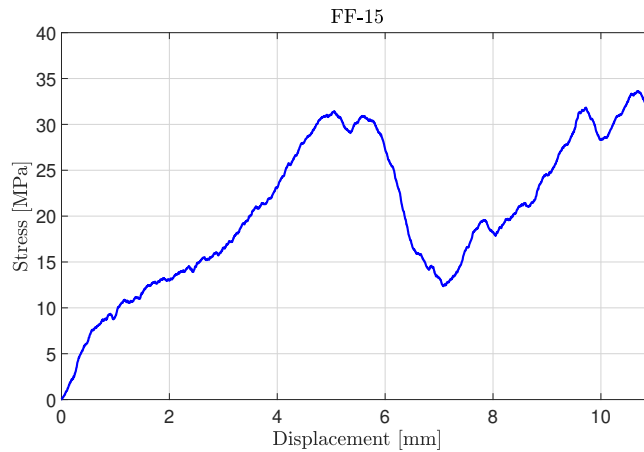


Figure 3.39: Stress-displacement curve of the FF-15 coupon.

Compared to CFRP, the FFRP flat coupons were even more unstable and were more prone to fail by buckling. While the failure of the CFRP coupons was only obvious with the coupon with 35 mm of unsupported length, the failure of the FFRP coupons experienced the same phenomenon with shorter unsupported lengths. Therefore, the testing of the FF-35 coupon was not even performed, as buckling was the most probable outcome of such an experiment. This could be potentially dangerous because the CLC fixture could be projected from of the test machine as a result of the lateral load arising from buckling.

Tubular coupons

The methods used to calculate the crashworthiness parameters of the FFRP coupons were the same as the ones used for the CFRP, with equations 3.2 and 3.3. The FFRP tubes showed slightly different behaviour from what was observed in the CFRP tubular coupons. Figure 3.40 shows the crushed FFRP tubular coupons.

As expected, the scatter of results in the FFRP tubes was higher than that observed in the

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CFRP tubes, as can be seen in figure 3.41, which presents the stress-displacement curves of each specimen. The data reduction was carried out between the vertical orange dashed lines marked in the plots. Thus, for the coupon TF-3 it was calculated in the range 15-45 mm, and for TF-4 and TF-5 in the range 15-40 mm.



(a) All TF-2 crushed tubes.



(b) All TF-3 crushed tubes.



(c) All TF-4 all crushed tubes.



(d) All TF-5 crushed tubes.

Figure 3.40: Crushed FFRP tubular coupons.

Figure 3.41a shows the stress-displacement curve from three of the four TF-2 coupons tested. As one can observe, after 10 mm of crushing, the crush stress decreases significantly. To better understand what was happening to these coupons, the third coupon TF-2-3 was crushed in intervals of 5 mm. Figure 3.42 shows images of each step. Figure 3.42a corresponds to the crushing of the trigger. Figure 3.42b shows the crushing up to the 10 mm displacement, showing that there are not yet evident fronds being formed. Figure 3.42c shows the crushed coupon after 15 mm. In this zone, the beginning of longitudinal cracks corresponding to tear lines can be observed, in what seems to be the beginning of a failure by splaying mode. However, failures away from the crush front also started to appear. In the inner zone of the coupon wall, this type of failure was also observed. In figure 3.42d, corresponding to the end of the tube crushing, it can be observed that several fronds were formed, as in the CFRP tubes. However, after a certain point, most of these fronds were crushed, but less efficiently (some portions seem to have less fractures within them),

and asymmetrically. Such phenomenon may have been related to the fact that the failures away from the crush front bent the tube walls off-axis. A possible cause for this behaviour might be the fact that the crush stress at the peak load was close to or just reached the compressive strength limit of the material, leading the material to fail by compression away from the crush front. Figure 3.42e shows these coupons without the debris wedge, where the described sequence of events can be even better understood.

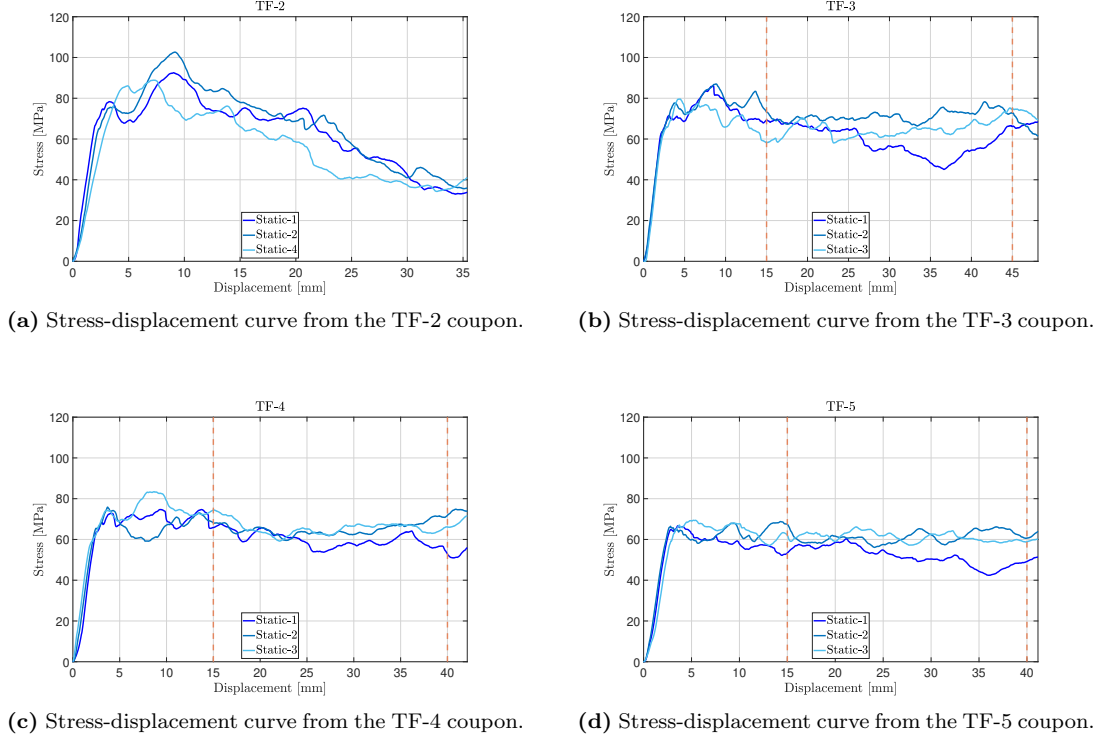


Figure 3.41: Stress-displacement curves from the FFRP tubular coupons TF-2 to TF-5.

To try to achieve a crush stress plateau for this particular coupon a fourth specimen was prepared. The trigger was ground with sandpaper so that its angle could be increased, and consequently, the peak load could be reduced. However, although the peak load lowered, this coupon still failed away from the crush front, as a plateau of crush front was not achieved. In future experiments, it is advisable to machine even steeper triggers, for example, with 65° or more.

Tubes TC-3 to TC-5 were crushed progressively predominantly by splaying. However, from figure 3.41 it can be observed that there was a drop of crush stress from around 25 mm of the displacement. By analysing the crushed coupons after testing it can be observed that similar effects as the ones observed in the TC-2 coupons were experienced. That is, some of the fronds were no longer suffering from delamination and radial fibre breakage, but, instead, they were bending outwards, as figure 3.43a describes. In addition, the material on the inside was more prone to fold than to separate into several fronds, in opposition to what happened to the CFRP tubular coupons.

The average crush stress of the FFRP coupons is presented in table 3.18. Compared to the carbon it can be seen that it is very low. Observing the standard deviation one can also observe that the FFRP tubes had a much larger scatter of results when compared to the ones observed in

3.7. Experimental results

the CFRP. Due to a difference in density, the relative reduction in SEA for FFRP tubes is lower than that for crush stress. Note that the average calculated density of the FFRP tubular coupons was 1.24 g/cm^3 and 1.57 g/cm^3 for the CFRP.

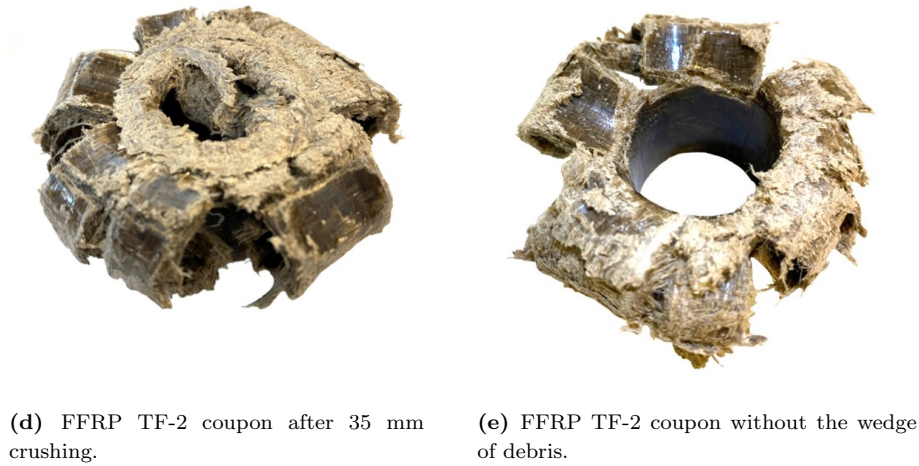
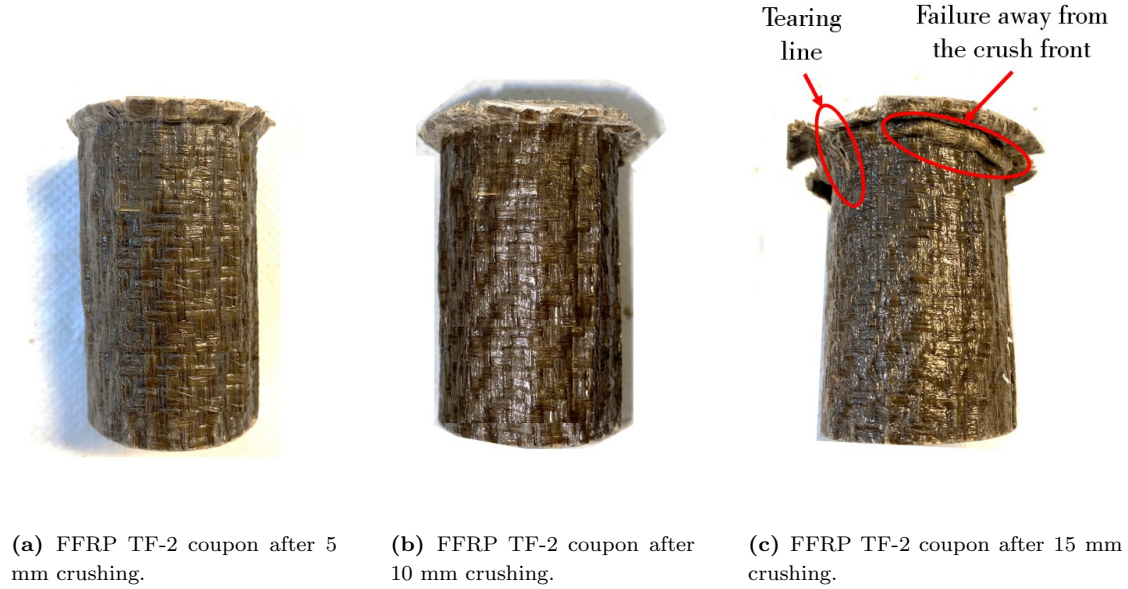


Figure 3.42: Frames of the FFRP TF-2-3 coupon crushing.

Storhmann et al. [19] used 2x2 twill flax fibre *pre-pregs* with 150 g/m^2 to manufacture FFRP tubular coupons, i.e. corresponding to half areal weight of the material used in this study. The tubes had approximately 48 mm internal diameter and an L/D ratio of 1, i.e., they were at the diameter range between the TF-3 and TF-4 tubes tested in the present study. The crush stress value obtained in the static test of that study was 11.3 MPa, i.e., almost one-sixth of the value obtained in this work. Several reasons may be behind this difference. The most probable one is that the material used in this work has better mechanical properties, including better fibres and resin. Secondly, the fact that the tube was half as thin may have increased the probability of the

occurrence of elastic instabilities that may have translated into lower crush stress values.

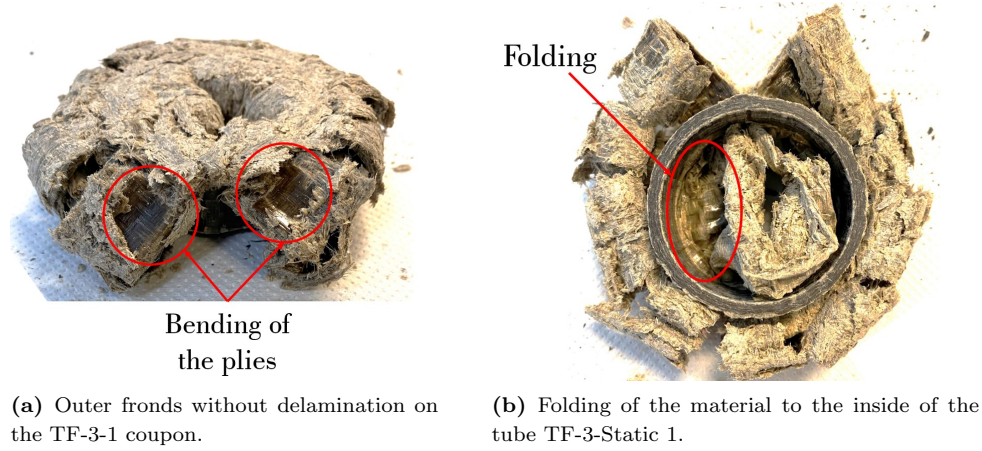


Figure 3.43: TF-3-1 coupon energy absorption failure modes.

Table 3.18: average crush stress and SEA of the FFRP tubular coupons.

Specimen	Average Crush stress [MPa]	Standard deviation [MPa]	SEA [J/g]	Standard deviation [J/g]
TF-3	64.9	6.2	50.7	4.9
TF-4	63.4	3.5	50.5	2.5
TF-5	58.1	5.2	48.3	4.5

Comparison between CFRP and FFRP crush stress

As with the CFRP tubes, a decreasing trend in crush stress can be observed (figure 3.44) with the increase in the radius of curvature of the coupons. In the case of the FFRP specimens, this trend is less conspicuous than in the CFRP coupons. Note that for the FFRP tubular coupons, although four tubular coupons were assessed, only three achieved a plateau for averaging the crush stress, while in the CFRP five different curvatures were studied.

In an attempt to understand why there is less effect of the radius of curvature on the energy absorption parameters of FFRP than CFRP, table 3.19 shows a sample of each of the tubular coupons tested. As was already highlighted and can be seen more clearly in the table, as the radius of curvature of the coupons increased, the number of fronds created in the CFRP coupons also tends to increase. However, the increasing rate is not proportional. That is, the larger the diameter of the tubes the fewer tearing lines were created per unit length of circumference⁴. That translated into a lower tear density in the coupons with larger diameter, which means that less energy was needed to tear the composite. As the crush stress is a measure per unit of area, that decrease in absorbed energy translated into a transitional decline of crush stress as the radius of curvature of the coupons increased. Note that the energy required to break the fibres in the tow is much higher than the one required to delaminate the composite. The theory presented previously is what is believed to be the most probable hypothesis for the existence of a transitional effect of curvature on the energy absorption parameters.

Whereas in CFRP the energy required to break the fibres in the tow is much higher than the

⁴Inverse of the average frond width calculated in table 3.19 by dividing the perimeter by the number of outer splayed fronds.

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splaying energy, in the FFRP these two energies are much closer, since the tensile and compressive forces are much lower (and these properties are the ones that dictate the energy required to break the fibres in the hoop direction). Therefore, in the case of FFRP, a higher number of tearing lines should not have as much effect on the energy absorption properties as in CFRP. Such difference between these two materials may be the most probable explanation for the lower contribution of geometrical parameters to the crush stress of the FFRP coupons. To corroborate such theory, it would be interesting to investigate this effect on different materials with lower and higher properties than the ones tested hereby. For instance, with coupons made by high strength fibres, such as HM63, and by coupons made of lower strength fibres, such as the AS4.

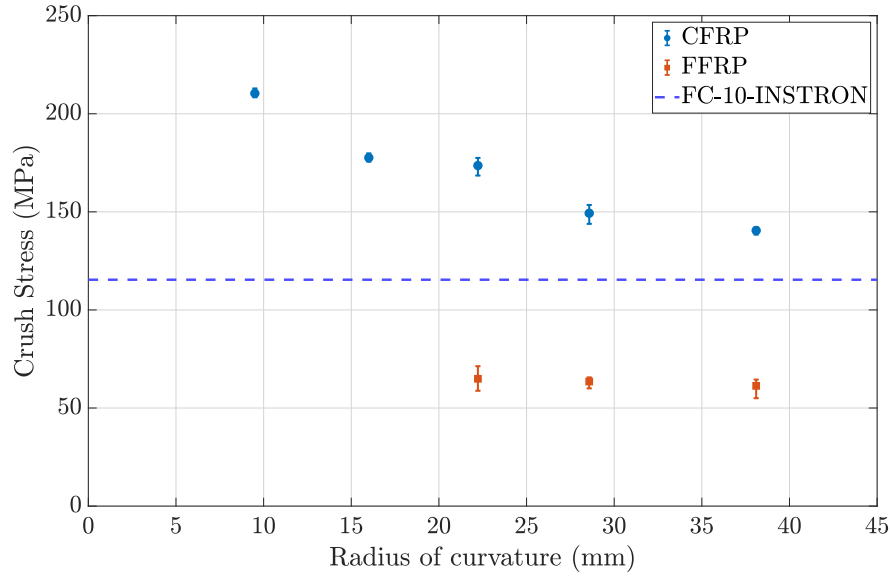


Figure 3.44: Comparison between the effect of the curvature on the crush stress of the FFRP and CFRP tubular coupons.

Chapter 3. Assessing geometry effects on monolithic coupon energy absorption

Table 3.19: Effect of the radius of curvature on the formation of tearing lines.

Coupon	Top Image	No. external fronds	Average frond width [mm]
TC-1		6	9.95
TC-2		7	14.36
TC-3		8	17.46
TC-4		8	22.44
TC-5		10	23.94
TF-2		8	12.57
TF-3		9	15.52
TF-4		9	19.94
TF-5		8	29.92

3.8. Concluding remarks

As mentioned in chapter 2, a material that possesses a higher CCR presents an improved ability to cope with geometrical stress concentrations and higher tolerance to buckling. However, in Ref. [28], the CCR was calculated only for flat coupons, but in this work it was also calculated for the curved ones. The higher curvatures achieved higher levels of crush stress, which in terms of energy absorption is very important. However, it was observed with the FFRP coupon with higher curvature, i.e, TF-2, that the stress sustained was so close to the compressive strength of the material that the coupon failed in compression away from the crush front. So, the CCR was too low, and therefore, that tube geometry crushed too unstably, not only because the compressive properties are not as high as in CFRPs, but also because the crush stress was too close to the limit. Table 3.20 summarises the CCR of the CFRP and FFRP coupons.

Table 3.20: CCR of the FFRP and CFRP coupons.

Coupon	CCR	
	CFRP	FFRP
FC-10-INSTRON	3.9	-
TC-1	2.1	-
TC-2	2.5	-
TC-3 / TF-3	2.6	1.9
TC-4 / TF-4	3.0	1.9
TC-5 / TF-5	3.2	2.1

3.8 Concluding remarks

The results presented before were aimed to assess the geometrical effect in monolithic CFRP and FFRP composite coupons for crush applications. However, due to time restrictions and material availability, the study of these effects on FFRP was limited and only preliminary. On the other hand, geometrical effects on the energy absorption parameters of the CFRP were extensively studied.

It was concluded that the manufacturing of tubular composite coupons can be laborious and several geometrical imperfections may arise, especially due to stretching and lifting of the plies under vacuum or high-pressure conditions in localised areas, which originates severe wrinkles that change the geometrical properties of the tubes. This anomaly is even more evident in the FFRP, which is more flexible than the CFRP. To obtain coupons with fewer geometrical defects it is necessary to carry out a time-consuming manufacturing process with several debulking phases and various corrections throughout the process.

With respect to flat coupons, it was concluded that there is still a need to develop better testing setups that allow drawing better and more precise conclusions. The test setup with the CLC test fixture previously used by Dalli et al. [26] was reproduced in this work, but it was impossible to achieve feasible results of crush stress because the coupons either failed prematurely by buckling or no plateau of crush stress was reached. Nonetheless, some different test setups are being developed in order to improve the setbacks that testing flat coupons have nowadays. Namely, INSTRON is developing a better fixture that allows the specimens to have a constant unsupported length throughout the entire testing length, which allows the specimens to be crushed for bigger lengths and therefore to reach a plateau of crush stress.

Regarding the geometrical effects on monolithic composite coupons, it was found that there is a decrease in the crush stress as the radius of curvature increases. This discovery is very interesting

and can be a big step forward in the way modern composite structures are modelled. That is, as the energy absorption parameters vary with the curvature, it is expected that by automatically assigning different crashworthiness parameters to different curved sections of crash structures the models can recreate a closer-to-reality behaviour, improving the methods that are used up to this day. Coupon testing plays an important role in the energy absorption characteristics of composites, as the crush stress of each different curvature can serve as an input for the previously referred models.

However, it could not be proved that some other geometrical parameters, such as the existence of free edges, do not influence the crush stress value of composite coupons. Even so, it was observed that the L/D ratio does not affect the crush stress values nor the crushing behaviour of coupons. To draw more accurate conclusions regarding a possible free-edge effect, it is necessary to run a wider number of experiments. However, for that study, it is prudent to use different setups than the ones used in the current work, to avoid the instabilities experienced.

Regarding the study of FFRP coupons for crush applications, the results achieved offered a better understanding of this type of material when subjected to crushing loads. Although this material is more prone to failures away from the crush front, due to its lower compressive properties, the results achieved were very promising and better than most of the studies carried out to this day. Furthermore, the low density of this material allows very reasonable levels of specific energy absorption, corroborating its potential to be used in composite structures for energy absorption applications.

Furthermore, a hypothesis was put forward to explain the effect of curvature on energy absorption parameters. It was shown that crushing coupons with larger radii of curvature results in a lower density of tearing lines, which are believed to be at the origin of the lower energy absorption capacity of larger diameter coupons. This effect was less pronounced in the FFRP coupons. It is assumed that this is due to the fact that the energy needed to break fibre tows in tension and compression is more comparable to the delamination energy. Therefore, any change in the tear density is not expected to have as much influence on the energy absorption parameters as in the CFRP.

Chapter 4

Assessing the energy absorption of hybrid laminates

The hybridisation of composite materials can be done to extract the best properties of the materials that make up the laminate. In this specific study, the two previously studied materials, FFRP and CFRP, will be hybridised in order to combine the excellent compressive and inter-laminar properties of CFRP woven fabric with the sustainability of the FFRP. The test program carried out will be a preliminary study to assess the potential of hybridising CFRP and FFRP for crashworthiness applications.

4.1 Introduction

Inter-ply hybridisation with different types of FRP plies stacked in certain patterns acts as the simplest and cheapest approach for producing hybrid structures [95]. The stacking configuration of hybrid laminates plays an important role in crashworthiness applications, as the crushing failure modes exhibit combined features of its monolithic composites, which can be determined by the hybrid ratio and stacking sequence [96]. There are boundless possible layup configurations for hybrid laminates which should yield different quantitative and qualitative results in crashworthiness applications.

Apart from the fact that CFRP hybridised with NFRP ensures lower levels of embodied energy, and thus improved sustainability, the combination of such types of FRPs is an effective way of reducing the high material cost of the carbon fibres while maintaining, or at least not compromising too much the composite structural performance [18]. The financial prospect is of paramount importance in thin-walled composite crash structures, as their employment is majorly done in motorsports applications, where budget caps must be followed to the letter, at the risk of heavy fines in the event of their non-application.

In this preliminary work, only one stacking configuration was used for the testing of the hybrid coupons. As with the monolithic coupons, the direction of the fabrics was restricted to 0° , to avoid lower stiffness and shear failure caused by plies at 45° [25]. The hybrid ratio was also kept the same for all the the coupons and it was chosen based on the results from the monolithic FFRP coupons and on the study carried out by Storhmann et al. [19].

4.2. Hybrid configuration

4.2 Hybrid configuration

As aforementioned, the stacking sequence of a hybrid laminate yields different properties, which affect the material's behaviour when subjected to crushing loads. Therefore, the selection of the hybrid ratio and stacking sequence plays a very important role in the crushing behaviour of composite materials. For example, Storhmann et al. [19] tested two different configurations when they performed an inter-ply hybridisation of CFRP with FFRP. Firstly, a laminate made up of a CFRP core of four plies blocked by two FFRP plies on each side was manufactured and tested, and then the opposite layup was produced, i.e., a four-ply core of FFRP blocked by the CFRP plies. The latter configuration ensured higher levels of crush stress and energy absorption both statically and dynamically. When the authors analysed the tested coupons it was concluded that the outer plies of the coupons were the ones that dominated the failure modes and the overall behaviour of the laminates, in both hybrid configurations. This observation was supported by quantitative results, which showed that the CFRP plies on the coupon's outer layers ensured higher levels of energy absorption. That might come from the fact that the bending stiffness of the laminate has better properties than if the stacking order was the other way around, and thus the laminate has enhanced compressive and tensile strengths.

The crush stress and SEA results from the FFRP achieved in chapter 3 were very promising in the sense that these values were higher than expected, taking into account the lower compressive strength of this material. Therefore, a hybridisation ratio of 50/50, that is four FFRP plies and four CFRP plies seems to be a good starting point to evaluate the hybridisation potential between these two materials.

Considering the information presented above, the stacking configuration chosen for the hybrid coupons was a core of four FFRP plies blocked by two CFRP plies on each side of the laminate, as schematically represented in figure 4.1.

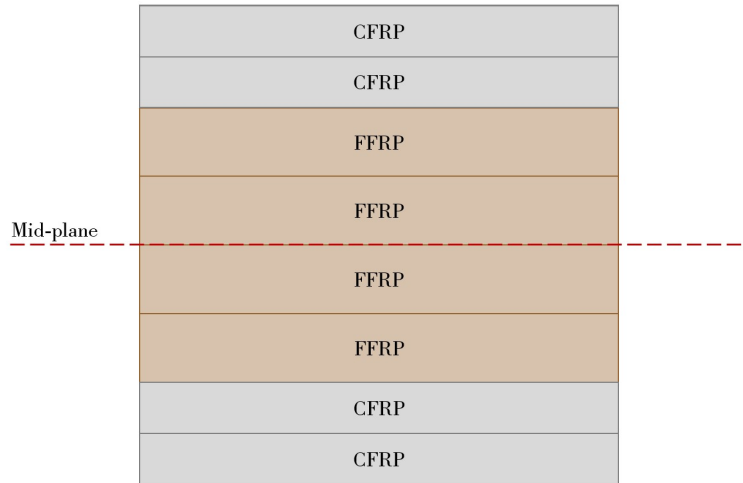


Figure 4.1: Stacking configuration of the hybrid coupons.

Although the ply hybrid ratio was set to 50/50, with four plies of FFRP and four plies of CFRP, as the crush stress is calculated per cross-sectional area, the hybrid ratio used for the calculation of the crashworthiness parameters was not based in the number of plies, but in the thickness of the plies. As the height of each ply of the tubular coupon was more or less the same, the hybrid ratio based on the thickness of the plies was roughly the same as its volumetric ratio. Therefore,

to calculate the volumetric hybrid ratio, the volumetric percentage of flax plies, R_F , was calculated with the following formula:

$$R_F = \frac{(t_F \times n_F)}{(t_F \times n_F + t_C \times n_C)} \quad (4.1)$$

where t_F represent the nominal thickness of the flax ply, t_C the nominal thickness of the carbon ply, n_F the number of flax plies in the laminate, and n_C the number of carbon plies. After this calculation was done, the volumetric ratio was approximately 58/42 (FFRP/CFRP).

4.3 Geometry and manufacturing

The hybrid coupons manufactured for this work had to be restricted to circular tubes because, as it was already proved, the available testing setup for flat coupons does not yield sufficiently good results to characterise the energy absorption parameters of the material. The following section briefly describes some considerations that had to be considered when developing hybrid coupons.

4.3.1 Geometry

As explained in chapter 3, the demoulding of the CFRP coupons was very challenging and required a laborious process, which included a turning process. Unfortunately, the aluminium tubular mandrels were damaged, so it was impossible to use them to manufacture hybrid coupons. Therefore, new aluminium mandrels had to be used. This time, in an effort to avoid the usage of a turning operation to remove the composite tubes from the moulds, solid bars of circular section were ordered. This way, the moulds could shrink more upon freezing and help with the demoulding process. However, for availability reasons, the bars had different nominal diameters from the ones previously used, but the closest internal diameters were chosen. Due to a lack of composite *pre-preg* material stock, and to optimise the amount available, one of the curvatures had to be left out of the manufacturing process. In this case, the one left out was the diameter between 45 mm and 80 mm. The geometry and the mass of the hybrid coupons manufactured is presented in table 4.1, and the geometry is sketched in figure 4.2. Note that in this case, the nomenclature of the hybrid coupons is slightly different. Since the layup configuration was the same for all the coupons, the letter indicates that the coupons are hybrid and the number distinguishes the curvature of the coupons, like H-1, H-2, H-3 and H-4.

Table 4.1: Geometrical parameters of the hybrid coupons.

Coupon	t [mm]	h [mm]	Di [mm]	De [mm]	Mass [g]
H-1	2.85	80	20	25.7	22.86
H-2	2.85	80	32	37.7	34.30
H-3	2.85	80	45	50.7	48.36
H-4	2.85	80	80	85.7	81.70

As can be observed, the geometry changed slightly compared to the previously tested coupons, apart from the change in the internal diameters. On one hand, the height of the tubular coupons was increased to 80 mm to achieve even longer plateaus of crush stress, and since the 70 mm tubes of pure FFRP were stable, the hybrid tubes should be stable at 80 mm height. On the other hand, the triggers were machined with an even steeper trigger, to avoid the problems observed with the

4.3. Geometry and manufacturing

TF-2 coupons. The FFRP tubular coupons tested in the previous chapter presented a high peak force, leading some of them to fail away from the crush front.

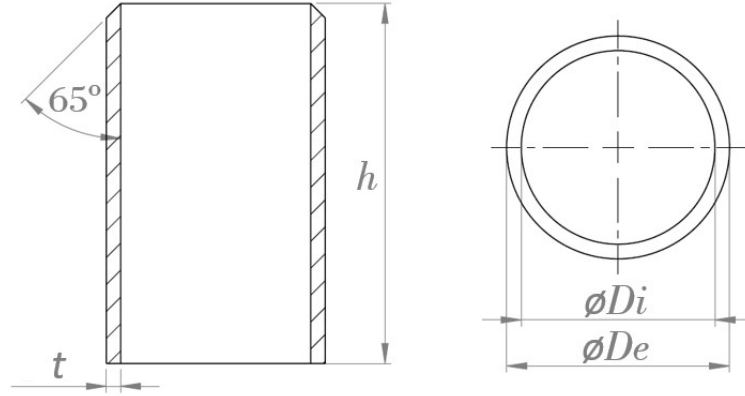


Figure 4.2: Geometry of the hybrid tubular coupons.

4.3.2 Manufacturing process

The manufacturing process of the hybrid tubes was carried out, once again, with the help of the company Dragon Equation in their headquarters. Due to time limitations, it was not possible to follow such a meticulous manufacturing process as the one used for the FFRP tubular coupons, namely no pressure debulking was done nor corrections to cut off the excess of each ply. Those precise steps are elementary to manufacture tubes with the fewer geometrical defects possible. This gains even more relevance when producing tubes with FFRP, as this material is very flexible. The manufacturing steps were mainly the same as the ones carried out for the CFRP tubes, described in section 3.3.

After the curing cycle was completed, it could be seen that the resins of both FRPs were compatible, which was very important to be verified. However, the hybrid tubes got stuck to the mandrels once again. PTFE tape was not available due to its high cost, so it is believed that the tape used to wrap around the aluminium moulds was not adequate for this application, as changes to its initial appearance could be observed. To remove the tubes from the moulds a turning operation had to be carried out. Even so, some of the tubes could not be demoulded, and consequently, most of the composite tubes had to be cut axially with a 4 mm gap, so that the coupons could be removed. Figure 4.3 shows one of the coupons with the previously described slit. Furthermore, several severe wrinkles were observed in most of the tubes, which is a consequence of hybridising the CFRP with the FFRP.

Although the coupons were cut with the same tool, with a width of 4 mm, the gaps on the coupons were smaller than that value, and they decreased as the diameter of the coupon increased. For example, the gap measured in the coupon H-1 was 3.3 mm wide, while the one measured in coupon H-4 was 1.7 mm. By cutting the slit, it could be seen that residual stresses were induced during curing.

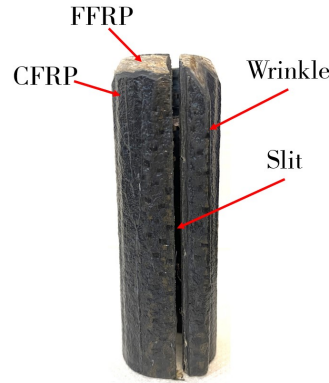


Figure 4.3: Coupon H-1 with the slit and a severe wrinkle.

4.4 Experimental setup

The setup used to test the tubular coupons was the same as the one for the CFRP coupon testing. That is, the tests were performed in a universal testing machine INSTRON 5900R with a load cell of 200 kN. They were self-supported on the lower plate and then an upper plate was lowered with a displacement rate of 10 mm/min, crushing the tubular coupons. Three specimens of each coupon size were tested. When possible, coupons with and without the slit were tested. Thus, the first and the second sample of the coupons H-1 and H-3 were fully closed, and the third sample had a slit. Regarding coupons H-2 and H-4, all of them had to be axially cut, so all the tested coupons had open section geometries.

4.5 Experimental results

In general, the hybrid coupons were crushed in a stable progressive manner. Very similarly to what happened to the CFRP tubular coupons, initially ply fragmentation was developed, creating a wedge of crushed debris along the circumference of the tube. Afterwards, the outer plies started to splay. As the crushing progressed the hoop stress in the fibre tows increased and, thus, for the splaying to progress, the tows had to fracture in the modes already explained previously. The splayed fronds folded more severely than in the monolithic CFRP coupons, due to the reduced stiffness and lower compressive strength. Figure 4.4 shows all the hybrid the coupons after testing.

When testing the coupon H-4 it was possible to observe a more unstable behaviour, caused by the opening of the slit. One of the coupons experienced folding of the plies after a certain point, instead of keeping splaying. This anomaly proves that testing these coupons with a slit makes them more unstable and thus more prone to failures away from the crush front. This phenomenon had already been observed in the CFRP coupon TC3-HS-2. Although the effect of a free edge did not change the crush stress it made the coupon more susceptible to fail catastrophically.

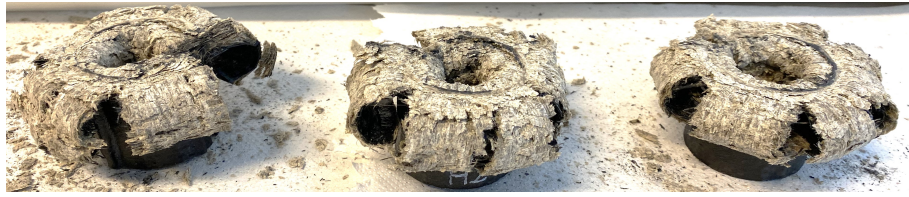
In general, all the coupons tested presented a behaviour more similar to that of the monolithic CFRP coupons. That may arise from the fact that the carbon fibre plies were stacked on the outermost walls of the tube, restricting the instability of the flax plies, and mitigating their possibility of failure away from the crush front. So, similarly to what happened in the study carried out by Storhmann et al. [19], it looks like the plies in the outermost positions seem to dominate the behaviour of the coupons. Furthermore, fewer tearing lines were created, and consequently, fewer

4.5. Experimental results

fronds were formed. That means that the tearing density was lower than in the case of the CFRP, and can be one of the justifications for the drop of crush stress that was observed.



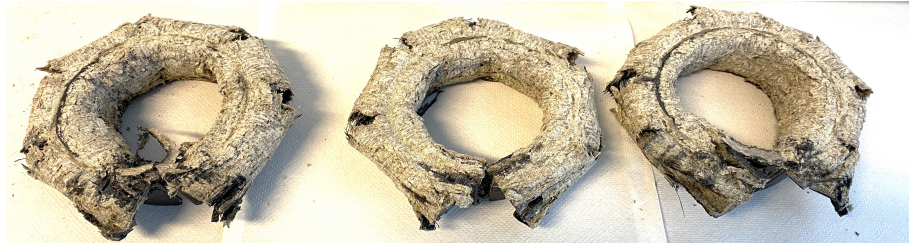
(a) H-1



(b) H-2



(c) H-3



(d) H-4

Figure 4.4: Samples of each hybrid coupon configuration after testing.

To calculate the crush stress, the reduction of the cross-sectional area caused by the slit was considered. So, for the coupons with a slit, the area of the gap had to be discounted from the cross-sectional area calculated by Eq. 3.2. However, as the cutting tool performs a straight cut through the thickness, a precise calculation of the removed cross-sectional area becomes complex to calculate. Therefore, the area missing was approximated to that of a rectangle, with height equal to the nominal thickness, i.e., 2.85 mm, and width equal to the thickness of the cutting tool, i.e., 4 mm, as shown in figure 4.5. To sum up, to the cross-sectional area of the closed tubular coupons, an area of $4 \times 2.85 = 11.4 \text{ mm}^2$ was subtracted.

The crush stress for the three specimens tested for each coupon is represented in figure 4.6. Comparatively to the results achieved on the CFRP and the FFRP, higher serrations can be observed. Such phenomenon might be caused by the fact that the interlaminar properties of the

laminate were not as high as in the monolithic forms, and therefore, there is more delamination between the folded plies. To calculate the average energy absorption parameters, the interval between 15-40 mm was the one used, as after that the internal fronds started to touch the bottom testing plate.

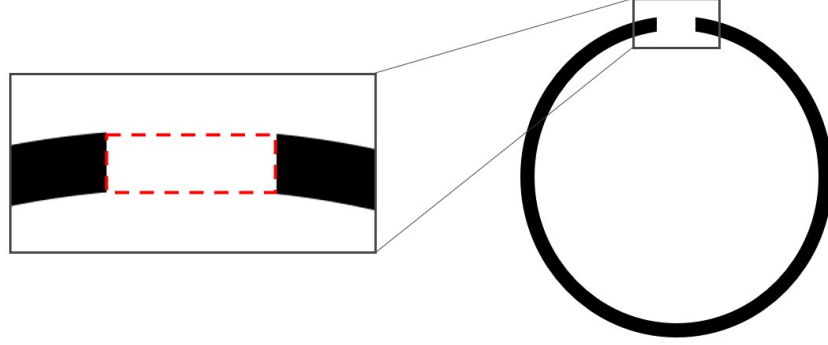


Figure 4.5: Schematic representation of the approximated slit area.

The average crush stress and SEA values are shown in table 4.2. One can observe that there is a significant reduction in crush stress compared to the CFRP coupons. That was already expected, as more than 50% of the laminate was made by flax fibre plies. The density of the laminate was approximately 1.40 g/cm^3 , which resulted in very interesting results of specific energy absorption. Note that to obtain the SEA it is only necessary to divide the crush stress by the density of the laminate.

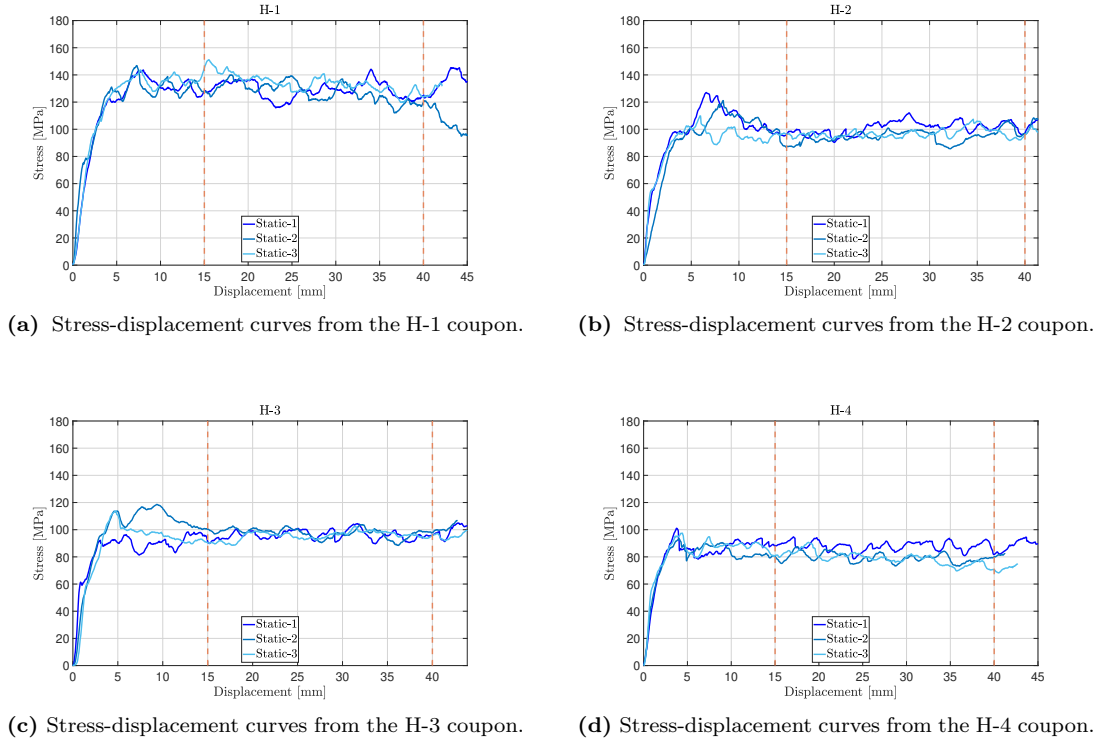


Figure 4.6: Stress-displacement curves from the tested hybrid coupons.

4.5. Experimental results

Table 4.2: Average crush stress and SEA from the hybrid coupons.

Coupon	Average Crush stress [MPa]	Standard deviation [MPa]	SEA [J/g]	Standard deviation [J/g]
H-1	130.1	3.5	92.9	2.5
H-2	97.5	3.3	69.6	2.3
H-3	96.4	1.0	68.9	0.7
H-4	82.1	5.1	58.6	3.7

When comparing the crush stress corresponding to the curvature radii of the hybrid laminates with the respective curvature radii of the monolithic CFRP and FFRP laminates, it can be observed that its value is not in the arithmetic mean of the monolithic values. Figure 4.7 presents a synthesis of the average crush stress as a function of the radius of curvature of the coupons tested throughout this work. It can be seen that there is a transitional decrease in crush stress with a very similar trend as the one observed for the CFRP, which once more seems to show that the outer plies of the coupons dominate the behaviour of the laminate [19].

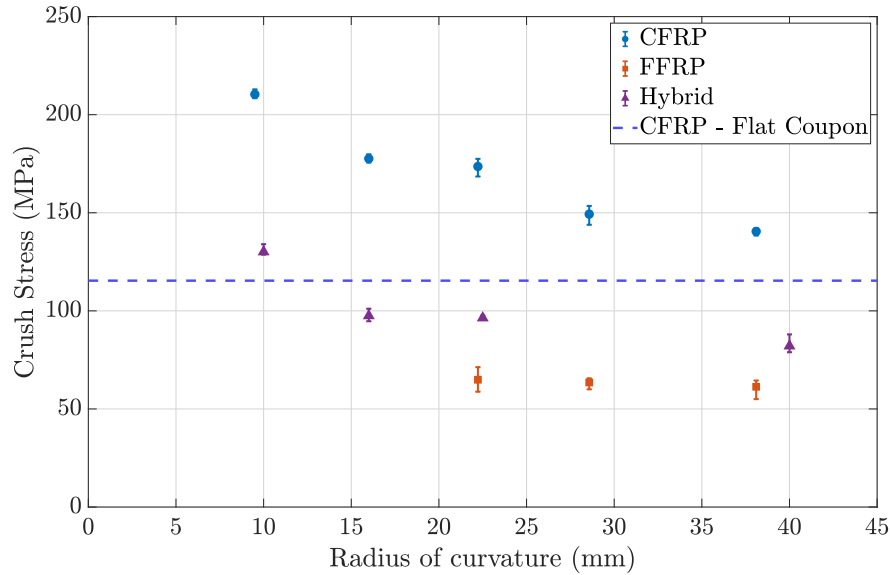


Figure 4.7: Crush stress-radius of curvature relation for all monolithic and hybrid coupons tested.

It can be observed that there was a considerable drop in performance compared to the monolithic CFRP. Table 4.3 shows a comparison between the values that were obtained for the CFRP and the FFRP coupons. Note that the linear prediction was done for only two of the coupon geometries, since these sizes were the ones that achieved results of average crush stress for all the laminates. The linear prediction value was calculated by averaging the crush stress from the CFRP and FFRP with the cross-sectional area proportion, i.e., the volumetric ratio, calculated by 4.1. However, the drop in crush stress, compared to the monolithic CFRP was higher than the one predicted by the volumetric average.

A very likely hypothesis for the drop in performance compared to the linearly predicted values might be related to the lower interlaminar properties of the hybrid composites compared to the CFRP. That is, the monolithic CFRP coupons had in their matrix phase exclusively the E745 toughened resin. On the other hand, the matrix from the FFRP was not toughened epoxy, and hence weaker than the E745. So, in the hybrid coupons, the strong ply interfaces were reduced by

5/7, as the toughened resin of the carbon *pre-preg* was only found in the interfaces between the 1st and 2nd plies, and between the 7th and 8th plies. Regarding the interfaces between plies two and three, and between plies six and seven, they were only as good as their weakest component, which was the resin of the flax *pre-preg*, a more generic standard resin that is not toughened.

Table 4.3: Performance comparison between the average crush stress of the monolithic and hybrid coupons based on the volumetric ratio of 58/42.

Coupon	Average Crush Stress [MPa]				Performance Drop [%]	
	CFRP	FFRP	Linear average	Hybrid	Drop vs CFRP	Drop vs Linear average
TC-1/H-1	210.4	-	-	130.1	38.2	-
TC-2/H-2	177.6	-	-	97.5	45.1	-
TC-3/TF-3/H-3	173.6	64.9	110.6	96.4	44.5	12.8
TC-5/TF-5/H-4	140.5	58.1	92.7	82.1	41.6	11.4

However, for this hypothesis to be corroborated it would be advisable to test other hybrid ratios and check if the drop in performance compared to the linear prediction would vary with the same proportion. For instance, by testing a 75/25 ply ratio of FFRP/CFRP no strong interfaces would exist, and it is expected that the crush stress value would only be better than the pure flax due to the extra stiffness in bending and splaying offered by the carbon fibres, and due to the circumferential strength to break the tows. The ratio 25/75 could be also tested to assess whether the drop in performance vs linear prediction would be less pronounced than in the 75/25 ply ratio. In this way, it would be possible to evaluate the effect of the interply properties on the performance of the hybrid laminate.

Regarding the SEA of the hybrid coupons, the performance of the coupons proves to be once again better than the monolithic FFRP but considerably lower than the CFRP. However, as the density of the hybrid laminate is lower than the CFRP, the drop in performance of the hybrid is less sharp, as can be observed in table 4.4.

Table 4.4: Performance comparison between the SEA of the monolithic and hybrid coupons based on the volumetric ratio of 58/42.

Coupon	SEA [J/g]				Performance Drop [%]	
	CFRP	FFRP	Linear average	Hybrid	Drop vs CFRP	Drop vs Linear average
TC-1/H-1	133.7	-	-	92.9	30.5	-
TC-2/H-2	118.6	-	-	69.6	41.3	-
TC-3/TF-3/H-3	110.4	50.8	75.8	68.9	37.6	9.1
TC-5/TF-5/H-4	89.3	48.3	65.5	58.6	34.4	10.6

The SEA results achieved are very promising and prove that there is potential for flax fibres to be employed in structural applications. For example, the hybrid coupons achieved levels of SEA that are comparable to those of metallic crash structures, which are known to be the most common ones used in the automotive industry for mass production. For instance, Mallick [32] reported values of SEA of 30-60 J/g for steel tubes and 70-85 J/g for aluminium. In this study, the hybrid coupons achieved values of SEA in the range of 56.4-95.9 J/g.

However, it is important to note that the geometric imperfections on the tubes might have had some stiffening effect, and therefore, the results might be overestimated. Thus, the manufacturing process of hybrid tubular coupons needs to be improved to avoid wrinkles during processing to achieve more reliable results.

4.6 Concluding remarks

Although the manufacturing processes to obtain flax/carbon tubes for crush testing were not ideal, which resulted in coupons with several geometrical defects, both materials were compatible, meaning a good interaction between the resin of both *pre-pregs* and the fibres. The progressive crushing was also possible to be achieved for all the coupons, and in contrast to the FFRP coupons, no failure away from the crush front was observed, most likely due to the constraining effect of the outer CFRP plies on the flax core. Furthermore, the outermost plies of the laminate, i.e., the carbon plies, seemed to be responsible for the qualitative behaviour of the laminate.

Regarding the energy absorption parameters of the hybrid coupons, it was observed that there was a drop in performance of 41-44% in crush stress compared to the monolithic CFRP coupons. This performance drop might have been caused by the lower interlaminar properties of the hybrid coupons, caused by the fact that there were less interfaces with the toughened resin than in the CFRP. Regarding the SEA of the hybrid coupons, the drop in performance was lower, because the density of the hybrid laminate is lower than that of the CFRP. Yet, the testing of the hybrid coupons showed promising results of SEA since they were at least comparable to the ones from metallic structures reported in the literature. Even so, it is still necessary to run further investigation, in order to keep developing and improving the composite systems of the FFRP by enhancing the fibre and the resin quality. Furthermore, more hybrid configurations should be studied, so that the crushing behaviour of these laminates and their limitations can be better understood.

Chapter 5

Conclusions and future work

In this thesis, the assessment of geometrical effects on coupon crush energy absorption was studied, as well as the potential for hybridisation between CFRP and FFRP for crashworthiness applications. In this chapter, the main conclusions regarding the state-of-art of composites in crashworthiness applications, and the experimental study on the monolithic and hybrid coupons carried out in this study are presented. Furthermore, based on those conclusions and the work developed, the future work that needs to be carried out on the testing of composite coupons for energy absorption applications is also recommended.

5.1 Conclusions

The use of composite materials for crashworthiness applications in moving structures is gaining more and more importance, as their employment ensures enhanced levels of specific energy absorption when compared to the previously used metallic structures. In previous years, several efforts have been put into practice to better understand the behaviour of these advanced materials when subjected to crushing loads. To assess the energy absorption of such FRPs, several coupon geometries, and both quasi-static and dynamic test setups were developed, and some analytical and numerical models have been studied.

Regarding the testing of coupons, it was found in the literature that tubular coupons ensure better levels of energy absorption than flat coupons. Furthermore, the fact that the tubular coupons can be simply supported in quasi-static test setups makes the use of such coupon geometry much more enticing. On the other hand, the manufacturing process of flat coupons is much simpler than tubular. However, several shortcomings have been found regarding the testing of this geometry. Flat coupons require a complex setup to test them in a stable manner, so that good data can be obtained.

The importance of characterising the energy absorption parameters of both flat and curved geometries was highlighted in a couple of studies, as their average crush stress is the parameter to feed in numerical simulations. However, it was found in the literature that models for large composite crash structures are still underdeveloped, and even though can reproduce reasonable quantitative predictions at a low computational cost, the discrepancy between experimental and simulation results emphasises the need to further understand the evolution of crushing behaviour in large composite structures. It is believed that such predictive tools can be improved if supplied

5.1. Conclusions

with enhanced data from coupon crush tests, which better account for different geometries.

In addition, due to their high-temperature transformation processes and the non-renewable (oil-based) nature of their raw materials, modern-day synthetic FRPs, such as CFRPs, have excessive levels of embodied energy. This fact requires the scientific community and, especially, car manufacturers to turn their efforts into more sustainable solutions. Natural fibre reinforced composites partially fulfil this requirement, such as FFRPs, so they are gaining popularity in the mobility industries. It is believed that by hybridising such fibres with carbon it is possible to achieve reasonable levels of energy absorption without compromising excessively the composite performance.

Regarding the manufacturing process of the coupons developed in this work, difficulties arose due to the complexities inherent to manufacturing *pre-preg* based composite tubes, leading to external geometric defects, and demoulding difficulties. Although the geometrical defects apparently did not have a significant influence on the quantitative results, it is necessary to corroborate such assumption, as for instance, a misinterpretation of the results can lead to false inputs of crush stress into numerical models. The obstacles faced while removing the tubular coupons from the moulds raise the production costs and are very time-consuming.

Nevertheless, a detailed test program was planned and carried out throughout this thesis. It corroborated the setbacks that arise from flat coupon testing, as the unsupported lengths from the tested flat coupons did not ensure neither feasible average crush stress values nor the required stability, leading to buckling. However, by means of collaborations with industrial partners, it was possible to contribute to a novel fixture for static and dynamic flat coupon testing, which allows achieving a steady-state crushing plateau from which the average crush stress of the coupons can be calculated. Even so, these tests were only part of a preliminary study, and therefore, need to be improved, and more data has to be collected.

Furthermore, by testing several coupons with different geometries it was discovered that there is a transitional decrease of the crush stress with the increasing radius of curvature of composite coupons. This fact proves that numerical models need to be fed with more precise energy absorption parameters. The positive contributions of this work regarding the assessment of geometrical effects on coupon energy absorption can change the way large composite crash structures are modelled because this new approach comprises the automatic assignment of curvature-dependent energy absorption parameters to numerical models. In addition, it was found that other geometrical parameters, such as the existence of free edges, make tubular coupon testing more unstable and prone to catastrophically-failure. However, in terms of crush stress, it was not possible to draw too many conclusions, due to the low data gathered, but it seemed to be a slight decrease in this value because the circumferential tows did not form closed hoops.

With respect to the experimental tests of the FFRP coupons carried out in this thesis, the results showed that the crushing of such composites is more unstable than CFRP, and the compressive strength is also much lower, which translates into worse values of crush stress. However, as the density of the FFRP is lower than that of the CFRP, the specific energy absorption of this NFRP presented very promising results.

Regarding the hybridisation of carbon fibres with flax fibres, issues arose due to the flexibility of the flax *pre-preg*, which translated into tubes with severe wrinkles. In addition, the same manufacturing issues faced with the CFRP tubular coupons were experienced, since the tubes did not demould easily. Therefore, the manufacturing process of these coupons must be enhanced in

future applications.

With concern to the hybrid coupons, it was concluded that qualitatively they crushed very similarly to the CFRP coupons. A 2D-curvature effect was also verified in the hybrid coupons, with a trend that resembled the one from the CFRP coupons. However, while the volumetric ratio was 58/42 (FFRP/CFRP), the ratio of toughened interlaminar regions to standard epoxy regions was reduced when compared to the CFRP by 5/7, possibly contributing to the performance drop that went below a linear average of the energy absorption of monolithic CFRP and FFRP.

Overall, the conclusions reached in this study contributed in a positive way to the development of enhanced characterisation of energy absorption parameters, since it was discovered that there is a transitional geometrical effect on composites crashworthiness parameters. Furthermore, novel hybrid composite coupons for crush applications were developed, and it was concluded that their values of SEA are at least as good as the ones observed in metallic structures.

5.2 Future work

Despite the efforts made to evaluate the geometrical effects on coupon energy absorption and the potential to employ more sustainable fibres in composites for crashworthiness applications, some work still needs to be done. Both topics addressed in this thesis still require some investigation to better understand some phenomena observed and to corroborate some hypotheses presented throughout this work.

Regarding the effects of geometry on the crashworthiness parameters, the development and testing of tubular coupons with a square cross-section are strongly recommended. As highlighted before, the open-section characteristic of flat coupons limits their representation of real-life crash structures. Therefore, it is believed that squared cross-section tubes could describe more precisely the behaviour experienced in large composite structures that possess flat sections.

It is known that large composite crash structures have in their geometry several curvatures and inclinations. However, in this study, only the effect of 2D-curvature was assessed. Thus, to ensure a more precise assignment of geometry-dependent energy absorption parameters to numerical models, the effect of inclination must be also investigated, especially in oblique loading situations. To do so, it is recommended to develop and test conic coupons with different inclinations. In this way, it would be possible to complement the curvature-dependent parameters here studied with the inclination-dependent parameters. Thus, fully describing most of the geometries found in modern-day composite crash structures.

In addition, further studies may be conducted to accurately validate the hypothesis set out to explain the existence of curvature-dependent energy absorption parameters. Throughout this work, it was observed that the crashworthiness parameters of the CFRP coupons were more dependent on curvature than the FFRP. This phenomenon was linked to the fact that the tearing energy of the CFRP is much higher than the splaying energy, whereas the FFRP tearing energy is much closer to its splaying energy. To corroborate such a theory, it is recommended to investigate the effects of the curvature of other composite materials with different tensile and compressive strengths.

Several studies in the literature have reported that the internal friction of the internal fronds is responsible for a high amount of energy absorption. In this study, the smaller tubular coupons achieved very high levels of energy absorption which might have been caused by excessive internal friction. To evaluate whether the SEA and crush stress values would change considerably without so

5.2. Future work

much of this internal friction, it is suggested to promote outward crushing. This could be achieved by developing and manufacturing steel trigger devices that can be simply supported on top of the tubes, to induce outwards splaying. This way, the friction energy caused by the interaction between the internal fronds could be estimated by calculating the difference between the normally crushed coupons and the induced outward crushing specimens.

In this work, the layup of the laminates was kept the same for all the experimental setups, i.e., only plies stacked in the 0° direction were employed. However, it is recommended that different stacking sequences and different thicknesses are evaluated to understand layup and overall laminate thickness effects on energy absorption. With those variables, an analytical predictive tool based on the thickness of the laminate can be developed. This would allow a simple and intuitive way of estimating the crush stress of coupons, based on experimental data.

As crash structures are designed for dynamic applications, it is of high relevance to repeat the same set of experiments in dynamic conditions, so that the geometrical effects previously studied can be validated in higher strain-rate circumstances. However, it is important also to develop a feasible test setup, so that the results can be correctly interpreted.

Regarding the hybrid coupons, it is recommended to test different hybrid configurations so that the hypothesis sketched for the drop in performance of these coupons in comparison to their linear prediction crush stress can be corroborated. Therefore, different FFRP/CFRP ply ratios should be manufactured, so that the performance decrease can be more clearly understood, and possibly improved through further research.

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Appendices

Appendix A - Crush stress and SEA values of all tubular specimens

Crush stress of the CFRP tubular coupons.			
Coupon	Specimen no.	Average Crush stress [MPa]	SEA [J/g]
TC-1	1	165.5	118.4
	2	167.8	120.1
	3	163.8	117.3
TC-2	1	165.5	118.4
	2	167.8	120.1
	3	163.8	117.3
TC-3	1	162.4	113.1
	2	154.2	107.3
	3	159.7	111.2
TC-4	1	134.5	93.3
	2	140.1	97.2
	3	144.1	100
TC-5	1	131.7	89.5
	2	129.5	88.0
	3	133.0	90.4
TC-5HL	1	132.8	89.4
	2	144.0	92.8
TC-3HS	1	149.6	90.8
	2	170	106.1
TC-4QS	1	139.5	89.8

References

Crush stress of the FFRP tubular coupons.

Coupon	Specimen no.	Average Crush stress [MPa]	SEA [J/g]
TF-2	1	-	-
	2	-	-
	3	-	-
TF-3	1	58.8	46.0
	2	71.3	55.8
	3	64.6	50.5
TF-4	1	59.9	47.7
	2	65.0	51.8
	3	65.5	52.2
TF-4	1	51.8	43.1
	2	61.2	50.9
	3	61.3	51.0

Crush stress of the hybrid tubular coupons.

Coupon	Specimen no.	Average Crush stress [MPa]	SEA [J/g]
H-1	1	128.7	92.2
	2	127.5	90.7
	3	134.0	95.9
H-2	1	101.1	70.9
	2	94.7	66.4
	3	96.7	67.8
H-3	1	96.1	68.1
	2	97.6	69.7
	3	95.6	67.7
H-4	1	88.0	62.9
	2	79.4	56.8
	3	78.9	56.4