UNIVERSIDADE
BEIRA INTERIOR

Hybridization effect on mechanical properties of composite laminates

(versão final após defesa)

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Dissertação para obtenção do Grau de Mestre em
Engenharia Aeronáutica
(mestrado integrado)

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Abril 2022

Acknowledgments

First of all, I would like to thank my master thesis supervisor Professor Paulo Nobre Balbis dos Reis for accompanying me during the elaboration of this work, and for his availability and teachings. I would also like to thank engineers Paulo Santos and Sara Valvez for their kindness, support, and good advice during the experimental part of this thesis, with whom I learned to produce the specimens used in this work and to use the Shimadzu to make the mechanical tests and collect data. Finally, I would like to thank my family, boyfriend and friends for their patience and support.

Resumo

Os materiais compósitos estão cada vez mais a ser utilizados na indústria aeronáutica. Apesar das fibras de carbono serem as mais resistentes e as mais usadas no setor aeronáutico, estas fibras colapsam de maneira bastante repentina devido a sua natureza frágil levando a danos catastróficos. Com o intuito de minimizar este efeito utiliza-se uma técnica alternativa que consiste em combinar estas fibras com outro tipo menos frágil, como por exemplo a fibra de kevlar, de modo a obterem material com um comportamento mais dúctil. Como o comportamento viscoelástico não é muito abordado na literatura aberta disponível, este trabalho pretende então estudar esta propriedade mecânica em vários compósitos híbridos envolvendo fibras de carbono, kevlar e vidro. Para o melhor entendimento deste fenómeno estudou-se igualmente o comportamento estático e tenacidade destes materiais. Para este propósito, o efeito da hibridização nas propriedades de flexão, resistência ao cisalhamento interlaminar, fluência e relaxamento de tensões foi estudado em dezoito combinações hibridas combinadas com uma matriz epoxídica. Observou-se que a hibridização pode criar um compósito mais tenaz e balanceado. A sequência de empilhamento tem uma influência significativa nas propriedades mecânicas dos laminados. Como tal, para todos os testes mecânicos, as fibras de carbono são melhores na compressão se hibridizadas com kevlar e melhores em tensão se hibridizadas com vidro. As fibras de vidro sempre apresentaram melhores resultados sob compressão e as fibras de kevlar sempre apresentam melhores resultados sob tensão, independentemente da outra fibra com a qual são hibridizadas. Com essas posições no laminado, os compósitos alcançam maior tensão e rigidez, mas menor deformação, maior resistência ao cisalhamento interlaminar, menor fluência e menor relaxamento de tensão. Quanto ao número de camadas de fibras, nas propriedades de flexão, uma menor percentagem de kevlar no laminado resulta em maior tensão de flexão e resistência ao cisalhamento interlaminar. Porém, para o comportamento viscoelástico dos compósitos híbridos, o número de camadas não tem influência direta nos valores de fluência e relaxamento de tensão, uma vez que ocorrem rearranjos moleculares. Além disso, foi feito um estudo das propriedades de flexão para diferentes taxas de deformação em compósitos de fibra de carbono e compósitos de fibra de vidro. Desta forma, pôde-se mostrar que existe uma relação entre a taxa de deformação e a tensão de flexão e rigidez dos compósitos. Com o aumento da taxa de deformação, ocorre um aumento da tensão de flexão e da rigidez.

Palavras-chave

Materiais compósitos; Hibridização; Propriedades Mecânicas

Abstract

Composite materials are increasingly being used in the aeronautical industry. Although carbon fibers are the strongest and most used in the aeronautical sector, these fibers collapse quite suddenly due to their fragile nature leading to catastrophic damage. In order to minimize this effect, an alternative technique is used, which consists of combining these fibers with another less fragile type, such as Kevlar fiber, in order to obtain a material with a more ductile behavior. As the viscoelastic behavior is not much discussed in the available open literature, this work intends to study this mechanical property in several hybrid composites involving carbon, kevlar and glass fibers. For a better understanding of this phenomenon, the static behavior and tenacity of these materials were also studied. For this purpose, the effect of hybridization on flexural properties, interlaminar shear strength, creep and stress relaxation was studied in eighteen hybrid combinations combined with an epoxy matrix. It was observed that hybridization can create a more tenacious and balanced composite. The stacking sequence has a significant influence on the mechanical properties of laminates. As such, for all mechanical tests, carbon fibers are better in compression if hybridized with kevlar and better in tension if hybridized with glass. Glass fibers have always performed better under compression and kevlar fibers always perform better under tension, regardless of which other fiber they are hybridized to. With these positions in the laminate, the composites achieve greater tension and stiffness, but less deformation, greater interlaminar shear strength, less creep and less stress relaxation. As for the number of fiber layers, in the bending properties, a lower percentage of kevlar in the laminate results in higher bending stress and interlaminar shear strength. However, for the viscoelastic behavior of hybrid composites, the number of layers has no direct influence on the creep and stress relaxation values, since molecular rearrangements occur. In addition, a study of the bending properties for different strain rates in carbon fiber composites and fiberglass composites was carried out. In this way, it could be shown that there is a relationship between the strain rate and the flexural stress and stiffness of the composites. As the strain rate increases, there is an increase in bending stress and stiffness.

Keywords

Composite materials; Hybridization; Mechanical properties

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List of Acronyms

C	Carbon fibres
CFRP	Carbon fibre-reinforced polymer
G	Glass fibres
GFRP	Glass fibre-reinforced polymer
HE	High elongation fibres
ILSS	Interlaminar shear strenght
K	Kevlar fibres
KFRP	Kevlar fibre-reinforced polymer
LE	Low elongation fibres
UBI	Universidade da Beira Interior

Nomenclature

δ	maximum deflection at mid-span [mm]
$\dot{\varepsilon}$	strain rate [s^{-1}]
ε_f	peripheral fibre strain [mm/mm]
σ_f	stress in the outer fibers at midpoint [MPa]
τ_s	interlaminar shear strength [MPa]
b	width [mm]
E	modulus of elasticity in bending [MPa]
h	thickness [mm]
I	moment of inertia of the cross-section [mm^4]
L	span [mm]
P	load at a given point on the load-deflection curve [N]
P_s	maximum load [N]
V_t	cross-head speed [mm/min]

Chapter 1

Introduction

Fibre-reinforced composites are one of the most remarkable families of materials for technological and structural applications. Nowadays they are widely used in sectors such as automotive and military industry, renewable energy industry, infrastructures, medicine, and sports, but their sector of predilection is the aeronautical field [1, 2].

Composite materials were included in the list of materials used in the aeronautical industry in the 60's, and since then the percentage of their presence in the composition of an aircraft has been increasing. Indeed, design engineers in this sector are very interested in these 'new materials' since they allow them to have almost total freedom in the design of new parts. In fact, such materials have the ability to be tailored for use and a great range of combination in terms of fibres and matrices are possible, opening up possibilities for various types of applications [1, 2].

Over the years the demands in the aeronautical industry have also increased and there is a constant need to update an existing aircraft. A desire to create more performing, lighter aircraft, which consequently use less fuel, leading to less pollution or an increase in payload, constantly pulls and motivates many researchers worldwide to find new ways to overcome those challenges [3–5]. The aircraft structural sector related to the materials used and the way they are applied is an area that can be constantly updated, in order to help fulfill certain requirements such as weight reduction for example.

Each element that makes up a composite laminate has its own properties. There are fibres with excellent qualities for certain industrial applications but applied to others they do not provide good results, that's why a good knowledge of the materials and what they can bring to the structure is important. When choosing a material for a component, designers must evaluate the range of possibilities they have analysing the properties of each material at short and long term. This allows better application and performance and various strategies have emerged with experience of the years of applications and research. One of the developed strategies is hybridization, a theme that will be portrayed in this work.

Another important parameter that is sought in aeronautics is the durability of materials. Throughout the service life of an aircraft component, it suffers from many loading modes (tensile, compressive, bending, impact etc.) due to conditions of use, temperatures that create expansion and compression phases that lead to fatigue, moisture, impact from objects falling on the component or by bird strikes etc.

Thus, materials that better withstand all these external and internal factors are sought in order to increase safety and reduce the maintenance and repairs required due to cracks, fractures, or other damages like delamination, fibre breakage, matrix cracking, and fibre matrix interfacial debonding [6]. This is where the need to study the mechanical properties of materials comes into play.

In this work an analysis will be made on the strain rate effect on flexural proprieties, ILSS as well as creep and stress relaxation behaviour of hybrid composites constituted by the three most popular fibres in the world of polymeric composites and widely used in aeronautics: kevlar, carbon and glass. For the hybrid configurations analysed in this work there is still a lack of research when studying its mechanical properties and since these are the principal fibres used in the industry, studying their position in the laminate, and knowing their strengths and weaknesses under different loads are interesting parameters to understand to improve their applications.

Throughout this work many of the properties of these three fibres will be highlighted and the reasons why they are so attractive in the industry will be elucidated.

In chapter 2 a quick review on theorical information about composites will be presented such as its characteristics and manufacturing processes, and the concept of hybridization. As the application centre of the research carried out in this work is the aeronautical field, in chapter 2 the evolution of the use of fibre-reinforced composites in this sector can also be read as well as the reasons for which they are used. To give a brief idea of each one of the four mechanical tests conducted in this work, an explanation on each one of them is found in chapter 3. This chapter also gives a review on some research on these matters and about the evolution and conclusions on what has been done until now. Finally, chapter 4 and 5 present the main purpose of this work, the experimental procedures are explained, and the results acquired leading to the conclusions (chapter 6) are analysed.

Chapter 2

Fibre-reinforced Composite Materials

2.1 Concepts

According to P.K. Mallick [7] fibre-reinforced composite materials consist of fibres of high strength and modulus embedded in or bonded to a matrix with distinct interfaces (boundaries) between them. Generally, this type of composites is made by stacking a number of thin layers of fibres (in form of laminae) and matrix, consolidating them into the desired thickness in order to obtain the desired properties in one or more directions. To this stacking we call it a laminate and it's the most common form in which fibre-reinforced composites are used in structural applications [8].

To achieve specific physical and mechanical properties fibre orientation in each layer as well as the stacking sequence of various layers in a composite laminate can be controlled. Nevertheless, when fibre and matrix are joined to form a composite, they retain their individual physical and chemical identities, the fibre's strength and stiffness being usually much greater than the ones of matrix material, and both components directly influence the composite's final properties. This junction produces a combination of properties that cannot be achieved with either of the components acting alone. The fibres being generally orthotropic, that is, having different properties in two different directions, by aligning most of them in the direction of the load we can reach a lightest and most efficient structure which is the goal of composite design.

The growing popularity of fibre-reinforced composites comes from the fact that they present several advantages when applied in the high-tech sectors, especially in the aeronautical industry where weight is a critical factor, regardless of the cost the lighter the better. As such, they are typically reputed for their low density, superior strength–weight ratios and modulus– weight ratios, as well as for their excellent fatigue strength and fatigue damage tolerance. Due to these properties these materials are more and more used as structural materials as substitutes for metals which are denser materials and have comparable or worse strength and modulus combinations [7].

In the following subchapters a more specific attention will be made on subjects such as matrix, fibre, and hybridization, this last one being a central topic in this work.

2.1.1 Matrix

In a fibre-reinforced composite the matrix is required to fulfil several functions, most of them are vital to the performance of the material. This component working as a binder enables us to make use of the fibres, without it they would be of little value to an engineer [9].

We shall therefore enumerate its functions since they are important to knowledge [7, 9]:

(1) to hold the fibres in place, keeping them aligned in the important stressed directions;

(2) to transfer stresses between the fibres, which are the principal load-bearing component enabling the composite to withstand compression, flexural and shear forces as well as tensile loads;

(3) to protect the fibres from mechanical damage (e.g ., by abrasion) and to provide a barrier against an adverse environment, such as chemicals and moisture.

When processing a composite material, it's important to control the characteristics of the matrix such as the viscosity, the curing temperature and curing time for epoxy polymers to avoid defects [7]. Moreover, through the quality of its grip on the fibres the matrix can also be an important way to increase the toughness of the composite. A crack originated at broken fibres can be stopped or slowed down with a ductile matrix (example, polymeric) as well as a brittle matrix (example, ceramic) may depend upon the fibres to act as matrix crack stoppers.

Composite materials can be classified according to various criteria, precisely the type of matrix being one of the most relevant. There are polymeric, metallic and ceramic matrices [10]. The ease of processing and the low density of the polymers make the polymer matrix composites today the most important in terms of performance and application field. Polymeric matrices are divided into two main categories: thermoplastic and thermoset. Thermoplastic matrices are made up mostly of so-called technical plastics. When the thermoplastic polymers are heated, these bonds are temporarily broken and there is molecular mobility that allows reconformation. Thermosetting matrices are made up of polymers in which the molecules form very rigid three-dimensional structures. Thermosets, unlike thermoplastics, cannot be reprocessed. Once heated they take on a permanent shape. These polymers are often supplied for processing in the form of a mixture of two or three components, resin, accelerator, and catalyst. The mechanical properties of resins tend to improve with a post-cure treatment at high temperatures. One of the main advantages of thermosetting resins is the greater ease of impregnation of the reinforcement, since before curing, they have viscosities much lower than those of thermoplastics [11]. As we can see in table 2.1, there are many choices available, but each type of matrix has an impact on the processing technique, physical and mechanical properties as well as on the environmental resistance of the finished composite [8].

Thermoplastic matrices	Thermosetting matrices
Polypropylene (PP)	Polyester
Polyamide (PA)	Vinylester
Polycarbonate (PC)	Phenolic Resins
Poly-ether-ether-ketone (PEEK)	Epoxy
Thermoplastic polyimides	Bismaleimide
Phenylene polysulfide (PPS)	Polyimide

Table 2.1: Polymeric Matrices

Even if they cost more compared to polyesters and don't resist to temperatures as high as bismaleimides or polyimides, Epoxy resins are the most widely used matrices for advanced composites. They have advantages such as a good adhesion to fibres and to resin, low shrinkage during cure, solid or liquid resins in uncured state, wide range of curative options and adjustable curing rate. However they are somewhat toxic in uncurred form and absorb moisture which can change its dimensions and physical properties and it is slow when curing [8].

Effectively, in terms of mechanical properties, each type of matrix has its influence on the composite material as to compressive, interlaminar shear as well as in-plane shear properties. The interlaminar shear strength being an important parameter for structures under bending loads, whereas the in-plane shear strength has its role when these is under torsional loads. However, it plays a minor role in the tensile load-carrying capacity of a composite structure. Thanks to its ability to keep the fibres in place the matrix provides lateral support so that the fibre does not buckle under compressive loading, this influencing the compressive strength of the laminate. Studying the interaction between fibres and matrix is also important because it can prevent structural damages creating more efficient and tolerant structures.

2.1.2 Fibres

In a fibre-reinforced composite laminate the principal component are the fibres. They are the ones who carry the major portion of the load so it's very important when selecting a fibre type for a structure to analyse the fibre volume fraction, fibre length and orientation since these parameters will influence characteristics of the composite laminate, such as the density, tensile strength and modulus, compressive strength and modulus, fatigue strength and fatigue failure mechanisms and electrical and thermical conductivities as well as the costs.

In table 2.2 [11] is presented some data on the properties of fibres comparing with solid metallic materials. The fibres data corresponds to the average values made available by the manufacturer of the fibres used for this work.

Material	Density [g/cm^3]	Tensile Strength [GPa]	Tensile Modulus [GPa]	Strain-to-failure (%)
Fibres:				
E-glass	2.54	2.5	74	4.8
S-glass	2.49	4.30	86.9	5.0
PAN carbon T-300	1.76	3.53	230	1.5
Kevlar 49	1.44	3	112	2.4
Conventional materials:				
Steel	78	0.34-2.1	210	
Aluminium	2.7	0.14-0.62	70	
Tungsten	19.3	1.1-4.1	350	

Table 2.2: Properties of fibres and metallic materials in their massive form

Various types of glass (E and S), carbon and kevlar are the principal fibres used in industry [7,8]. However, the most used of all these reinforcing fibres for polymeric matrix composites are glass fibres, more precisely E-glass and S-glas fibres. Of all commercially available reinforcing fibres the one with the lowest cost is E-glass, which is the reason for its widespread use. On the other hand, S-glass being originally developed for aircraft components and missile casings, has the highest tensile strength among all fibres in use but has higher manufacturing cost [7].

For high-performance applications, carbon fibres are the most widely used, especially in the aeronautic field. They offer an amazing range of properties, including excellent strength and high stiffness. Although they are stronger than glass or kevlar fibres, carbon fibres are not only less impact-resistant but also can experience galvanic corrosion in contact with metal [7]. However, carbon fibre's properties are stimulating searches for alternative and less expensive materials.

Kevlar fibres provide exceptional impact resistance and good elongation, they have additional good properties such as high specific strength, toughness, creep resistance and moderate cost, for specific applications. But, as in all materials, they also have its limitations. They are weak in bending and show obvious damage if subjected to kinking or buckling, resulting in a bad performance under compression and for transverse tension. They are mostly used for bulletproof vests and other armor and ballistic applications [8].

2.1.3 Hybridization

As seen previously, composite materials have found their place in the industry world and their application sectors are always increasing. They are a solution to optimize many structures and to spare in fuel when applied in the transport world [12]. But the demands and requirements are increasing, and engineers are looking for new materials with even better properties for better performance and lower costs. It is with this in mind that the idea of hybridization arose.

Hybrid composites are materials made by combining two or more different types of fibres in a same resin matrix [9]. With this strategy we can create more balanced materials in terms of mechanical properties, better tailor the materials' properties to suit particular design requirements for specific applications [9] and reduce costs as well. In fact, some fibres such as glass fibres are relatively cheap and available in the market, while carbon fibres are more expensive. This way the advantages of both fibres can be used and the weaknesses of each of them can be reduced [13].

Actually, under different mechanical test conditions, a composite consisting of same reinforcing material may not show better mechanical properties than a hybrid composite. For example, high modulus fibre like carbon has the advantage of providing stiffness and major load bearing qualities but are relatively low in compressive strength whereas E-glass or Kevlar are low modulus fibres and make a composite with lower stiffness, higher elongation, and more damage tolerant. So, in this case, the combination of two fibres in the composite laminate offers the possibility of making a cheaper material while improving its toughness, but with a loss in stiffness. Even so, this laminate will provide better performance or result than an individual fibre laminate [14].

Low elongation (LE) and high elongation (HE) fibres are the two type of fibres usually blended in a hybrid composite. This brings advantages to the laminate because the first fibre to fail when under tensile stress is the LE fibre but since HE fibre has always larger failure strain the laminate can bear a higher load. It is also important to highlight that there is a difference and often a confusion between the use of terms as brittle/ductile fibres and LE/HE fibres. A HE fibre does not necessarily have a large failure strain, but it is always larger than the one of the LE fibre, while ductile fibres have a large failure strain and the brittle ones do not deform much [14]. There are many configurations to combine these two fibre types, these are represented on figure 2.1 [14].

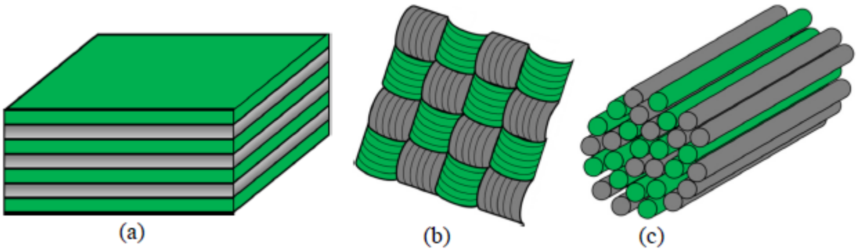

Figure 2.1: The three main hybrid configurations: (a) interlayer or layer-by-layer, (b) intralayer or yarnby-yarn, and (c) intrayarn or fibre-by-fibre.

The simplest and cheapest production method is the interlayer configuration where the layers of the different fibre types follow a stacking scheme. This is the structure used in this work. For the intralayer configuration the different yarns are woven into the same fabric. There is also the possibility of mixing the different fibres resulting in an intrayarn hybrid. There is also the possibility of forming more complex configurations by combining two of these methods.

The different fibre types' dispersion in the laminate has also its importance in the mechanical behaviour of the composite. In figure 2.2 [14] are described the different fibres' dispersion possibilities.

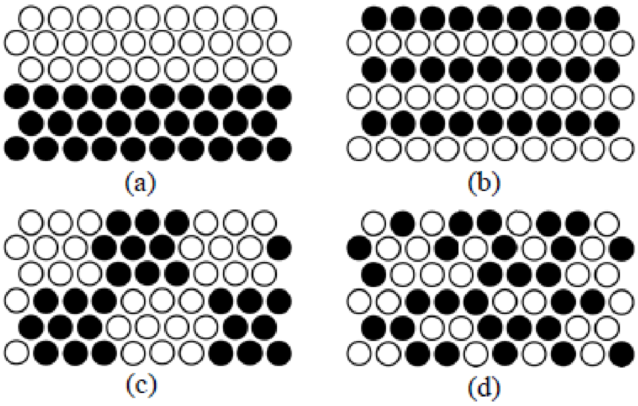

Figure 2.2: Illustration of the various degrees of dispersion (a) two layers, (b) alternating layers, (c) bundleby- bundle dispersion, and (d) completely random dispersion.

In figure 2.2(a) there is a low degree of dispersion because the two fibre types are disposed in two distinct layers. This is also the dispersion degree of the laminates used in this work. For better dispersion, the better configuration is the one with the two fibre types completely randomly distributed in the laminate 2.2(c) and (d) [14].

When a hybrid composite shows a better or worse performance than an individual fibre reinforcement composite it means they have a positive or negative hybrid effect respectively [15].

To define a hybrid effect there are two possible definitions. The most basic one is correlated with the improvement of the failure strain of the LE fibre in a hybrid composite compared with the failure strain of a LE fibre in a non-hybrid composite. This definition is illustrated in figure 2.3(a) [14]. The second definition involves the deviation from the rule of mixtures, it is illustrated in figure 2.3(b) [14].

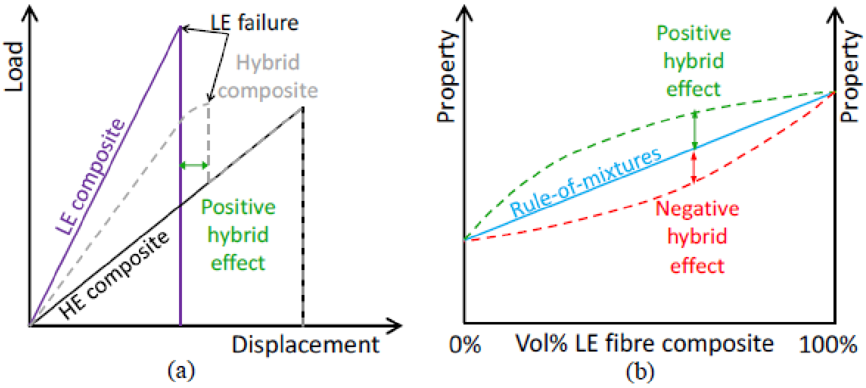

Figure 2.3: Illustration of the definitions of the hybrid effect: (a) the apparent failure strain enhancement of the LE fibres, under the assumption that relative volume fraction is 50/50 and that the hybrid composite is twice as thick as the reference composites, and (b) a deviation from the rule of mixtures.

2.2 Composites in the Aeronautical Field

With their winning combination of high strength, low weight and durability, fibre-reinforced composites structural applications are major in the aeronautical field. The provided lower weight results in lower fuel consumption and emissions, enhanced aerodynamic efficiency and lower manufacturing costs, and enables to increase the payload.

The aviation industry was the first interested in such benefits and military aircrafts manufacturers were the first to seize the opportunity to apply composites on their aircrafts to make use of their excellent characteristics in order to improve the speed and manoeuvrability of their products. Planes have traditionally been made from metals as aluminium, steel, and titanium but since fibre-reinforced polymer composites can provide a much better strength-to-weight ratio than metals, these are being substituted [16].

The wide applications of composites began with fibreglass composites and boron fibre-reinforced epoxy. Fibreglass was first used in the Boeing 707 aircraft in the 50's, where it comprised about two percent of the structure. Ever since, the company increases the percentage of composites on each generation of new aircraft built. Kevlar fibres and carbon fibres reinforced epoxy introduction in this field yield place in the 70's and carbon fibre-reinforced composite became the primary material in many wing, fuselage, and empennage components. Quickly the good structural properties of these materials and their durability providing a great performance, gave designers confidence to develop other structural aircraft components resulting in an increase of the amount of composites used in this industry. For example, in the military aircrafts field, the F-22 fighter aircraft contains 25% by weight of carbon fibre-reinforced polymers.

On commercial aircrafts, by 1987, 350 composite components were placed in service, these were made of a high-strength carbon fibre-reinforced epoxy structures. Airbus, with their A310 aircraft, which was introduced in 1987, was the first commercial aircraft manufacturer to make extensive use of composites. A significant weight reduction was made since the composite components weighed about 10% of the aircraft's weight, for example the composite vertical stabilizer, which is 8.3 m high by 7.8 m wide at the base, is about 400 kg lighter than the aluminium vertical stabilizer previously used [3]. Another example is the Airbus A320. This aircraft was introduced in 1988 and was the first commercial aircraft to use an all-composite tail [4].

As to the latest generation of airliners such as the Airbus A380 or the Boeing 787, composite materials have been employed in the primary load carrying structure: the wings. For the A380 this application helps enable a 17% lower fuel use per passenger [17], whereas on the commercial side, Boeing 787 Dreamliner has the record of 50% of composites used on its structure as shown in figure 2.4 [18].

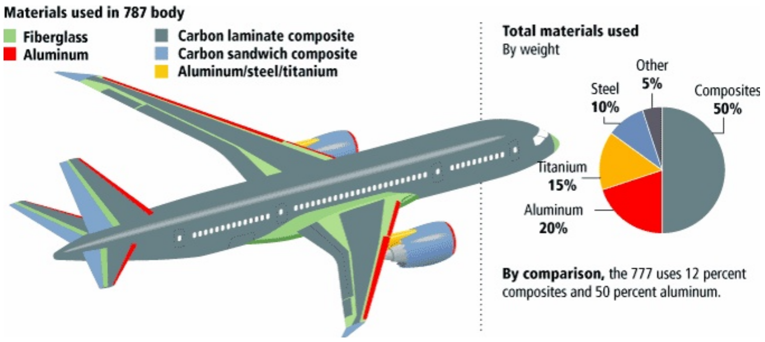

Figure 2.4: Percentage and application of different materials on B787 Dreamliner

Besides their excellent mechanical properties mentioned above and the weight reduction, there are additional advantages of using fibre-reinforced polymeric composites over aluminium and titanium alloys.

One of these advantages is the reduction of fabrication and assembly costs by reducing the number of components and fasteners. The easier handling of fibre reinforced polymeric composites allows the manufacture of complex structures without the need of too many procedures or additional components unlike metals. For example, thermoforming is a manufacturing process used for polymeric composites and through it it is nowadays possible to produce complex parts in one piece. The vertical fin assembly of the Lockheed L-1011 has 25.2% less weight when it is made of carbon fibre-reinforced epoxy than when it is made of aluminium, leading to 72% fewer components and 83% fewer fasteners [7,16].

The use of fibre-reinforced composites also results in a reduction of maintenance and repair costs due to a higher fatigue resistance and corrosion resistance. For example, the metal fins used in helicopters flying near the ocean coast suffer from corrosion and this leads to an 18-month repair cycle for patching the resulting corrosion pits. This solution is only temporary since after a few years in service, the whole fin must be replaced or rebuild because the accumulation of patches repairs adds enough weight to the fins to cause a shift in the centre of gravity of the helicopter. Considering that carbon fibre-reinforced epoxy is resistant to corrosion, by substituting the metal fins by ones made of this material this problem is solved and therefore the rebuilding or replacement cost is eliminated [7, 19].

The third advantage is that the laminated construction used with fibre-reinforced polymers has the capability for high-degree of optimization by tailoring the directional strength and stiffness of the airframe structure. For example, a more favourable airfoil shape that enhances the aerodynamic characteristics critical to the aircraft's manoeuvrability can be produced by appropriately adjusting the fibre orientation angle in each lamina as well as the stacking sequence to resist the varying lift and drag loads along its span.

Lower toxicity and increased resistance to fire [16] are important parameters to consider for aircrafts and these are also fibre-reinforced polymeric characteristics.

Fibre-reinforced composites also allow the possibility of low dielectric loss in radar transparency as well as achieving low radar cross section. For example, the outer skin of B-2 and other stealth aircrafts is almost all made of carbon fibre-reinforced polymers. The stealth characteristics of these aircrafts are due to the use of carbon fibres, special coatings, and other design features that reduce radar reflection and heat radiation [7, 19].

Unfortunately, composite materials have also their limitations such as high cost; a relatively low impact damage tolerance (from bird strikes, tool drop, etc.), susceptibility to lightning damage and of internal damage going unnoticed; the laminated structures have weak interfaces: poor resistance to out-of-plane tensile loads; moisture absorption and consequent degradation of high temperature performance; and multiplicity of possible manufacturing defects and variability in material properties. In addition, when they are used in contact with aluminium or titanium, they can induce galvanic corrosion in the metal components. Fortunately, there is a solution to that, the protection of the metal components from corrosion can be achieved by coating the contacting surfaces with a corrosion-inhibiting paint, but it is an additional cost [7, 19].

Even presenting weaknesses, the benefits of applying composite materials are significant. As we follow the history of composites in the aeronautical world, we see that over the years, with experience and research, engineers tend to add or replace components in aircraft in order to have more and more structures made of these materials.

2.3 Manufacturing process

Manufacturing implies the transformation of uncured or partially cured fibre-reinforced thermoset polymers into composite. This process involves curing the material at elevated temperatures and pressures for a predetermined length of time, parameters which significantly affects the quality and performance of the molded product. The curing duration depends on a number of factors, including resin chemistry, catalyst reactivity, cure temperature, and the presence of inhibitors or accelerators [7].

The method chosen to combine fibres and matrix into a composite depends on the performance goal to be achieved, the nature of the two elements as well as on the scale and geometry of the structure to be manufactured [9].

The range of processes used to manufacture composites is nowadays wide. Some of these processes are hand layup, prepeg layup, autoclave processing, bag molding process, compression molding, pultrusion, filament winding or liquid composite molding processes [9].

Since the method used to carry out this work is the hand layup in combination with vacuum bag molding, we will focus on the description of this process.

In this method, the stacking and impregnation of successive layers of reinforcement (woven) is done manually in an open mold. To facilitate demoulding, a release agent is applied to the mold. Each layer of reinforcement placed is impregnated with catalysed resin and compacted with the help of rollers [11]. This fibre-matrix set is then put under vacuum in a bag with pressure on it. The curing cycle begins at room temperature and then the mold is removed and the laminate is put into an oven to finish the curing process [8].

The main advantages of the method are simplicity, reduced initial investment, few restrictions on the geometry of the parts to be made but it is by nature very slow and labour-intensive [11].

To avoid or reduce defects, including voids, interply cracks, resin-rich areas, or resin-poor areas on the resulting composite laminate, a good resin flow and compaction are necessary when consolidating the layers of woven fabric. This requires the application of pressure perpendicular to the layers during processing. This pressure applied squeezes out the trapped air or volatiles, as the liquid resin flows through the fibre network, suppresses voids, and attains uniform fibre volume fraction. It is important to do so because among the various defects produced during the molding of a composite laminate, the most critical defect influencing its mechanical properties is the presence of voids [7].

Chapter 3

Mechanical behaviour and literature review

Since in this work it will be studied the strain rate effect on the bending properties (bending strength and stiffness), interlaminar shear strength as well as the creep and stress relaxation behaviour of hybrid fibre-reinforced composites, this chapter presents some theorical information about each one of these performed mechanical tests and a literature review on these thematics.

3.1 Mechanical Testing

In engineering, structures are subjected to mechanical and thermal loads, thus the materials that constitute them deal with stresses and strains. In such manner, before applying a material on a structure it is essential to study and test it, preventing future defects and damages. This way when designing a structure, a better material selection can be made so that it can fulfil the requirements [7].

Fibre-reinforced composites are widely and increasingly being used, nevertheless, the use of these advanced composites in structures is still limited. One of the reasons is their mechanical properties' dependence on time, temperature, and fibre orientation [20].

The purpose of mechanical tests is to determine the bending properties of a material measuring loads and displacements [8].

Creep, stress relaxation, flexural strength and interlaminar shear strength are some particular mechanical tests that can be performed on fibre-reinforced composites to take project-level considerations about their reactions under loads, to identify their weaknesses and strengths so they can have more specific applications and as damage prevention. Under different mechanical test conditions, a composite consisting of same reinforcing material may not show equal mechanical properties [15].

3.1.1 Strain rate and bending properties

An important way to perceive the performance of a fibre-reinforced polymeric material is by its rate of loading. High strain rates (loadings that occur over a short period of time) tend to be more advantageous for the elastic properties of materials which are associated with load-bearing performance involving properties such as strength and stiffness. On the other hand, low strain rates (loadings that occur over a longer period of time) are better for the viscous flow, impact resistance or toughness of a material [21–23].

The strain rate of a material is identified through compression, tension, or flexural tests however, in this work we will focus only on the bending mode.

Flexural properties such as bending strength, stiffness or strain are determined through 3-point bending tests. In such tests the maximum axial fibre stress occur on a line under the loading nose. The method consists of deflecting at a constant rate a specimen at the midspan supported on a beam until it fractures or until the deformation reaches some predetermined value. During flexure, one surface is under tension while the opposite surface is under compression [10].

Usually in most composites, we define high performance reinforcing fibres as being brittle, this meaning that they deform elastically to failure showing little or no non-linear deformation. As for the matrix, when unreinforced with fibre, it is usually capable of some irreversible plastic deformation with a failure strain much greater compared with fibres [9].

Graphic 3.1 [9] shows the different stress/strain curves of the different elements that constitute a laminate, that is fibre and matrix, and the curve corresponding of the composite when the two elements are joined with a fibre volume fraction of 50%.

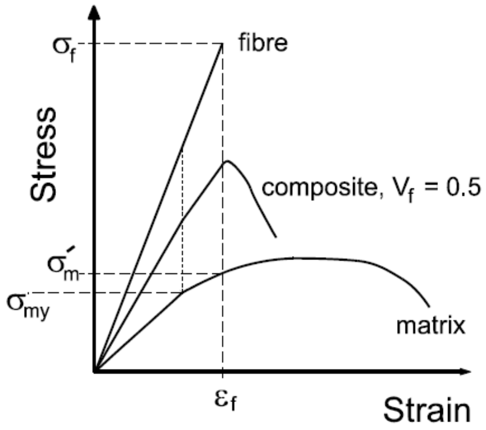

Figure 3.1: Stress/strain curves for brittle fibre/ ductile matrix

σ'_m is the stress in the matrix corresponding to the fibre failure strain. This shows us the behaviour of each element under stress: when the matrix reaches its yield stress σ_{my}, it continues to bear load although there's a decresase of the slope of the stress/strain curve. If the fibres carry most of the load, when it reaches its ultimate strength failure occurs.

The flexural properties obtained with these bending tests may vary according to the specimen depth, temperature, atmospheric conditions, and the difference in the strain rate. For example, non-resin regions in the composites introduces voids which can cause the laminate to lose its strength [22]. The data collected with these kinds of tests are useful for quality control and specification purposes [24].

When a material is tested in flexure with a 3-point bending test, the maximum stress in the outer surface of the test specimen occurs at the midpoint. This flexural stress may be calculated by means of the following equation 3.1 [24]:

$$\sigma_f = \frac{3PL}{2bh^2} \quad (3.1)$$

where:

σ_f= stress in the outer fibres at midpoint, (MPa)

P= load at a given point on the load-deflection curve, (N)
L= span, (mm)
b= width, (mm)
h= thickness, (mm)

The stiffness modulus is obtained by linear regression of the load-displacement curves using equation 3.2 which is the linear elastic bending beams theory relationship :

$$E = \frac{PL^3}{48I} \quad (3.2)$$

where
E= modulus of elasticity in bending, (MPa)
I= moment of inertia of the cross-section, (mm^4)

In this work I is obtained as follows:

$$I = \frac{bh^3}{12} \quad (3.3)$$

Equation 3.4 is used to calculate the maximum strain in the outer fibre at the mid-span [24].

$$\varepsilon_f = \frac{6\delta h}{L^2} \quad (3.4)$$

where:
ε_f= peripheral fibre strain, (mm/mm)
δ= maximum deflection at mid-span, (mm)
h= thickness, (mm)
L= span, (mm)

As for the strain rate, this can be calculated using the following equation 3.5 [24]:

$$\dot{\varepsilon} = \frac{d\varepsilon_f}{dt} = \frac{6V_t h}{L^2} \quad (3.5)$$

where:
$\dot{\varepsilon}$= strain rate, s^{-1}
ε_f= peripheral fibre strain, (mm/mm)
V_t = cross-head speed, (mm/min)
h= thickness, (mm)
L= span, (mm)

When determining bending strengths two types of failures can be found: failures limited by the normal strength and failures due to shear strengths. Failure due to normal stresses result in the fracture of the extreme outer layers in compression or tension whereas failure due to shear stresses occurs by delamination at the midplane area of the specimen.

3.1.2 Interlaminar shear strength (ILSS)

The interlaminar shear strength is a measure of the strength of the bond that exists between the various layers within the composite. This parameter is important since the way in which two or more separate elements adhere to each other is relevant because the mechanical response of the material depend on loads being shared between its constituents and the propagation of cracks are affected by their different mechanical properties. For example, when discussing the strength and toughness of a composite, analysing the strength of the interfacial bond between fibres and matrix are a way to distinguish a good material from an inadequate one [9]. The bending of beams can cause appreciable shear stresses, this occurs either within the matrix or at the fibre-matrix bond line, which while not large enough to cause failure of a traditional metallic structural material can fail a composite [8].

The interlaminar shear strength can be calculated from equation 3.6 [8]:

$$\tau_s = \frac{3P_s}{4bh} \quad (3.6)$$

where
τ_s= interlaminar shear strength, (MPa)
P_s= maximum load, (N)
b= width, (mm)
h= thickness, (mm)

In order to maximize the ratio of the shear stress generated at the midplane with respect to the tensile or compressive stresses generated in the outer fibres, the specimen size for interlaminar shear strength tests is a rather short, thick beam tested in 3-point bending [25].

It is not generally possible to relate the short-beam strength to any material property due to the complexity of internal stresses and the variety of failure modes that can occur on a specimen. However, as said before, failures are normally determined by resin and interlaminar properties so the test results have been found to be repeatable for a given specimen geometry, material system, and stacking sequence [26].

ILSS tests can be used for quality control and process specification purposes. In addition, composite materials who went under this same test can be compared if failures occur consistently in the same mode [27].

3.1.3 Viscoelastic Behaviour

A material for which relationship between stress and strain depends on time is called a viscoelastic material [10]. Creep and stress relaxation are the most fundamental experiments used for characterizing the viscoelastic properties of materials [28].

Carbon and glass fibres do not exhibit time-dependent behaviour but when combined with a viscoelastic matrix they appear to do so turning it an interesting subject to analyse. On the other hand, Kevlar fibres are polymeric, as such they are viscoelastic but less than a matrix. The viscoelastic properties of polymeric composites are complex. They are prone to creep and sensitive to stress relaxation due to their time-dependence, making it a challenge when considering them for long-term applications. Therefore, a better knowledge on the viscoelastic behaviour of fibre-reinforced polymers is important in order to provide guidance for optimizing composite structure, and for predicting their long-term properties [29].

3.1.3.1 Creep

Composites are viscoelastic materials having time dependent mechanical properties and creep resistance is directly associated with viscoelastic strain and fibre/matrix interfacial behaviour [30]. Thus, we can define creep has a time-dependent deformation under a constant load at a specified temperature.

During their usage materials are subjected to different stresses for a certain duration, this constant state of stress is accompanied by an increasing amount of strain, impairing their service durability and safety. Therefore, creep is a crucial material property at a long-term point of view, it's a serious concern and gives limits to their applicability in aviation and automotive industries, by studying it engineers can determine the expected deformation of a material and this way, can prevent a future damage [31].

Stress level and temperature are important parameters when a material is under a creep strain. At high temperatures and/or high stress levels, the creep phenomenon becomes more critical. Naturally it also depends on the type of material used, while creep in metallic materials occurs only at elevated temperatures, creep in polymeric materials can be significant at any temperature [7, 32].

Laboratories conduct either tensile creep tests or a flexural creep tests over a period of a few hours to a few hundred hours to generate material data [7]. Gathering all this data is useful for the industry world. With it, it is possible to compare materials, to design more efficient fabricated parts and to characterize plastics for long-term performance under constant load. It is essential to predict the creep modulus and strength of materials under long-term loads and to predict dimensional changes that may occur as a result of such loads [33].

Materials under creep tests go through several stages as represented on graphic 3.2 [34].

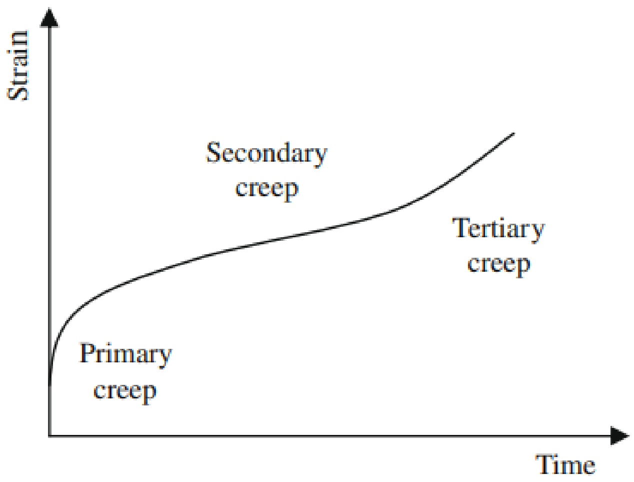

Figure 3.2: Different creep stages

An initial elongation occurs when a constant load is applied on a specimen which is known as instantaneous strain, ε_0. Despite the fact that the applied stress is below the yield stress, there is a plastic strain, i.e. a strain that is not totally recoverable. Rapidly, a decreasing deformation rate occurs known as the primary stage, this is followed by a steady-state linear deformation stage, known as the secondary creep stage, some materials do not have this stage. The tertiary deformation is the final stage where rapid deformation at an accelerated rate occurs, this tertiary creep only occurs at high stresses and for ductile materials, so some materials do not go through it as well [33].

3.1.3.2 Stress Relaxation

Stress relaxation is the decrease in stress in response to strain generated in a material [35]. For example, when a structure remains in a deformed condition for some finite period of time, this causes a certain amount of plastic deformation. Relaxation relieves the state of stress and this affects the equipment reactions. This amount of relaxation depends on time, temperature, and stress level.

For polymeric materials, stress relaxation is also an important parameter to study, it is also a way of characterising polymer viscoelasticity [29].

Stress relaxation tests may be conducted on materials subjected to different types of stresses, that is tension, compression, bending and torsion. In this project, the stress relaxation method studied is the material under bending mode.

In stress relaxation tests, a constant deformation is maintained while the evolution of stress on the specimen is observed over time. Stress relaxation parameter show a decrease with time [7]. By graphic 3.3 [35] we can see a typical stress relaxtion curve.

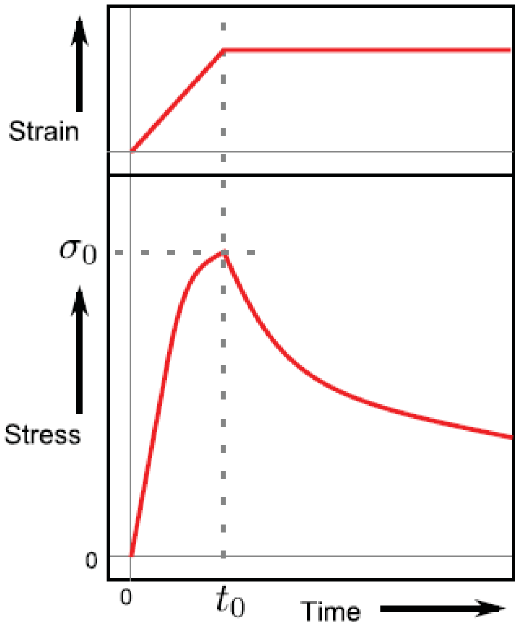

Figure 3.3: Characteristic Behavior During Force Application Period in a Relaxation Test

t_0 refers to the zero time, representing the moment when the desired stress or constraint conditions are initially reached in a stress relaxation test.

To calculate the maximum fibre stress in a flexural stress relaxation measurement the following equation 3.7 is used [35].

$$\sigma = \frac{3PL}{2bh^2} \quad (3.7)$$

where:
σ= stress, (MPa)
P= load at a given point on the load-deflection curve, (N)
L= span, (mm)
b= width, (mm)
h= thickness, (mm)

These tests are necessary to collect data for certain applications, for example when designing mechanically fastened joints to assure the permanent tightness of bolted or riveted assemblies, or to predict the decrease in the tightness of gaskets [35].

3.2 Effect of hybridization on mechanical performance

Aircraft are globally complex structures. Fruit of the engineers' work and ingenuity, they are constantly updated in order to be increasingly profitable and performing.

Whether it is a single engine private plane, a giant commercial airliner, an helicopter or a supersonic fighter plane, all those aircraft types with complex designs have specific structures, and in the aeronautical industry these structures have to meet characteristic requirements such as safety standards, fuel sealing, easy access for equipment's maintenance, vacuum, radiation and thermal cycling also must be considered etc. And to add to this long list, special materials are required to be developed for durability [16].

Since the appearance of composite materials, many studies have been carried out in order to optimize their functions on a structure and to open more application possibilities. However, the constant evolution of technology also calls for new materials, with new requirements. Materials with high specific strength, high specific stiffness, enhanced dimensional stability, energy absorption, corrosive resistance as well as reduced cost are required [5]. Fibre-reinforced composites have all these characteristics, however their high stiffness and strength contrast with limited toughness. The same way, composites made of the same reinforcing material system have its limitations since they have different responses when undergoing different loading conditions during the service life. Therefore, over the years research has been made to overcome this weakness.

Many different approaches have been proposed to overcome this disadvantage, making the materials more damage resistant and less brittle. One of the strategies found is creating a toughener polymer matrix by adjusting its chemistry or by adding rubbers, thermoplastics or nano-scale reinforcements [36–38]. Another solution to this problem was found in hybridization, which is a fundamental theme in this work.

By combining two or more types of fibres, we can highlight and combine the desired qualities of all fibres and reduce their disadvantages, this offers a better mechanical property balance than non-hybrid composites. For example, a way of improving the specific mechanical strength and modulus without much increase in the thickness of the glass laminate is to add some percentage of high modulus carbon fibres in the laminate [39].

Metal fibres have a high stiffness and large failure strain but have a high density whereas polymer fibres present ductility and low density, having a limited temperature resistance and lower stiffness. So, replacing brittle fibres by ductile ones can be a way to increase the failure strain and toughness [14]. In addition, this blend of fibres with different properties can be used as a warning sign before final failure [40]. If a tension load is applied in the fibre direction of a hybrid composite, the more brittle fibres will fail before the ductile ones.

An effective method of improving the ultimate strain and impact properties of high modulus fibre composites by hybridization is to add some percentage of low modulus fibres like E-glass or Kevlar. Such an arrangement would lead to possible decrease in in-plane strengths of hybrid composites compared with those of high modulus fibre composites [5].

Volume fraction, material type of each ply, ply angles and stacking sequence of fibre layers in the laminate are important parameters to consider since they yield additional possibilities to optimise the mechanical performance of hybrid composites [14, 41, 42].

In addition to being a means of improving the performance of materials, hybridization also allows to reduce costs. The first type of fibre being used in the 60's was carbon fibre. As its popularity increased thanks to its excellent properties, designers found in this fibre a solution to improve their structures looking to apply it to more components. Unfortunately, due to the high costs of this material, an alternative had to be found and in hybridization engineers found a solution to this issue. For example, replacing carbon fibres in the middle of a laminate by cheaper glass fibres can significantly reduce the cost, while the flexural properties remain almost unaffected.

Consequently, researchers were interested in hybridization. But in the 80's the carbon fibres prices dropped as well as the active researches that had taken place since the early 70's on hybridization, the focus shifting towards understanding the mechanical behaviour of non-hybrid composites [43].

With the appearance of new materials and with the invention and improvement of processing technologies, the interest in hybrid composites as a possible strategy for toughening fibre-reinforced composites appeared and studies on hybridization remerged.

The performance of an engineering material is judged by its mechanical properties and behaviour under tensile, compressive, shear, and other static or dynamic loading conditions in both normal and adverse test environments [7]. As such many studies have been made on all kind of fibre-reinforced composite combinations.

In 1987, Kretis [44] studied the tensile properties of hybrid fibre-reinforced plastics. His study was based on unidirectional material since multidirectional laminates introduced additional variables which so far weren't well investigated. In terms of tensile properties, the shape of the stress/strain curve for hybrid materials varies depending on the type of fibres and resin used as well as its proportions and the way they are intermingled.

When under tensile load, if the low elongation (LE) fibres crack, a redistribution of stresses occurs leaving the high elongation (HE) fibres, with the additional load to sustain. If as the bond between the two types of fibre is good, the load will diffuse through the HE fibres back into the LE material, a small delamination occurs around the breaking zone, relieving the LE material locally. In this case, the stiffer fibres are still contributing to stiffness, and to strength. For example, Song et al. [45] found out that the laminating position of the carbon fibre plays an important role in the stacking design of carbon/glass and carbon/aramid fibres composite and the concentration of central carbon layers results in a proportional increase in tensile strength.

The volume fraction of each type of fibre in the material influences the stress level of the HE fibres after the LE fibres failure. For high fraction of HE fibres, the stress contribution of HE fibres at their failure strain dominates the strength, as so the stress can reach higher levels than the stress at the failure strain of the LE fibre. On the other hand, for HE fibres low fractions the stress at HE failure does not exceed the stress at the failure strain of the LE fibres [44].

The flexural properties are most determined through a 3-point bending test in which a loading nose deflects a specimen at a set span and loading rate until fracture. When deflected the underside of the test specimen is under tension while the upper side will be subjected to compression. Along the mid-plane of the specimen there are shear stresses, bending failure may be caused by tensile, compressive, shear, or a combination of these stresses. The principal failure modes found in these kind of tests by literature are fibre breakage and delaminations, but fibres breakage in compression side is the main damage mechanism observed [12, 42, 46–48]. Therefore, we can conclude that the strength of a composite material depends on the mechanisms of damage accumulation and failure, that is the way in which damage occurs in the material and the manner in which it accumulates to reach some critical level which causes final failure, as well as on the properties of its constituents. It is thereby influenced by some aspects of the composite construction like fibre type and distribution, the fibre aspect ratio, and the quality of the interfacial adhesive bond between the fibres and the matrix [9].

Santos et al. [12] and Ghafaar et al. [42] reported that full carbon composites have the maximum bending stress and bending stiffness and full glass fibre laminates the lowest value. As for the hybrid laminates made of carbon and glass fibres, the presence of glass fibres decreases the bending properties, and this decrease increases with the glass fibre content. In this work, a study was also made on the strain rate, concluding that independently of the material, higher strain rates led to higher maximum bending stresses and bending modulus. In addition, when comparing glass composites with carbon composites, Madhavi et al. [49] reported that the flexural stress behaviour of the carbon fabric composite is four times greater than glass fabric reinforced composite.

Regarding the flexural properties of hybrid composites, they depend highly on the stacking sequence. As such, Giancaspro et al. [46] noticed that glass fibre composites fail more easily when under tension whereas carbon fibre composites are more sensitive when under compression. Wonderly et al. [50] also reported that the ratio of compressive strength over tensile strength is different for carbon and glass fibre composites, this being 0.34 and 0.73 respectively. However these values depend on the carbon fibre type [51] and how well the fibres are supported against buckling. Therefore, placing different fibre types alternatively or by adding carbon fibre on the tensile side of glass fibre composites the flexural strength will increase, this is not the case when it is added to the compressive side [52, 53]. Subsequently, Dong et al. [54] studied the optimal design for the flexural behaviour of glass and carbon fibre reinforced polymer hybrid composites and concluded that the highest flexural strength is achieved for a relative content of 12.5% of glass fibres, all placed on the compressive side.

According to Dong et al. [55] the flexural strengths for carbon/glass intralayer hybrids are 40% and 9% higher than full carbon and full glass composites, respectively.

As for Kevlar 49 composites, they have higher tensile stiffness and strength than carbon and glass fibres [56], and a lower density but since they are known to buckle, kink and yield under compressive and flexural stresses, they are not suitable for such testing conditions [57]. Studies were carried out on the flexural behaviour of kevlar-epoxy composites [58], on their elastic-plastic behaviour [59] and researches were made to improve their performance in flexural and compressive applications through hard surface coatings [60] and asymmetric hybridization with carbon fibres [61]. The great difference between the tensile and the compressive strengths of kevlar fibre-reinforced composites has important consequences for its flexural behaviour. The strain at the compressive face is larger than that at the tensile face causing the shift of the neutral axis to the tensile side with the growing compressive yield region. When they are subjected to axial compression or bending they may exhibit a non-linear plastic deformation as consequence of structural defects developed in the chain [62]. Before fibre fracture it is usually preceded by longitudinal fragmentation and splintering. This non-catastrophic failure mode gives Kevlar 49 composites superior damage tolerance against impact or other dynamic loading, which is not observed in glass or carbon fibres [7].

The mechanical performance of a fibre-reinforced polymeric composite depends strongly on its fibre/matrix interface and on suitable interfacial fibre/matrix bonding.

A strong interface between fibre and a ductile matrix results in improvement in tensile strength and compressive strength [63–65]. Strategies such as surface treatment can produce composites with higher interlaminar shear strength. A low interlaminar shear strength is due to weak adhesion and poor bonding between the fibre and matrix [66]. However, in order to improve toughness many times a weak interface is desired between fibre and a brittle matrix since a weak and elastic interface provides better crack resistance. Consequently, we can say that it is not necessarily advantageous to apply composites with the highest shear strength values. An explanation to this statement is that when a material is brittle the cracks run normal to the fibres and pass through them, resin and interface various times. However, if the composite has as an interface of moderate strength cracks follow a path that consists in deviating through the interlaminar planes because these are the weak regions, resulting in delaminations. This way the material will be tougher [9, 67]. Therefore it is important to have in consideration the resistance of the fibre composite to crack propagation and since the initial crack grows parallel to the fibre direction and is controlled by the toughness of the matrix, investigations have led to the use of tougher resins with the addition of thermoplastic resins, rubber and particles [68–72]. Srivastava et al. [73] using CFRP under the short-span three point bend test described how fracture toughness can be improved by the addition of nano fillers. Other studies [74–79], have been carried out using this kind of test to investigate the effect of nanoparticles and interfacial modifications in the interlaminar shear strength of woven composites made of glass or carbon. Fibre surface treatments also affects fibre–matrix interfacial adhesion [80, 81].

Another alternative approach to modify the interfacial bond strength was shown by Dransfield et al [82] is to ‘stitch’ the laminae together with fibres running in the direction perpendicular to the plane of the laminate, improving the delamination resistance (ILSS) and toughness of the composite. Nonetheless, Adanur et al [83] have proven that this method has its limitations since there is a maximum stitch density otherwise these improvements can be reversed.

The presence of voids or moisture in the resin also aggravates the interlaminar shear strength making it weak. For example, in composites made of carbon and epoxy 10vol% of voids could reduce the ILSS by about 25% because with moisture absorption the matrix strength reduces and there is a deterioration in the interfacial bond strength reducing the ILSS [9].

Fibre orientation has a strong influence on interlaminar behaviour of the specimens.

Almeida et al. [84] studied the interfacial behaviour on carbon fibre-reinforced composites with variation on the orientation of the fibres. They proved that 0° configuration specimens have the most non-linear behaviour since when the maximum load is reached this is followed by several load drops. These sudden decreases are caused by multiple horizontal cracks on the specimens. For higher angles the stress supported by the specimen's failure is lower than for the 0° sample. At 0° failure occurs essentially by interlaminar shear, delamination finds its place at the mid-plane. For the other specimens' angle configuration, a bending effect is identified, and the main failure occurs at the bottom surface.

Madhavi et al. [49] reported that the ILSS of carbon fabric reinforced composite is five times greater than glass fabric reinforced composite.

Hybridization can also be a way to improve ILSS. Turla et al. [85] studied the ILSS of glass and carbon fibre reinforced epoxy matrix hybrid composite and the ILSS on full carbon composite and full glass composite. Yet, the hybrid laminate was made up of seven intercalated layers of carbon and glass fibres, the orientation being equally varied. The results showed that the ILSS of hybrid composite is significantly improved as compared to the two full fibre composites. Padmanabhan et al. [57] conducted a study on the effect of the thickness on the ILSS and witnessed an evident improvement in ILSS due to increased thickness or layers of fabric used. The explanation for this arises is that the beam tends to be more elastic due to increased number of layers, thereby enhancing the flexural rigidity. Also using the hybridization technique, it was shown that incorporating strips of GFRP into a CFRP laminate is an efficient way to act as crack arresters [86]. Yet the width of the strips must be sufficient to dissipate the energy of a crack moving rapidly in the CFRP by localized debonding and splitting.

Kevlar fibres are known to have a weak interface with matrix and because of better adhesion with glass fibres, epoxies in general produce higher ILSS than other thermosetting matrices. Increasing the matrix volume fraction and avoid the void content in the laminates increase the ILSS. Normally, the reduction of ILSS is caused by fabrication defects such as internal microcracks and dry strands [7, 87].

Polymeric composite materials present a viscoelastic behaviour which shows itself when under different conditions such as creep under constant load, time-dependent recovery of deformation followed by load removal, stress relaxation under constant deformation, and time-dependent creep rupture.

Many structures as high-speed robot arms, space structures or even airplane components demand vibrational energy dissipation. Consequently, viscoelastic damping can also be an important attribute on materials used for these applications. On the other hand, viscoelastic behaviour can also be undesirable. This occurs when creep strains become excessive, when stress relaxation reduces the stiffness of a component which has restoring force requirements, or when the viscoelastic effects are sufficient to lead to delayed failures or buckling of the structure [88].

As we can see the mechanical properties can be considered beneficial for certain applications and less for others, hence it is important to understand well the mechanisms of materials when under different loads.

When composite materials are under mechanical loads, due to viscoelasticity the load is shifted from the time-dependent matrix material to the fibres which are less time-dependent. This transfer serves to relieve the stress to the material component which is more capable of carrying the load. This move is a beneficial way to ease matrix cracking and other damage [88].

The creep properties of polymer materials are known to show time dependency [89, 90], are affected by aging time [91, 92], moisture content [93, 94], thickness [95], fibre orientation [96], fibre length [97], rate of loading and temperature. For example, while creep in metallic materials only occurs at higher temperatures, on polymers creep can be significant at any temperature [32]. Fibre/matrix interface is also very important because the creep displacement is controlled by the bonds' breakage and their propagation [98, 99].

Nevertheless, the creep behaviour of fibre-reinforced polymer composites is usually difficult to predict due to its complexity. Properties can change with time under the load. According to Sullivan et al. [100] one of the reasons for this variations is the thermosetting matrix whit amorphous characteristics which make it difficult to discuss the results only considering physical behaviour, being important to associate with the respective chemical structures.

When under long-term loading, mechanical properties will decline with time and stress and strain levels on the specimens will vary [101]. An complex behaviour rises as the stiffness of the material decreases with time, this decrease rate ascends with stress. To reduce the stiffness 'rate alteration and in order to increase the stiffness of the composite so that it better tolerates long-term loading and environmental conditions, the resin of the composite can be reinforced through either chemical method analysis and polymer structure change of the resin or adding different filler such as alumina or silica [102].

Even if this complexity exists, the study of this behaviour on composites is important for durability and reliability measurements as well as eventual failure caused by stress and temperature under time, to prevent damages when applied on structures.

The study of the influence of fibre orientation on long-term characteristics of laminates is also essential for safe design. Almeida et al. [84] studied this parameter on different carbon fibre-reinforced composites orientation configurations. They observed that creep behaviour changes with the orientation angle, especially the instantaneous deformation which is the initial one. Furthermore, transverse load is prone to creep as it depends purely on the tensile separation of the fibre/matrix interface, their interactions being of the frictional type.

Santos et al. [12] studied the creep phenomenon on carbon/glass fibre-reinforced composites showing that the different layer configuration has an impact on this property. The conclusion to this mechanical test was that an higher content of glass fibres in the laminate are responsible for higher creep displacements. As evidenced on this paper the displacement after 180 min of the glass fibre laminates was about 3.8% higher than the value observed for full carbon laminates. Fibres have a contribution to this aspect since both elastic deformation and viscous flow are retarded by its presence leading to a delayed creep process [99, 103–106].

Comparing the viscoelastic behaviour of Kevlar-49, carbon and glass fibres, carbon fibres exhibit negligible viscoelastic behaviour compared to the glass fibres [12, 107]. For Kevlar-49 it was found that creep failure strain depends on the initial strain and is lower than strain to failure under simple tensile loading [108].

Unlike creep, where displacement increases with time, in relaxation tests stress decreases over the time.

Fibre type [62, 106], fibre orientation, fibre loading, and fibre/matrix interaction influences the relaxation mechanisms.

Santos et al. [12] studied the stress relaxation on carbon/glass fibre reinforced laminates. Similarly to the creep behaviour, full carbon composites are less sensitive to stress relaxation behaviour than full glass fibre composites, thus stress relaxation is greater with the highest content of glass fibres. Saha et al.'s [109] concluded that the rate of stress relaxation decreases from one ply to three plies on carbon fibre-reinforced composites. As for kevlar fibres relaxation is independent of the stress level applied [110].

To improve stress relaxation modulus of polymers, rigid fillers can be added, to decrease it elastomeric ones are a possible solution [111].

After relieving stress, recovery gives important information about elastic and anelastic recovery. Total recovery can be attained depending on the loading stress and temperature. If after removing the applied stress on the material there is an unrecovered strain to large, dimensional stability might be decreased and in more serious case it can even lead to structural failure [112–114].

As well as for the creep behaviour, composites' microstructural changes also occur for stress relaxation due to the resin giving stress/strain variation. The consequence of the exceedance of the maximum resistance by the imposed stress/strain of a composite can be the matrix/fibre debonding, the fibre breakage or the destruction of matrix interlayers between fibres. Relaxation is mainly consequence of molecular rearrangements, fibre alignments, decreased fibre/matrix bonding etc. and depends on temperature and strain/stress levels [112–114].

An example of a useful use of the knowledge of stress relaxation behaviour can be applied for bolts fastened to composites. According to Sreekala et al. [115] collecting data on this mechanism behaviour under different strain levels allows to predict the dimensional stability of load-bearing structures and the retention of force (by modulus).

Mechanical performance is fundamental to the selection of a structural material. Increasing knowledge in the wide world of mechanical properties is important as it has been seen throughout this chapter. There are many types of fibre as well as many types of matrix. The mechanical properties of many composite configurations that can have a better performance than those currently applied are still not well known. In this work a study will be made on the viscoelastic behaviour of hybrid polymeric composites made of kevlar, carbon and glass fibres. Furthermore, interlaminar behaviour and flexural strength will be analysed for the same laminate configurations. In the literature there is little information about these mechanical properties in hybrid composite materials.

Chapter 4

Materials, Equipment and Experimental Procedures

The purpose of this work is to study the mechanical properties (flexural properties and strain rate effect, interlaminar shear strength, creep and stress relaxation) of several configurations of hybrid polymer composites constituted by glass, carbon and kevlar fibres. Therefore, in this chapter the different materials used and their configurations, the manufacturing method as well as the equipment used to carry out the tests will be presented.

4.1 Sample Manufacture

Carbon fibre woven bi-directional fabric (taffeta with 195 g/m^2), glass fibre woven bi-directional fabric (taffeta with 190 g/m^2) and kevlar fibre woven bi-directional fabric (taffeta with 170 g/m^2) with an Ebalta AH 150 resin and IP 430 hardener, provided by Rebelco, were used to prepare different composite laminates.

Three groups of sample combinations each one with four stacking sequences as shown in table 4.1 were prepared by hand lay-up. Further, for the experimental tests there are three more configurations for each group to be considered as we can see in this same table, it was only necessary to turn the specimen to have these configurations with the layers in the opposite order, so the same plate was used for the two complementary stacking sequences. The "numbers" represent the quantity of layers while the "letters" C, K and G represent the carbon fibres, kevlar fibres and glass fibres, respectively. The first number and letter represent the side under compression where the loading nose acts, for example, 4G+4C means that there are four layers of glass fibres under compression and four layers of carbon fibres under traction.

Group 1	t	Group 2	t	Group 3	t
8C	1.8	8G	1.5	8K	1.9
2C+6G/6G+2C	1.6	6G+2K/2K+6G	1.6	6K+2C/2C+6K	1.9
6C+2G/2G+6C	1.7	4G+4K/4K+4G	1.7	4K+4C/4C+4K	1.9
4G+4C/4C+4G	1.7	2G+6K/6K+2G	1.8	2K+6C/6C+2K	1.8

Table 4.1: Sample stacking sequence and its correspondent approximate thickness [mm]

Each combination was placed inside a vacuum bag and putted under compression with a load of 2.5 kN during 48 hours in order to maintain a constant fibre volume fraction and a uniform laminate thickness. During the first 10 hours, a vacuum pump attached to the bag was used so that the air bubbles trapped in the composite could be eliminated. Then, following the manufacturer's datasheet recommendations [116], the plate was putt in an oven at 80°C for 5 hours for the post-cure process.

Each laminate produced had an overall dimension of 330x330xt mm^3, with an approximate thickness t presented in table 4.1.

Following the specimens' dimensions recommended by the standards for each test type [24, 25, 33, 35], specimens were cut using an automated diamond saw machine with a constant cooling system, allowing clean edges and a small dimension error.

For each experimental test and for each configuration a minimum of 6 specimens were cut in order to have greater precision in the results. That said, it makes a minimum of 126 specimens per test used.

4.2 Equipment

A Shimadzu universal testing machine presented on figure 4.1, model Autograph AGS-X, equipped with a 10 kN load cell (figure 4.2) was used for all four experimental tests. This machine was linked to the computer software Trapezium X, so that results could be collected and analysed.

Figure 4.1: Shimadzu

Figure 4.2: Shimadzu load cell

4.3 Experimental Procedures

The experimental study was performed using the specimens and equipment described previously, and carried out at room temperature.

The four mechanical tests were carried out under a 3-point bending test but had to follow some rules given by the standards. For the creep test D 2990 standard was used [33], for the strain rate and flexural test the D 790 standard [24], for the stress relaxation test the E328 standard [35] and for the interlaminar shear strength test the D 2344/D 2344M standard [25].

All four experimental tests were performed on the 21 specimens' configurations shown previously on table 4.1. Before testing, each specimen was measured with a digital caliper: width and thickness dimensions are important for the procedure and various calculations. Next, the specimen's ends were putt on two supports with the good span dimension, and then the load being applied by means of a loading nose was directly centred on the mid-point of the test specimen. For the creep, stress relaxation and strain rate tests, a span of 25 mm for laminates [8G] and 30 mm for all other laminates was applied. For the interlaminar shear stregth test all spans used were of 10 mm.

The first experimental test to be performed was the 3-point bending test for the bending properties, using a displacement rate of 2 mm/min, and the strain rate, with a displacement rate of 200, 20, 2, 0.2 and 0.02 mm/min which correspond to strain rates ($\dot{\varepsilon}$) (calculated with equation 3.5 chapter 3) of 2.84×100, $2.84\times10^{-1}\mathrm{s}^{-1}$, $2.84\times10^{-2}\mathrm{s}^{-1}$, $2.84\times10^{-3}\mathrm{s}^{-1}$ and $2.84\times10^{-4}\mathrm{s}^{-1}$ for glass fibre laminates and 2.34×100, $2.34\times10^{-1}\mathrm{s}^{-1}$, $2.34\times10^{-2}\mathrm{s}^{-1}$, $2.34\times10^{-3}\mathrm{s}^{-1}$ and $2.34\times10^{-4}\mathrm{s}^{-1}$ for carbon fibre laminates. The test was stopped manually when the stress value dropped, verifying a clear failure mode or when the maximum strain in the outer surface of the test specimen was reached. Load-deflection data was collected, the deflection being the displacement of the centre line of the sample, in the direction of the applied load during bending [24].

This test permitted us to collect the maximum bending stresses for each configurations (table A.1, appendix A) which was needed for the creep and stress relaxation tests. For these two procedures, the initial stress applied on the specimen is 50% of the values of the maximum bending stress. These values are presented on table 4.2.

Group 1	σ [MPa]	Group 2	σ [MPa]	Group 3	σ [MPa]
8C	422	8G	317	8K	189
2C+6G	298	6G+2K	348	6K+2C	200
6G+2C	347	2K+6G	233	2C+6K	245
6C+2G	327	4G+4K	323	4K+4C	234
2G+6C	410	4K+4G	166	4C+4K	320
4G+4C	393	2G+6K	233	2K+6C	315
4C+4G	319	6K+2G	166	6C+2K	323

Table 4.2: Stress applied for creep and stress relaxaton tests

As for the 3-point bending test fulfilled for the creep test on the specimens, a full load (table 4.2) was applied rapidly and smoothly on the specimens with a displacement rate of 1 mm/min until the final constant applied load was reached. After a 180 min test duration, load-displacement data was obtained with constant load values accompanied by increasing displacement values [33].

The 3-point bending stress relaxation tests were also carried out with a duration of 180 min. The specimen was subjected to an increasing load (table 4.2) until its coincident bending strain was reached. While the strain was maintained constant, the temporal drop of the stress was measured [35]. As for the two previous tests, load-displacement data was collected obtaining constant displacement values and a progressive decrease in load.

And finally, interlaminar shear strength tests performed as a 3-point bending test a displacement rate of 1mm/min was applied. The test was stopped manually when a load drop-off of 30 % was attained, a two-piece specimen failure occurred, or if the head travel exceeded the specimen nominal thickness. Load versus displacement data was collected after finishing the test [25].

Chapter 5

Results and discussion

In this chapter, the results of the experimental tests will be discussed interconnecting them with different studies already carried out by the literature. Each mechanical test will be discussed in the order in which they were performed since the bending properties, the failure modes and the interlaminar shear strength can be related to the creep and stress relaxation behaviour.

5.1 Strain rate and bending properties

As seen in chapter 3, the strain rate has an influence on the flexural behaviour and properties (stress, stiffness and strain) of a fibre-reinforced composite. As such, to prove and show this influence a brief analysis of this parameter was made in this work for full carbon composites and full glass composites since it was proven that it has the same behaviour for all the other configurations.

Figure 5.1 shows the strain rate effect on the bending properties for full glass fibre laminates. In figure a) we can see an homogenous behaviour for all curves obtained for 2.84×10-2 s^{-1} and in figure b) the increase in higher strain rates is accompanied by a noticeable increase in the bending stress and strain. This is mainly due to the strain energy of the material: at lesser strain rates the strain energy is lower than at higher strain rates [22, 117, 118]. At lower strain rates, the impact of the load applied is slow but severe and propagates itself through the matrix, weakening the laminate's interface strength leading to a less flexural strength [119]. But at a higher strain rate, the crack propagates more rapidly and linearly resulting in sudden failure leading to the increase of the strength of the composites [120]. Therefore, flexural strength is very sensitive to the strain rate.

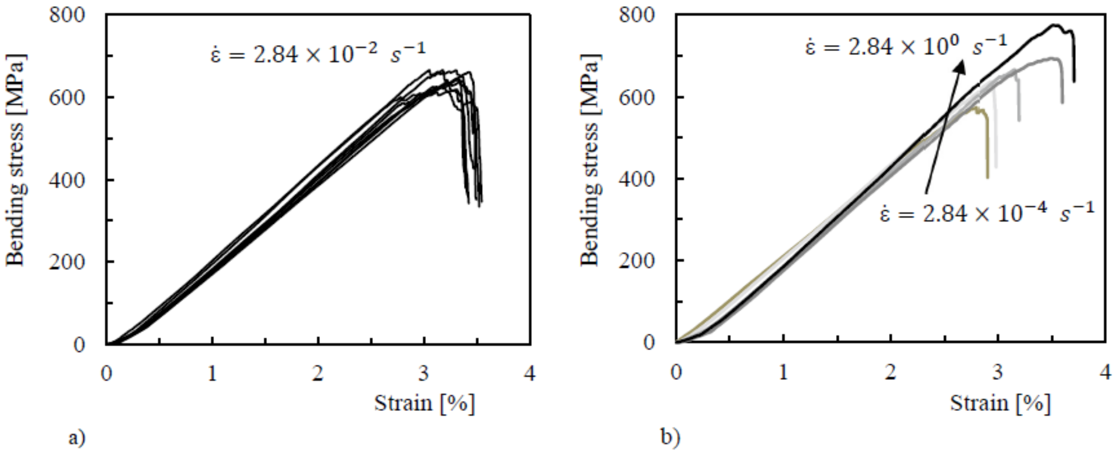

Figure 5.1: Bending stress-strain curves for glass fibre composites: a) Tested at 2.84 × 10-2 s-1; b) Representative curves of all strain rates.

Figure 5.2 presents the maximum bending stress and bending stiffness properties against the logarithm of strain rate of full carbon and full glass composites. Their average values are represented by the symbols and the horizontal lines are their respective maximum and minimum values. Independently of the material, higher strain rates lead to higher maximum bending stresses [12,22,23]. For example, the maximum bending stress for full glass fibres laminates increased 28.4%, that is from 571.3 MPa at 2.84×10^{-4} s^{-1} to 733.4 MPa at 2.84×100s^{-1}. The same occurred for full carbon fibres laminates which had an increase of 22.5%, that is an increase from 719.1 MPa to 881 MPa. Similarly for both laminate types there was an increase in the bending stiffness with the increase of the strain rate of 6.4% for full glass fibre laminates and 2.5% for full carbon fibre laminates (comparing the lower strain rate value with the higher value).

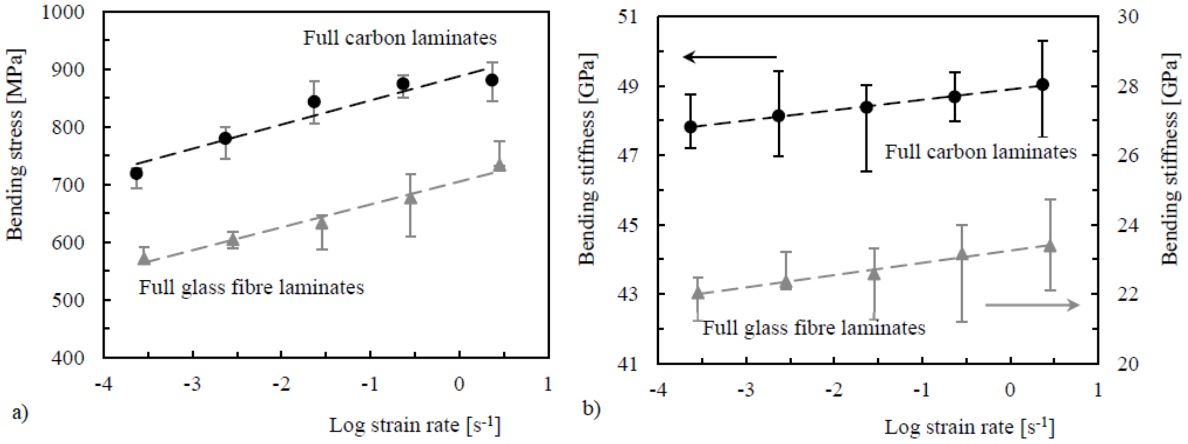

Figure 5.2: Effect of the strain rate on the: (a) Bending stress; (b) Bending stiffness.

Flexural static tests were performed in order to obtain the hybridization effect on the bending properties.

Before analysing the hybrid configurations, a brief study was made on the full fibre composite configurations, that is on the 8G, 8C and 8K laminates, to understand how each different fibre blended with epoxy reacts under 3-point bending.

Figure 5.3 represents the flexural stress-strain curves obtained for the three non-hybrid configurations (8G, 8K and 8C), completed by table 5.1 where the corresponding properties' values and standard deviations are presented. 8C and 8G curves follow a elastic regime until failure, this is a typical behaviour for brittle materials. On the other hand, 8K curve begins with an elastic regime, entering then in a plastic regime until its failure. This behaviour shows its ductile nature.

Analysing these curves, it is possible to observe that the maximum bending stress has the maximum value for the full carbon fibre composite and the lowest value for full kevlar fibre composite with a difference in percentage of 55.2%. The glass fibre composite lies between these two with 25% less bending stress value compared to the full carbon fibre composite. These results are supported by several researches [8,10,12,42,49,57] which evoked similar conclusions.

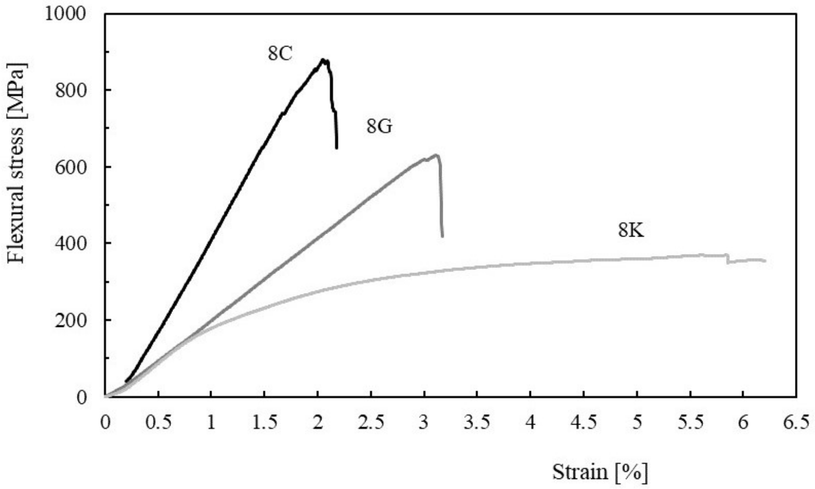

Figure 5.3: Representative Stress/Strain curves for the non-hybrid composites configurations

Laminate	Bending stress [MPa]		Bending stiffness [GPa]		Bending strain [%]	
	Average	Std Dev	Average	Std Dev	Average	Std Dev
8C	843.3	33.2	48.4	0.9	2.0	0.06
8G	632.5	11.8	22.1	0.7	3.3	0.09
8K	378.2	8.8	21.0	1.3	6.2	0.46

Table 5.1: Bending properties values of all non-hybrid composites

Due to its fragile or ductile nature, an expectable pattern can be noticed between the bending stress, bending stiffness and the bending strain of these non-hybrid composites: the higher the bending stress value, the higher the bending stiffness and the lower the bending strain. Therefore, a classification can be made where there is in first place the carbon laminate with the highest bending stress and bending stiffness value but with the lowest bending strain, which demonstrates its typical brittle nature as discussed before. This is followed by the full glass laminate with intermediate values, which also shows its brittle nature but with a higher elongation to failure compared to the carbon fibre laminate. And finally, kevlar has the lowest bending stress and bending stiffness value but the highest bending strain, which highlights its ductile nature and classifies it as a high elongation fibre [8, 10].

It is also important to enhance that a beam under 3-point bending stress has a neutral axis which separates the side under compression (where the load cell is applied) from the side under tension [10]. This leads to a different fibre behaviour and a different mechanism of failure on each side of the laminate. This can be observed in figures 5.4, 5.6 and 5.5 where the respective damage mechanisms for each composite material can be seen. Joining this microscopical pictures to the data previously presented, this can highlight and justify the results obtained. Therefore, figure 5.4 confirms the conclusions taken before since the carbon fibre laminate shows fractures under compression for high bending stresses and delamination for the tensile side, without reaching major strains. It is also visible that even delaminating under tension, this composite cannot bend due to its fragile nature and higher stiffness, and the fibres on this side would end up being fractured on this side if the test had continued.

Figure 5.4: Failure mode of a carbon fibre reinforced laminate (8C)

Glass fibre laminates in figure 5.5 shows the occurrence of delamination in the compression side and fibre and matrix cracks on the tension one. This laminate demonstrates a greater ability to bend compared to the carbon laminate. As such, observing the image it is noticeable that before fracturing in tension (this being the fracture mode that leads the laminate to reach its highest bending stress) there is a stretch of the components, this providing a greater capacity for displacement and proof a lesser stiffness.

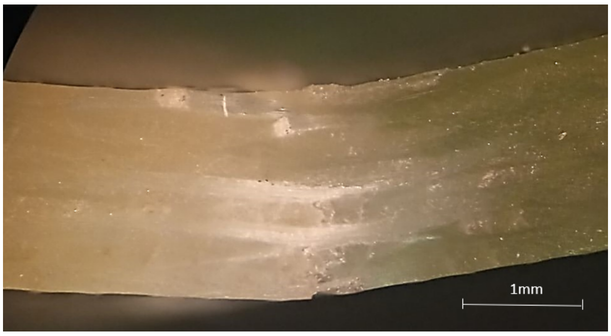

Figure 5.5: Failure mode of a glass fibre reinforced laminate (8G)

Kevlar laminates were the hardest in which a failure mode could be identified, this way picture 5.6 was chosen where a more evident damage can be observed. For the structure to crack a higher strain is needed, and the cracks are preceded by longitudinal fragmentation, splintering, and even localized drawing, which give a more ductile behaviour and the capacity for a greater strain. Kevlar is more sensitive to yielding and buckling under compression and delaminations occur in general.

Figure 5.6: Failure mode of a kevlar fibre reinforced laminate (8K)

Inserting in the same laminate with an epoxy matrix two different types of fibre and varying the number of layers of each fibre, significantly varies the mechanical properties of the laminate under bending. This will be studied in the results obtained in each of the three groups presented below.

In figure 5.7 are represented the different stress/strain curves corresponding to the different stacking configurations of layers of carbon and glass fibre in the laminate (Group 1). Their corresponding bending properties useful for its characterization are in table 5.2.

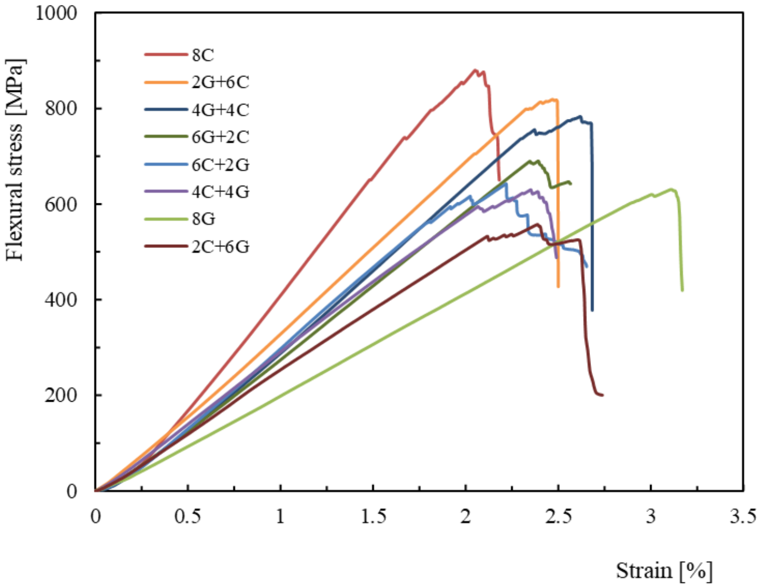

Figure 5.7: [Group 1] Representative Stress/Strain curves for carbon/glass configurations

Laminate	Bending stress [MPa]		Laminate	Bending stiffness [GPa]		Laminate	Bending strain [%]	
	Average	Std Dev		Average	Std Dev		Average	Std Dev
8C	843.3	33.2	8C	48.4	0.9	8G	3.3	0.09
2G+6C	820.0	35.0	2G+6C	38.8	0.6	4G+4C	2.59	0.08
4G+4C	785.2	20.5	6C+2G	37.4	4.4	2G+6C	2.48	0.10
6G+2C	694.6	16.8	4G+4C	34.8	1.9	6G+2C	2.47	0.07
6C+2G	652.9	27.6	4C+4G	31.9	2.8	2C+6G	2.44	0.08
4C+4G	637.2	12.8	6G+2C	30.7	1.6	4C+4G	2.38	0.09
8G	632.5	11.8	2C+6G	27.7	2.8	6C+2G	2.17	0.1
2C+6G	596.1	25.1	8G	22.1	0.7	8C	2.0	0.06

Table 5.2: [Group 1] Bending properties

Furthermore, an illustration of the different laminate configurations is represented in figure 5.8, taking into account the presence of a neutral axis that separates the compression side from the tension one. This figure is organised in function of the decrease of the bending strength, i.e. the first laminate represented (8C) corresponds to the configuration with the highest value.

Figure 5.8: Illustration of the decrease in strength in function of the evolution of the glass and carbon fibre layers in the laminate

Analysing the bending stress values, 8C has the highest ultimate strength followed by 2G+6C, 4G+4C and 6G+2C configurations which all begin with glass fibre layers. Giancaspro et al. [46] and Sudarisman et al. [52] already reported that glass fibre has better behaviour when under compression whereas carbon fibres have better behaviour when under tension. This graphic also confirms their statements. With the increase of carbon fibres on the tensile side there is an increase in the bending stress (this can also be observed in the illustration 5.8 where there is a higher concentration of carbon in the first laminates represented). This is also reliable on the conclusions of Dong et al. [54] because when there are two layers of glass fibre on the compressive side this has better flexural stress values than with four or six layers. Likewise, when carbon is under compression and glass under tension, as both fibres are not in their optimal positions, the value of the maximum strength reached by the laminate decreases with the decrease in the amount of carbon that constitutes it. This is due to the fact that carbon gives greater rigidity to the laminate. This can be verified by the bending stiffness values, which represents the resistance of the material to deformation. However, 8G configuration has a higher bending stress value than the 2C+6G one. This is certainly due to the fact that this laminate is in a fragile configuration where both types of fibre are not in the positions that favour the laminate, furthermore, it only has two layers of carbon which, under compression, quickly become damaged, failing to provide great resistance.

Fibre glass does not have as much stiffness compared to carbon, so in this parameter there are two phenomena: the more layers of carbon fibres does the laminate have, the higher is its stiffness' value, and when comparing two complementary configurations (e.g. 6G+2C and 2C+6G) the one with the G in compression and C in tension has higher values because as we saw earlier these are their fibres' optimal positions.

As for the bending strain, it appears that the configurations with fibre glass in compression and carbon fibre under tension are the ones that deform the most. However, contrary to what would be expected, the 6G+2C configuration deforms less than 4G+4C and 2G+6C. It would be expected that with the increase of glass layers there would be an increase in strain, this occurs in the following complementary configurations where 2C+6G has a greater value than 4C+4G, this one has a greater value than 6C+2G, and finally 8C is the configuration that deforms less as expected since carbon is known to be more stiff and have no plastic deformation. The fact that there is an exception in the pattern with 6G+2C could suggest that the responsible for the smallest deformation would be the two layers of carbon which, being few, would resist less to traction, previously fracturing, making the deformation smaller.

Besides, when looking at the damage pictures 5.9 and 5.10 it can be seen that the main damage is caused by the carbon fibre layers. Both in compression and tension this fibre presents an evident fracture damage and delamination. As for the glass fibre, its damages are more subtle involving a delamination under compression and the begin of a fracture under tension.

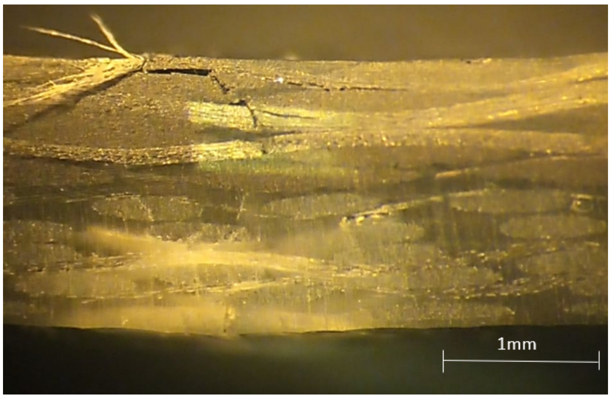

Figure 5.9: Failure mode of a Carbon/Glass (4C/4G) laminate

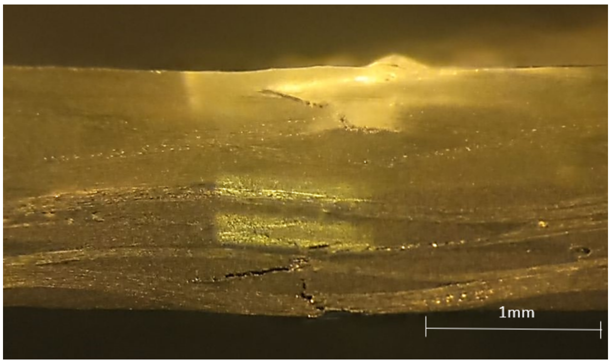

Figure 5.10: Failure mode of a Glass/Carbon (4G/4C) laminate

All this data reunited leads to the conclusion that for the hybrid laminates composed of glass and carbon fibres, when under bending, carbon layers control the stiffness of the laminate whereas the glass fibres provide a higher strain. The main failure mode being caused by the carbon layers, this demonstrates that when the hybrid laminate reaches the limit deformation for the carbon layers, they end up delaminating and fracturing before fibre glass reaches its stiffness limit.

In this group 2G+6C and 4G+4C are two hybrid configurations with great bending properties when compared to the others since they have a higher strength, higher stiffness and can bear higher deformations.

Figure 5.11 corresponds to the different stress/strain curves of the different stacking configurations composed of kevlar and glass fibre (Group 2). Their corresponding bending properties, useful for its characterization, are in table 5.3.

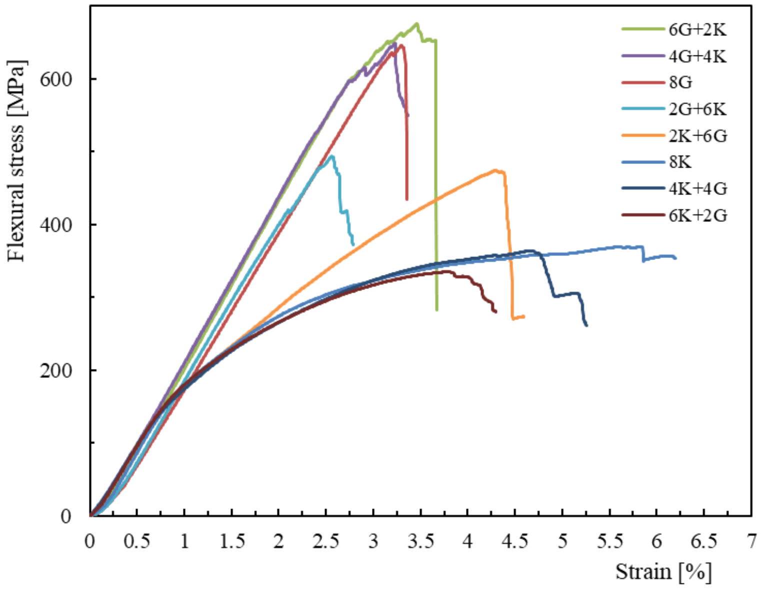

Figure 5.11: [Group 2] Representative Stress/Strain curves for kevlar/glass configurations

Laminate	Bending stress [MPa]		Laminate	Bending stiffness [GPa]		Laminate	Bending strain [%]	
	Average	Std Dev		Average	Std Dev		Average	Std Dev
6G+2K	696.5	41.2	6G+2K	23.9	1.5	8K	6.2	0.46
4G+4K	646.8	20.3	4G+4K	23.2	1.4	4K+4G	4.7	0.30
8G	632.5	11.8	2G+6K	23	1.8	2K+6G	4.4	0.08
2G+6K	500.6	14.0	8G	22.1	0.7	6K+2G	4	0.13
2K+6G	465.4	16.0	8K	21	1.3	6G+2K	3.4	0.10
8K	378.2	8.8	6K+2G	20.5	2.2	8G	3.3	0.09
4K+4G	354.1	13.1	4K+4G	19.9	1.5	4G+4K	3.2	0.16
6K+2G	332.3	7.0	2K+6G	19	0.9	2G+6K	2.4	0.22

Table 5.3: [Group 2] Bending properties

In addition, an illustration of the different laminate configurations is represented in figure 5.12. This figure is organised in function of the decrease of the bending stress, i.e. the first laminate represented (6G+2K) corresponds to the configuration with the higher bending stress.

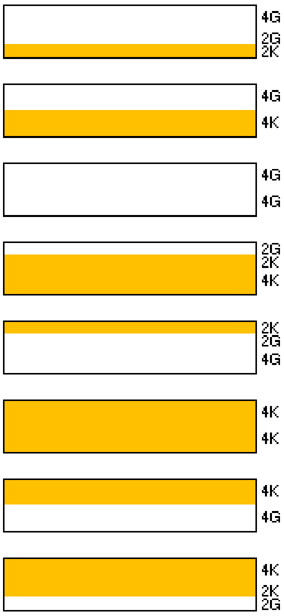

Figure 5.12: Illustration of the decrease in strength in function of the evolution of the glass and kevlar fibre layers in the laminate

In this group, it can be noticed that there are two types of behaviour in the laminates tested: half of the specimens have little strain but reach higher maximum stress and stiffness values, having a curve without plastic deformation; the other half of the specimens follow a curve with elastic deformation followed by a plastic deformation, reaching greater strains but lower values of maximum stress and stiffness.

In the first case, with higher values of ultimate strength is the 8G configuration and the configurations where the fibre glass layers are located on the compressive side while on the tension side are the Kevlar ones. In these hybrid laminates, the more layers of glass, the higher maximum stress values are achieved. The increase in fiberglass layers in compression also makes the laminate more stiff [46,50,52,53]. One of the characteristics of kevlar fibre is that in tension it is quite resistant, allowing the laminate to deform less and to withstand more stresses [57]. In these first four configurations we notice that 8G reaches higher maximum stress values than 2G+6K. By looking at the sequence illustrated in figure 5.12, it can seen that in the first two configurations (6G+2K and 4G+4K) there are four layers of fibre glass in compression, the same occurs for 8G, so it can be concluded that only two layers of fibre glass in compression makes the laminate more fragile to damage and fractures more quickly.

The second case correspond to the 8K configuration plus all the others, that is with kevlar layers under compression and glass fibre layers under tensio. These configurations deform more but reach lower maximum stress values. The more layers of kevlar there are under compression and the fewer layers of fibre glass under tension, the more quickly the material fractures, kevlar are known to have bad compression results [62], in this position it tends to bend and form microcracks making the laminate more fragile and less rigid.

The same phenomenon occurs in this group as in group 1 where 6K+2G deforms less than 4K+4G or 2K+6G when it would be expected that this configuration deforms more than the other two. By analyzing the curve of this laminate (6K+2G) it can be seen that it follows a similar trajectory as the 8K or 4K+4G curves, stopping sooner due to a stress break generated certainly by the fragility of only having two layers of glass fibre. In this group it has also been verified that the biggest deformations occur when the kevlar is under compression, but in the case of glass fibre being in this position, the more layers it has, the more the laminate deforms.

In figures 5.13 and 5.14 there is no apparent failure mode in the kevlar fibres whereas the glass fibres reveal a vertical crack on the tension side and a slight fibre crack mingled with delaminations on the compression one. These cracks may also occur due to the contact of the surface with the loading cell. This proves that the ultimate failure was caused by the glassfibre damages, these occured before it was possible for the laminate to reach a strain high enough to fail the kevlar fibres.

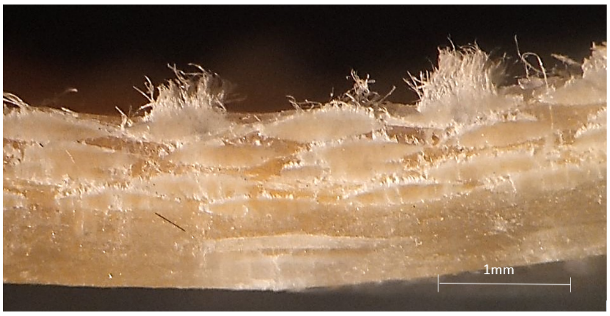

Figure 5.13: Failure mode of a Kevlar/Glass (4K/4G)

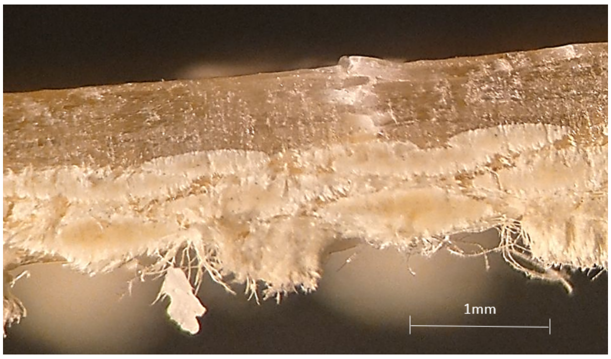

Figure 5.14: Failure mode of a Glass/Kevlar (4G/4K)

In figure 5.15 are represented the different stress/strain curves corresponding to the different stacking configurations of layers of carbon and kevlar fibre in the laminate (Group 3). Their corresponding bending properties useful for its characterization are in table 5.4.

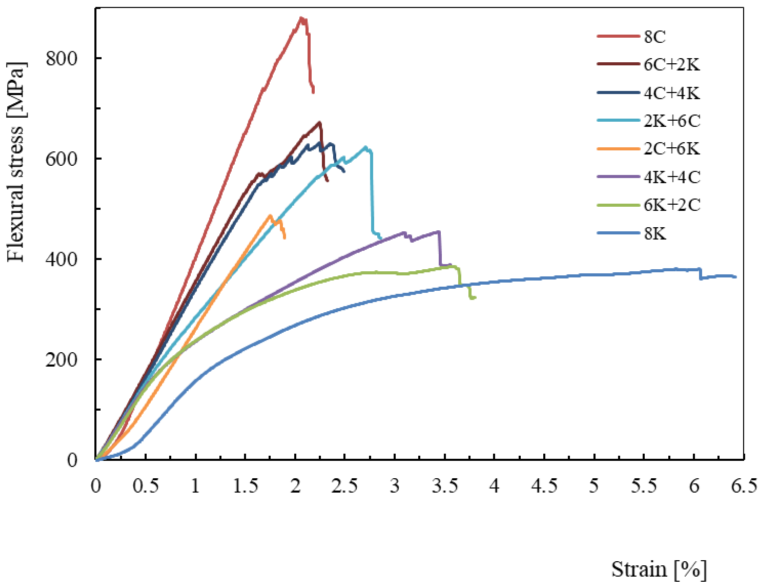

Figure 5.15: [Group 3] Representative Stress/Strain curves for kevlar/carbon configurations

Laminate	Bending stress [MPa]		Laminate	Bending stiffness [GPa]		Laminate	Bending strain [%]	
	Average	Std Dev		Average	Std Dev		Average	Std Dev
8C	843.3	33.2	8C	48.4	0.9	8K	6.2	0.46
6C+2K	644.6	32.0	6C+2K	42.5	6.0	6K+2C	3.8	0.3
4C+4K	638.7	19.0	4C+4K	34.5	2.4	4K+4C	3.4	0.18
2K+6C	629.4	32.2	2C+6K	29.9	2.9	2K+6C	2.6	0.19
2C+6K	488.8	34.7	6K+2C	29.1	3.5	6C+2K	2.04	0.20
4K+4C	471.4	18.3	4K+4C	25.6	1.8	4C+4K	2.038	0.09
6K+2C	399	20.1	2K+6C	24.2	1.8	8C	1.98	0.06
8K	378.2	8.8	8K	21	1.3	2C+6K	1.8	0.06

Table 5.4: [Group 3] Bending properties

The stress/strain curves in these graphs show two different behaviours. All configurations with carbon on compression side and kevlar on the tension one have a higher bending stress and stiffness with lower strain, but only present an elastic deformation. Besides, the increase in maximum stress and stiffness values are accompanied by an increase in the number of carbon layers in the laminate. This can also be observed in figure 5.16 where it can be seen that the percentage of carbon in the laminate tends to be higher for laminates with higher bending strength values and the percentage of kevlar in the laminate tends to be higher for lower bending strength values. As seen in group 1, in this group it is also noticeable that the configuration with only two layers of carbon in compression has different results than what it would be expected, being a more fragile configuration. The two layers of carbon under compression quickly become damaged, failing to provide great resistance. This weakness can also be seen in its results regarding strain because it is the configuration that deformed less. Carbon under compression is not very resistant and therefore the more layers it has the better is its performance. Kevlar under tension hybridized with carbon shows similar good bending properties as when hybridized with glass fibre and follows the same stacking pattern in terms of the number of plies related to the evolution of the properties. In this position the laminate deforms less with the increase of the number of its plies and withstands more stresses [7, 57].

Figure 5.16: Illustration of the decrease in strength in function of the evolution of the kevlar and carbon fibre layers in the laminate

The second behaviour type is observed on the opposite positions of the fibres in the laminate, that is, kevlar under compression and carbon under tension the curves. These show a different behaviour with an elastic deformation followed by a plastic one. There is more strain but less bending stress and stiffness. As seen in group 2, kevlar does not have good results when under compression [62] leading to the fact that the more layers there are on this side, the less is the stress that it can withstand and the higher the strain.

Failure modes presented in the microscopic figures 5.17 and 5.18 show damages on the carbon fibre plies but for the kevlar ones they are not visible and consist in delaminations. These pictures prove that for kevlar to fail a higher strain is needed, and the ultimate failure occurs in the carbon fibres since these aren't resistant to high strains.

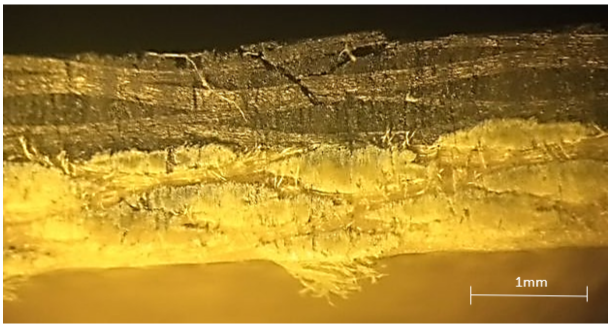

Figure 5.17: Failure mode of a Carbon/Kevlar (4C/4K)

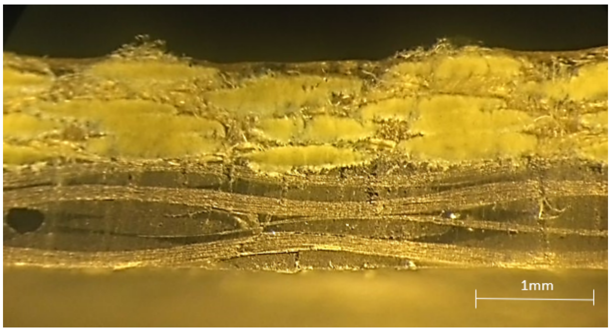

Figure 5.18: Failure mode of a Kevlar/Carbon (4K/4C)

When comparing the three groups, group 1 has the most homogeneous behaviour. In group 2 and 3 it can be seen in each figure an evident presence of two areas with two kind of curves and a gap between them separating the configurations with higher strains from the ones with higher bending stiffness and bending stress. When looking at the fibres' role in a hybrid laminate the carbon fibre always has the function of the LE fibre, whereas the kevlar fibre works as a HE fibre improving the strain of the composite when hybridized with carbon or glass fibres. Glass fibre has an intermediate comportment, when it is hybridized with carbon it is a HE fibre but when with kevlar it is a LE fibre.

Since ductility refers to the maximum strain in the stress–strain curve [10] we can say that kevlar is more ductile and glass and carbon fibres are more brittle. This can also be seen on the stress/strain curves. For the two brittle materials failure occurs at the end of the elastic regime, whereas the ductile material undergoes considerable plastic deformation before failure. Analysing the three groups we can say that hybridizing a brittle fibre with a less brittle one increased the ductility of the laminate and consequently its strain, but on the other hand the brittle fibre brought a higher strength and stiffness to the composite creating a more balanced material. Carbon and glass fibres tend to fail by brittle cracks whereas kevlar fibres fail by series of small fibril failures that absorb significant amounts of energy and are responsible for their high toughness [12, 121–124].

Using the definition of hybrid effect in terms of the failure strain exposed in chapter 2, there is a positive hybrid effect regarding the various hybrid configurations studied except for 2G+6K and 2C+6K, due to the fragility of having 2 layers of brittle fibres in contact with the loading nose resulting in failure before attaining a higher strain.

5.2 Interlaminar shear strength

ILSS depends essentially on the matrix properties and fibre/matrix interfacial shear strengths rather than the fibre properties. Full fibre laminate ILSS values are presented in table 5.6. When comparing these results, the full kevlar laminate has 46.6% lower values than carbon whereas glass has 12.7% lower values than carbon and 38.9% higher values than kevlar. These results are confirmed by literature [7, 49, 85, 87]. Kevlar is sensitive to delamination as shown on the microscopic image 5.6 and this is a critical failure mechanism, often characterized by a low interlaminar shear strength [67].

Laminate	Maximum load [N]		ILSS [MPa]		% of decrease in ILSS
	Average	Std Dev	Average	Std Dev	(8C as reference)
8C	458.8	8.28	53.6	1.29	
8G	292.4	13.71	46.8	2.15	-12.7%
8K	283.0	12.54	28.6	1.09	-46.6%

Table 5.6: Interlaminar shear strength of the non-hybrid composites and the decrease in percentage keeping 8C as reference

Hybridization can be an effective way to improve the ILSS of composites [85], therefore, the following graphs representing the several results obtained through an ILSS test on different hybrid configurations will be analysed.

Figure 5.19 and table 5.7 show the ILSS values obtained for the hybrid laminates made of glass and carbon fibres, corresponding to group 1.

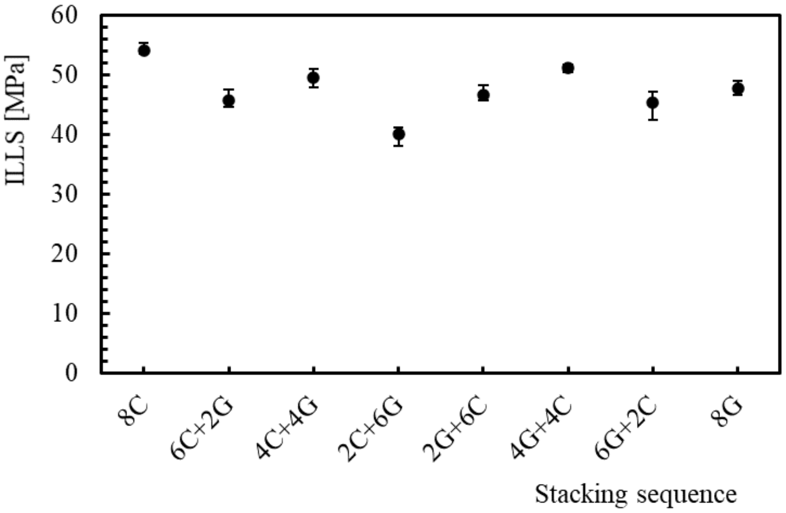

Figure 5.19: [Group 1] Interlaminar shear strength for Glass/Carbon configurations

Laminate	Maximum load [N]		ILSS [MPa]		% of decrease in ILSS
	Average	Std dev	Average	Std dev	(8C as reference)
8C	458.8	8.28	53.6	1.29	
6C+2G	370.8	12.93	45.6	1.04	-14.9%
4C+4G	321.0	12.54	48.9	1.98	-8.8%
2C+6G	220.9	16.20	39.6	2.91	-26.1%
2G+6C	367.2	13.65	46.7	0.96	-12.9%
4G+4C	336.3	3.16	51.1	0.58	-4.7%
6G+2C	253.0	12.30	45.3	2.10	-15.5%
8G	292.4	13.71	46.8	2.15	-12.7%

Table 5.7: [Group 1] Interlaminar shear strength values of carbon and glass laminates and the decrease in percentage keeping 8C as reference

Analysing this data it can be verified that the best results of ILSS correspond to the four configurations with in compression four layers of the same material and in tension equally four layers equally of the same material (8C,4C+4G,4G+4C and 8G). Researches [63–65,85] found out that glass and carbon fibres have a good bondage with an epoxy matrix and the increase in thickness of the laminate promotes the increase in ILSS [57]. This elucidates results obtained: under a certain load (compression or tension), the configurations with the ticker and the higher amount of layer of the same fibre provide a higher interface bondage. For a better image visualization, the configurations are represented in figure 5.20.

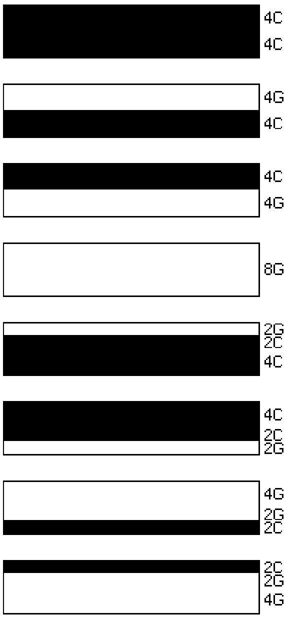

Figure 5.20: Illustration of the carbon and glass fibre configurations in descending order in terms of their ILSS results

6C+2C, 6G+2C, 2C+6G and 2G+6C are configurations with two layers of carbon and two layers of glass fibres under a same type of load leading to a lower ILSS. As observed in the flexural tests, glass fibre under compression and carbon fibre under tension are the best configurations for a hybrid laminate under a 3-point bending. This parameter also influences the ILSS results leading to a slight improvement in the results of the 4G+4C laminate compared to the 4C+4G one. The same occurs for the other complementary configurations, 2G+6C wins over 6C+2G and 6G+2C wins over 2C+6G. Being so, under bending, the bondage between fibres, matrix and interface is better for glass fibre when it is under compression and for carbon fibre when it is under tension. The stress/strain curves in the flexural tests also showed that carbon fibres, when only having two layers, easily damages. Since the ILSS specimens were slightly bended, the same occurs for ILSS where the two laminates with the worst result are 6G+2C and 2C+6G, and since carbon is fragile in compression, 2C+6G is the configuration with the lowest ILSS values.

In this group ILSS is only shown to be beneficial for 4C+4G and 4G+4C configurations. As both carbon and glass are brittle materials, the number of layers of the same material under the same type of tension shows to have great relevance for a good interface. If the laminate has four layers with two different fibres under the same tension, the interlaminar bond is weaker.

The group 2 results correspond to figure 5.21 and table 5.8 with laminates made of glass and kevlar fibres. The ILSS values are generally higher for the configurations with glass on the compression side and kevlar on the tension one. This configuration results' conclusion is similar to the ones collected in the stress/strain curves of the flexural tests: the way each fibre bend and generates damage influences the fibre/matrix and interface bondage. In bending and under compression, when hybridized with kevlar, glass fibre shows to have a stronger fibre, matrix, and interface bondage whereas kevlar under tension generates less delaminations or cracks than if it was under compression. In this case, hybridization of kevlar with glass generates a better interlaminar strength but a full glass laminate has always better results.

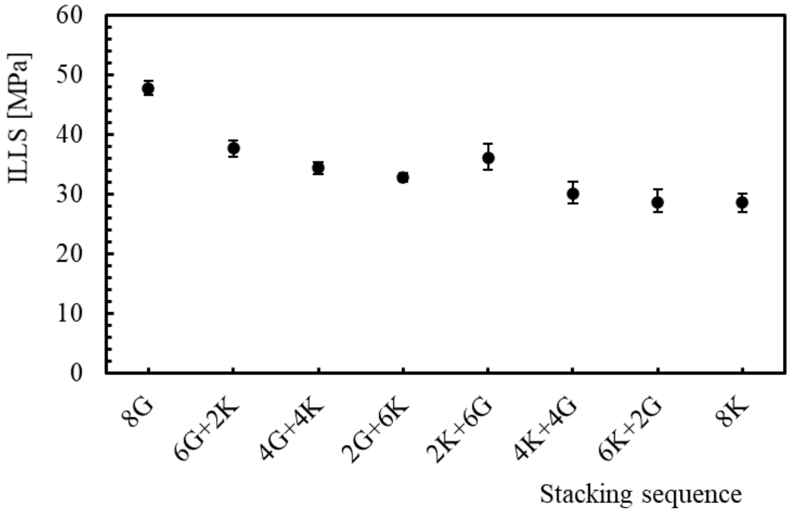

Figure 5.21: [Group 2] Interlaminar shear strength for Kevlar/Glass configurations

Laminate	Maximum load [N]		ILSS [MPa]		% of decrease in ILSS (8G as reference)
	Average	Std dev	Average	Std dev	
8G	292.4	13.71	46.8	2.15	
6G+2K	283.7	8.51	37.6	1.15	-19.7%
4G+4K	299.2	7.10	34.4	0.81	-26.5%
2G+6K	293.8	10.51	32.5	0.98	-30.6%
2K+6G	257.6	29.33	34.5	4.05	-26.3%
4K+4G	267.1	15.78	30.8	2.22	-34.2%
6K+2G	298.4	31.26	33.2	3.21	-29.1%
8K	283.0	12.54	28.6	1.09	-38.9%

Table 5.8: [Group 2] Interlaminar shear strength values of kevlar and glass laminates and the decrease in percentage keeping 8G as reference

Graph 5.21 also shows that the increase of the number of plies of glass in the laminate generates a higher ILSS independently of its position. The same phenomenon can be observed in figure 5.22 where the higher the percentage of kevlar in the laminate the lower the ILSS and therefore the higher the percentage of glass in the laminate, the higher the ILSS. Kevlar is known by literature [7, 87] to have a weak interface with matrix and glass fibre to have a good matrix adhesion leading to the increase of the ILSS.

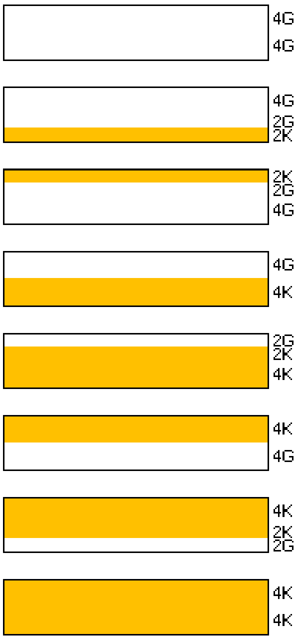

Figure 5.22: Illustration of the kevlar and glass fibre configurations in descending order in terms of their ILSS results

In this group the first condition to influence the laminate's response to the ILSS test is the percentage of glass fibre in the composite and secondly its position in the laminate.

In group 3, graph 5.23 and figure 5.24 are the ILSS results for the carbon and kevlar laminates. In this group, carbon fibre showed to have a better ILSS when under compression when hybridized with kevlar whereas kevlar has shown to resist better to damages when under tension leading to a stiffer laminate as seen in the flexural tests. The increase of the number of plies of carbon in the laminate also generates a higher ILSS independently of its position. The same phenomenon can be observed in figure 5.24 where the higher the percentage of kevlar in the laminate the lower the ILSS and therefore the higher the percentage of carbon in the laminate, the higher the ILSS.

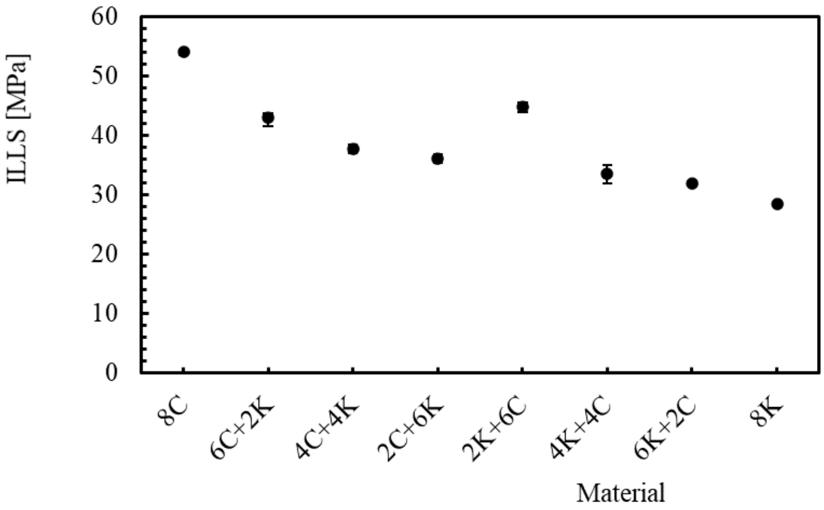

Figure 5.23: [Group 3] Interlaminar shear strength for Kevlar/Carbon configurations

Laminate	Maximum load [N]		ILSS [Mpa]		% of decrease in ILSS (8C as reference)
	Average	Std Dev	Average	Std Dev	
8C	458.8	8.28	53.6	1.29	
6C+2K	386.9	15.46	42.5	1.53	-20.7%
4C+4K	354.5	16.47	37	1.69	-31.0%
2C+6K	350.4	4.95	36.2	0.82	-32.5%
2K+6C	403.3	7.08	44.8	0.58	-16.4%
4K+4C	327.6	17.52	34.5	1.57	-35.6%
6K+2C	309.2	5.00	31.9	0.7	-40.5%
8K	283.0	12.54	28.6	1.09	-46.6%

Table 5.9: [Group 3] Interlaminar shear strength values of carbon and kevlar laminates and the decrease in percentage keeping 8K as reference

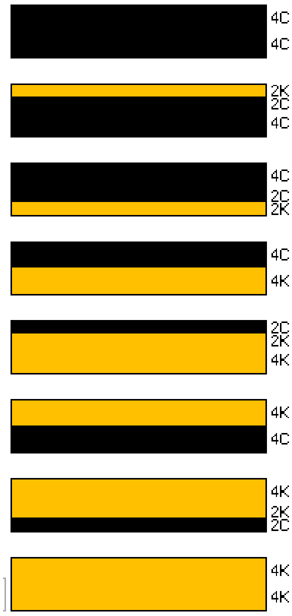

Figure 5.24: Illustration of the kevlar and carbon fibre configurations in descending order in terms of their ILSS results

Reuniting all three groups for conclusions, in a hybridized laminate carbon and glass fibres have shown to bring a stronger bondage between all elements in the composite whereas kevlar always showed a weak matrix adhesion. Therefore, the smaller the amount of kevlar in the hybrid composite the better is its ILSS. Involving the fibres' position in the hybrid laminate, glass under compression and kevlar under tension always brings better results. Unlike the previous two fibres, carbon fibre's position depends on the other fibre with which it forms a laminate. With Kevlar it has better results under compression but with glass it works better under tension. These results can be related to the previous studied test, in which it has been concluded that these same fibres' positions in the laminate provided better bending properties. With a better ILSS there is also a better bending stiffness. Nonetheless, a high ILSS is not always desirable. Glass and carbon fibres are brittle fibres and kevlar are ductile ones. Thus, brittle materials tend to crack creating a path that pass-through fibre and matrix, on the other hand for ductile materials delaminate more. A material with an intermediate ILSS has cracks that follow a path that goes through the weak regions forming delaminations, which give a more tough behaviour to the composite [9, 67].

Unlike in Turla et al.'s work [85] in which hybridization always improved the ILSS, in this ILSS tests it was verified that for kevlar laminates hybridized with glass or carbon, the ILSS always improved (keeping full kevlar laminate as reference), however the same did not occur when assuming full carbon laminate as a reference since it has the higher ILSS value. This difference with Turla et al.'s work [85] shows that stacking sequence, number of plies and the difference in fibre orientation have a major influence in the ILSS results.

5.3 Creep behaviour

Concerning the creep behaviour, figures 5.25, 5.26, 5.27 and 5.28 show typical curves obtained from the experimental tests, where the displacement is the value obtained at any instant of the test divided by its initial value. When under creep, materials go through several stages [33] as explained in chapter 3. Stress and strain levels vary during creep and the stiffness decreases [31, 101, 102]. In this work, the materials only passed through the primary and secondary stages, the test ending before it could evolute through the tertiary one. After the initial elongation, strain rate decreases as strain increases, this is followed by a more steady stage in which strain adopts a minimum and relatively uniform rate.

Figure 5.25 represents the creep curves obtained for the non-hybrid laminates.

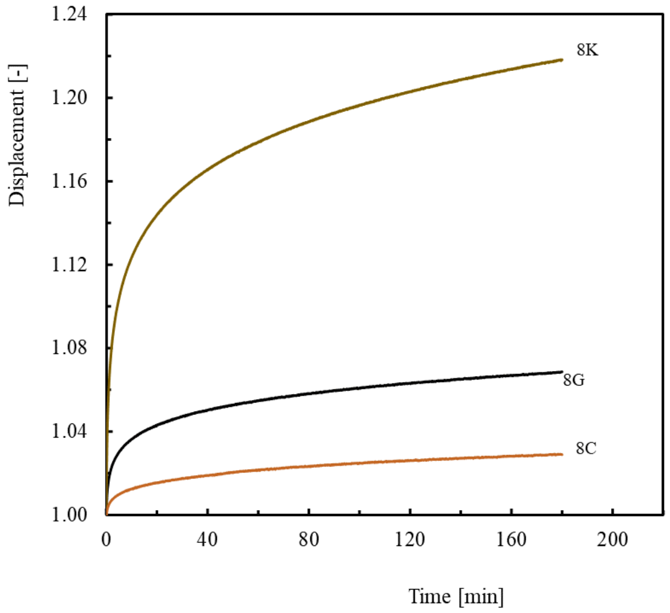

Figure 5.25: Creep of the carbon, glass and kevlar configurations

This graph shows that there is an evident gap between the kevlar laminate's displacement and the one of full carbon or full glass laminates. Compared to its initial porition, kevlar's displacement is about 21.8% whereas full glass fibre laminates have 6.9% of displacement and full carbon fibre only 2.9%. As we saw in the previous experimental test, kevlar fibres have lower ILSS, followed by glass fibres and the highest values goes to carbon fibres. This parameter is important because the creep displacement is controlled by the bonds' breakage and their propagation [30, 98, 99]. Kevlar is also a high strain fibre with a polymeric nature making it more sensitive to creep [125, 126] as well as the stiffer nature of carbon and glass fibres makes them more creep resistant.

Group 1, in figure 5.26, show the time-dependent displacement curves of the carbon and glass fibre hybrid laminates and its correspondent displacement percentage and standard deviations.

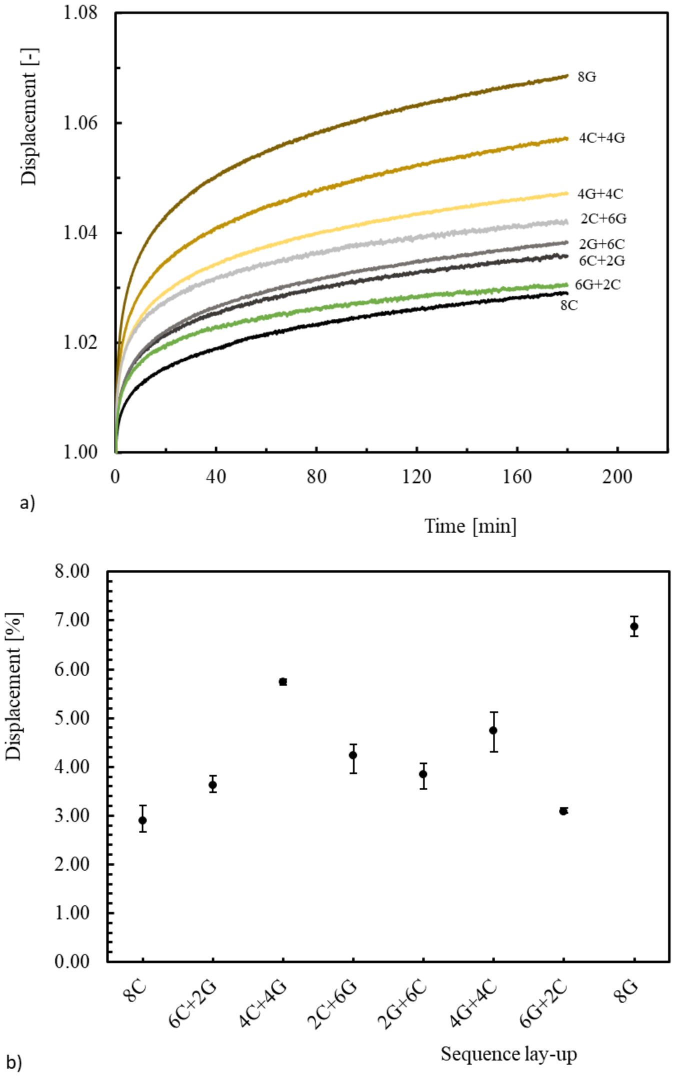

Figure 5.26: [Group 1] Creep for Carbon/Glass configurations: a) creep curves; b) average values and standard deviations

For these configurations, it was noticed that creep differences weren't very significant, varying very little from one hybrid configuration to another. For example, the creep displacement of the 4C+4G configuration, which is the laminate with the highest value, has only a 2.7% higher value compared with the 6G+2C configuration, which is the hybrid configuration to have the lowest value. Creep response of a laminate made of carbon and glass fibres seem to depend strongly on the number of layers of a same fibre in the laminate. When involving the stacking sequence, 4G+4C and 4C+4G have the higher creep whereas all the other configurations with six plies of carbon fibre or glass fibre have a lower creep. Additionally, six layers on the side of the loading nose provide less creep than the six layers on the tensile side. These creep tests are conducted under bending, this way the fibres' behaviour over time are influenced by the type of load imposed on them. This way, in terms of fibre type position, like for the ILSS tests, the best results correspond to glass fibre under compression and carbon fibre under tension. This way 6G+2C wins over 6C+2G, and the same occurs for 2G+6C and 2C+6G, and 4G+4C and 4C+4G.

In group 2, figure 5.27 shows the time- dependent displacement of the kevlar and glass hybrid laminates and their displacements' percentage and standard deviations.

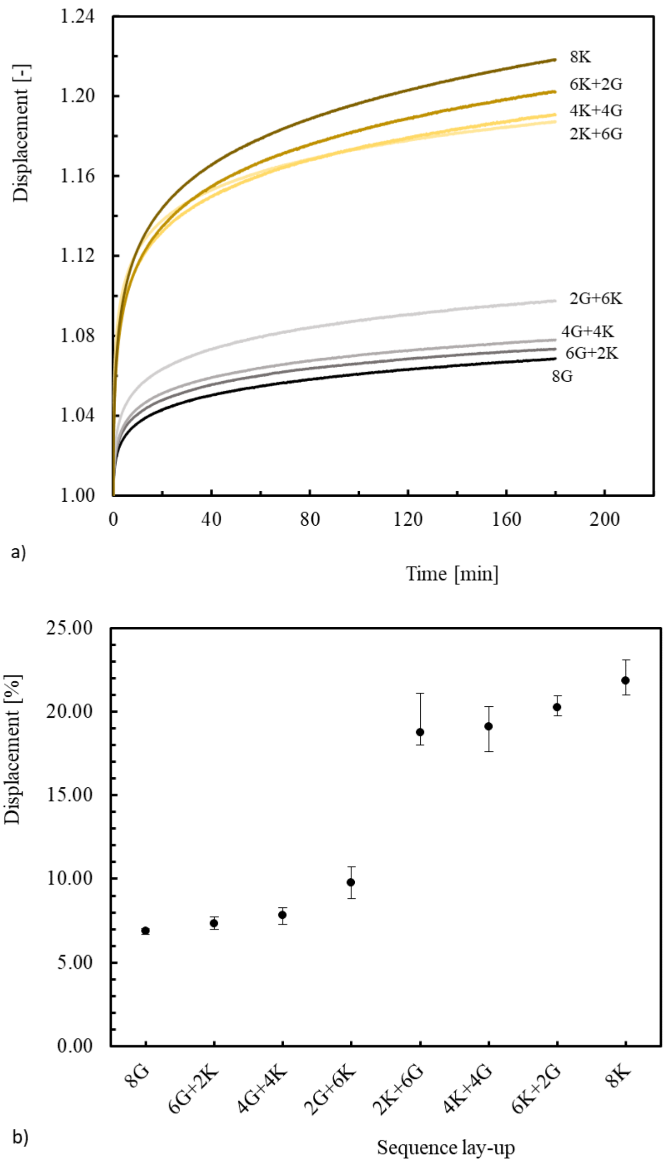

Figure 5.27: [Group 2] Creep for Kevlar/Glass configurations: a) creep curves; b) average values and standard deviations

In this graph there is a significant gap between all the configurations with glass fibre on the compression side and the configurations with it on the tensile side (a difference of 9% displacement between 2K+6G and 2G+6K configurations). This difference is due to the fibre, matrix and interface bondage [30, 98, 99, 102] and this depends strongly on each fibres' position in function of its different behaviour under tension and compression. A good bondage brings more stiffness to the laminate leading to less creep. The ILSS tests demonstrated that fibres and matrix bondage and stiffness were generally higher for the configurations with glass on the compression side and kevlar on the tension one, and the increase of the kevlar's layers in the laminate led to a decrease in ILSS. Therefore, configurations with kevlar on the compression side have a higher displacement than when on the tension one [56, 62] and the increase of its plies in the laminate also lead to an increase in creep independently of its position in the laminate [57].

Group 3, in figure 5.28, show the time-dependent displacement curves of the carbon and kevlar fibre hybrid laminates and its correspondent displacement percentage and standard deviations.

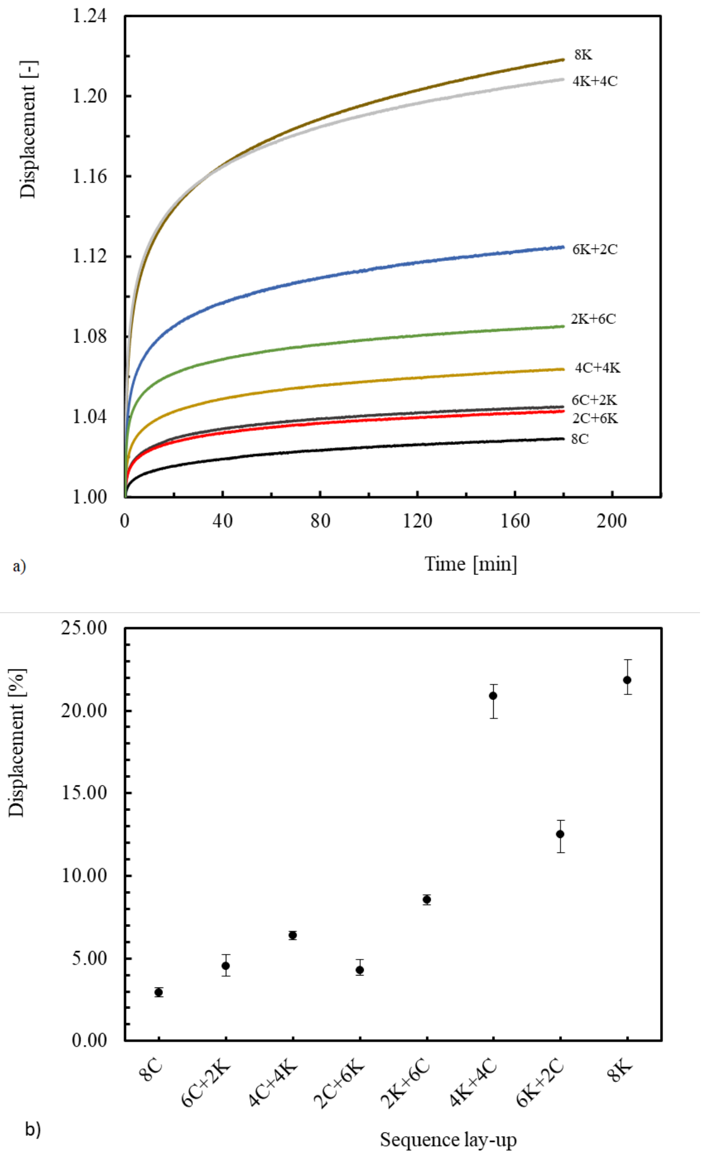

Figure 5.28: [Group 3] Creep for Kevlar/Carbon configurations: a) creep curves; b) average values and standard deviations

In hybrid laminates, two factors influence their creep behaviour: the first factor to be considered will be the position of each fibre and then, the second one consists in the number of layers of each fibre in the laminate. When observing the evolution of the creep curves in correlation with the fibres position, the configurations with less displacement correspond to the ones with carbon fibres under compression and kevlar fibres under tension. Kevlar's ILSS values are also lower if it is under compression leading to a weak interfacial strength and consequently to a easy propagation of microcracking, buckling and debonding that leads to a higher displacement [98, 99]. Carbon also is a fibre with negligible viscoelastic behaviour as reported before which explains this creep results, contributing to the lower elastic deformation. When studying the number of plies'influence in creep, whether carbon fibres are in compression or tension, configurations 4K+4C and 4C+4K are always the ones that deform the most. Having six layers of a same fibre seems to give less displacement.

The viscoelastic behaviour of hybrid laminates in these creep results established that fibres' position and its percentage in the laminate are major influenceable parameters. This is essentially due to the way fibres bond with the matrix. Glass fibres hybridized with carbon or kevlar fibres, show always less creep if on the compressive side whereas kevlar fibres give better results to the laminate if under tension. Carbon fibres' position in the laminate for less creep depends on the other fibre with which they are hybridized. If with glass fibres, the best results of creep correspond to its position on the tension side, but if hybridized with kevlar, the laminate has a better behaviour with it on the compressive one. When analysing the number of plies influence in the results obtained, these results do not always coincide with the ones obtained in the ILSS tests. As such, molecular rearrangements and stress and strain variations also have an impact on each configuration's behaviour [62, 106, 112–115].

5.4 Stress relaxation behaviour

Figures 5.29 represents the stress relaxation curve of the non-hybrid composites while figures 5.30, 5.31 and 5.32 represent the stress relaxation curves deviations of the hybrid ones and the percentage of its average values and standard deviations. These figures plot the average bending stress versus time, where σ is the bending stress at any given moment of the test and σ_0 is the initial bending stress. For all laminates, a pattern was noticed: there is a decrease from an initial value (σ_0) to one that is not yet constant due to the short duration of these tests. We can also notice two phases in the curves: an initial rapid decrease in stress, described in literature as an initial regime [48,127], followed by a slower and smooth one.

From figure 5.29 it can be observed that full kevlar composites are more sensitive to stress relaxation than full glass composites or full carbon, this last one being the ones with less sensitive values for this test. After 180 min. it was noticed a decrease of 16.2% in stress for the kevlar composites, 12.7% for glass composites whereas for carbon ones the decrease was only of 3.2%. These viscoelastic behaviour have also been verified in some researches, especially involving carbon and glass fibres [12, 62, 107, 114, 128]. Kevlar fibres have a polymeric nature [125,126] making them more sensitive to stress relaxation. Composites' microstructural changes occur for stress relaxation due to the resin giving stress/strain variation leading to bonds breaking and their propagation, molecular rearrangements, fibre alignments, etc. [12, 112–114]. Therefore there is a correlation of these results with the ones obtained previously in the ILSS tests [62, 106, 115]. These proved that kevlar has a low ILSS while, on the other hand, carbon and glass fibre laminates have higher ILSS.

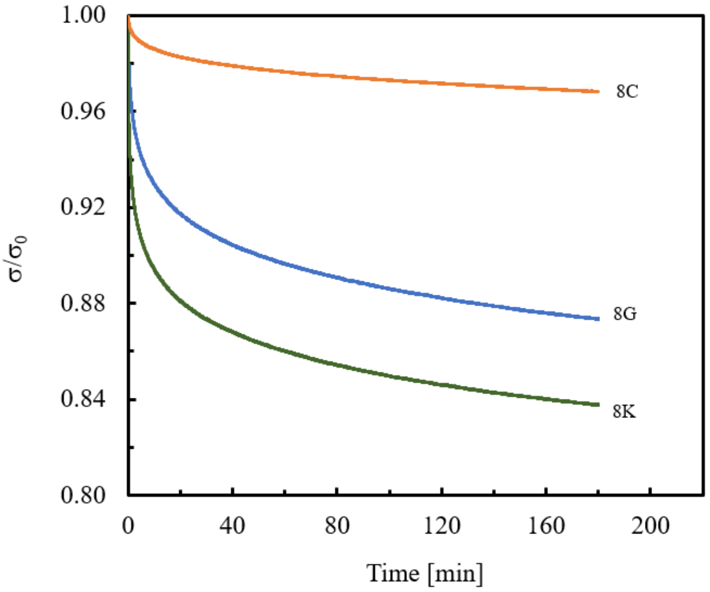

Figure 5.29: Stress Relaxation of the carbon, glass and kevlar configurations

When incorporating other fibres in the laminate, stress relaxation changes occur. Hybridization response to this mechanical property show to depend on more factors besides the ILSS like the adaptation at the molecular level of the fibres and the matrix, the fibres position in the laminate and its number of plies. This will be seen in the following three groups.

Group 1 is represented in figure 5.30. These two plots show the stress relaxation curves of the carbon and glass fibre hybrid laminates and its correspondent stress relaxation percentage and standard deviations. In this group, hybridization of glass with carbon increases stress relaxation in comparation with the full carbon fibre laminate. Stress relaxation differences weren't very significant, varying very little from one hybrid configuration to another (2.6% stress relaxation increase from 6G+2C to 4C+4G, which are respectively the configuration with the less relaxation and the one with the highest amount of relaxation). In complementary laminates (for example, 6C+2G and 2G+6C), the one who always has the best results corresponds to the one with glass fibres under compression and carbon fibres under tension. In such laminates, fibres are in their optimal positions and have a stronger fibre/matrix bond.

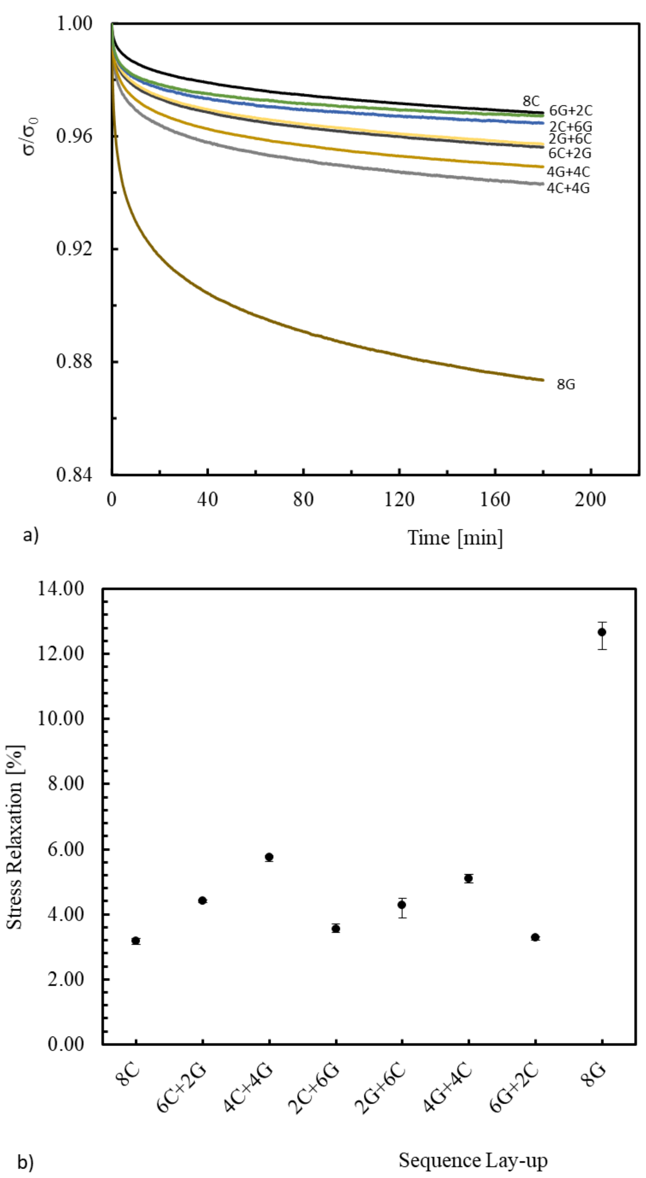

Figure 5.30: [Group 1] Stress relaxation for Glass/Carbon configurations: a) stress relaxation curves; b) average values and standard deviations

Including the stacking sequence, 4G+4C and 4C+4G are the configurations with higher stress relaxation whereas all the other configurations with six plies of carbon fibre or glass fibre have a lower value, but with a very low stress relaxation percentage of difference from each other. Within the laminates with six plies, the ones with six layers of glass fibres have less stress relaxation than the ones with six layers of carbon. However, ILSS results showed how 4G+4C and 4C+4G have a stronger fibre and matrix bondage compared to all the other hybrid configurations. As such, the reason for these variations are at molecular level involving the fibre and matrix rearrangements and adaptation.

Group 2 is represented in figure 5.31. These two plots show the stress relaxation curves of the kevlar and glass fibre hybrid laminates and its correspondent stress relaxation percentage and standard deviations.

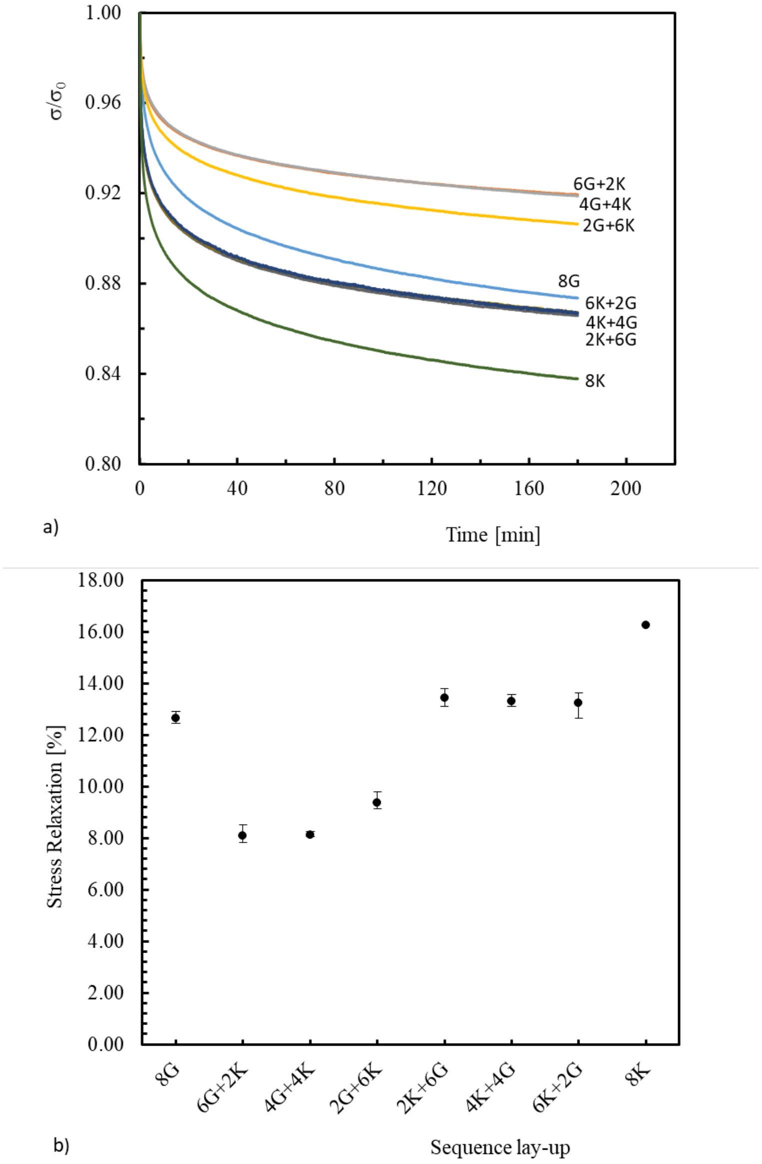

Figure 5.31: [Group 2] Stress relaxation for Kevlar/Glass configurations: a) stress relaxation curves; b) average values and standard deviations

In this group, there is an evident dependence between the position of the fibres in compression or tension and the amount of relaxation that occurs. The gap between the two types of fibre disposition is about 3.9% (comparing 2G+6K and 6K+2G). Thus, stress relaxation is lower when adding glass fibres on the compression side and kevlar on the tensile one. These are these fibres' optimal positions in a laminate providing the best mechanical properties. The increase of glass fibres on the compressive side reduces the stress relaxation, but if this fibre is on the tension side, then, if its plies number increase the stress relaxation increases as well.

Group 3 is represented in figure 5.32. These two plots show the stress relaxation curves of the carbon and kevlar fibre hybrid laminates and its correspondent stress relaxation percentage and standard deviations.

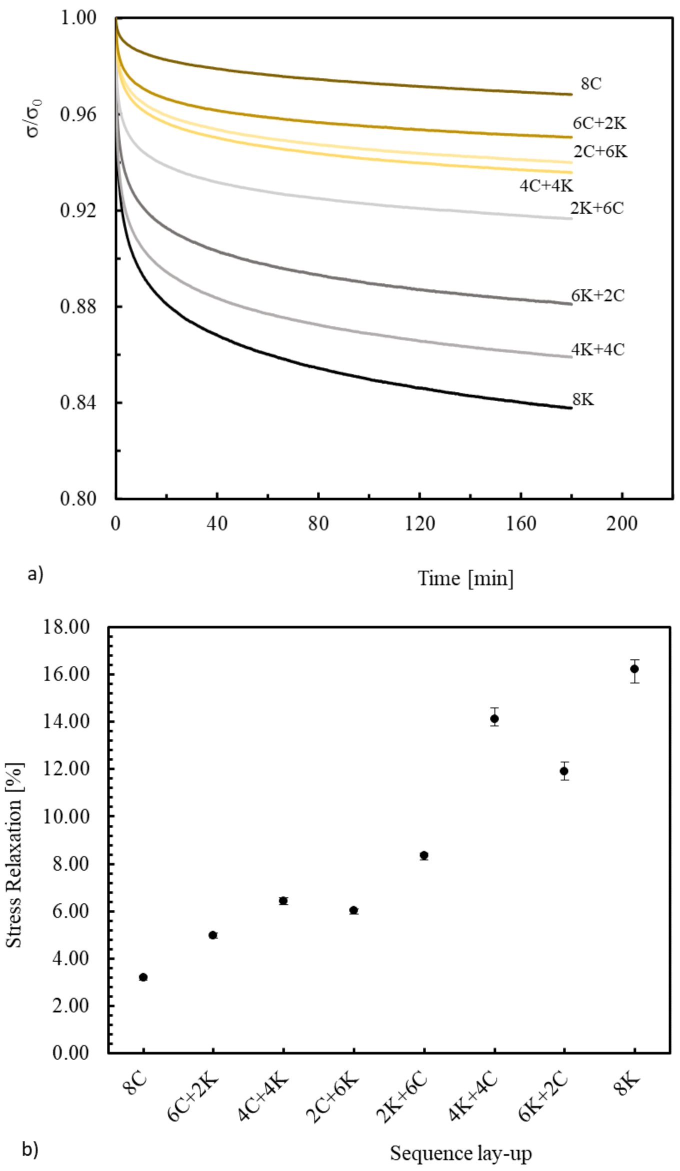

Figure 5.32: [Group 3] Stress relaxation for Kevlar/Carbon configurations: a) stress relaxation curves; b) average values and standard deviations

The first parameter in this group that separates laminates in terms of their behaviour under constant deformation is the position of each fibre in the laminate. The configurations with less stress relaxation are the ones with carbon fibres on the compressive side and kevlar fibres under tension. This fibre disposition also corresponds to the laminates with higher stiffness and ILSS. Besides, all laminates with this configuration have a homogenous behaviour varying very little from one laminate to another (4C+4K has 1.5% more relaxation than 6C+2K). However, if kevlar is on the compression side and carbon on the tension one, the difference between each one of these laminates is significant, 2K+6C has 5.8% more relaxation than 4K+4C. The second parameter to consider, taking into account the division of the laminates already made by the first one, is the evolution of the number of layers of each fibre in the laminate as stress relaxation rises. 4C+4K and 4K+4C have always more relaxation than if there are six layers of carbon or kevlar fibres in the composite. This also happens during creep tests.

Like for creep behaviour, these stress relaxation tests have shown that a good fibre/matrix bonding is essential to decrease the stress relaxation [62, 106, 115]. The ILSS values obtained previously have an influence on the configuration's behaviour under stress relaxation in terms of each fibres' position in the laminate. Independently of the other fibre with which they are hybridized, glass fibres provide always less relaxation if on the compressive side whereas kevlar fibres give better results to the laminate if under tension. Carbon fibres' position in the laminate depends of the other fibre with which they are hybridized. If with glass fibres, the best results of stress relaxation correspond to its position on the tension side, but if hybridized with kevlar, the laminate has a better behaviour with it on the compression one. When analysing the number of plies influence in the results obtained, these results do not always coincide with the ones obtained in the ILSS tests. As such, molecular rearrangements and stress and strain variations also have an impact on each configuration's behaviour [62, 106, 112–115].

Chapter 6

Final conclusions

Hybridization is a promising strategy to obtain a better balance of mechanical properties compared to non-hybrid composites. Regardless of the various published works, knowledge is not fully consolidated for more complex loading conditions, or the available information is contradictory. Therefore, the main goal of this study was to analyse the bending and interlaminar shear strength of hybrid composites as well as its viscoelastic behaviour through creep and stress relaxation tests. A brief strain rate study was also carried out in order to understand how this property affects the performance of the laminate under different load rates. For this purpose, carbon, glass and kevlar fibres were combined with different fibre contents and placed in very specific positions. From this study, it was possible to conclude that:

- The strain rate experimental test showed that flexural stiffness and flexural strength of composites increases with the increasing of the strain rate, this phenomenon being independent of the type of material used.

- For non-hybrid composites, the maximum bending stress and modulus were obtained for the carbon/epoxy composite, while the bending strain was the smallest. In the opposite side, the kevlar/epoxy composite showed the lowest bending stress and modulus, while the bending strain had the highest value. The response of the glass/epoxy composite was between these two. These results were explained by the intrinsic properties of the composites' constituents and by the damage mechanisms that proved to be very specific for each laminate. The interlaminar shear strength followed the same trend, with the highest ILSS value for the carbon/epoxy composite and the lowest for the kevlar/epoxy composite. And finally, creep and stress relaxation behaviours, which are infleunced by ILSS and by the fragile or ductile nature of each fibre type, also showed higher values for the kevlar/epoxy composite and lower values for the carbon/epoxy one.

- Regarding the hybridization effect on the bending response, the highest values were obtained for composites involving carbon and glass fibres, with the latter placed on the compression side. On the other hand, regardless of the fibre type, the results were very similar when kevlar fibres were placed on the traction side, showing their excellent tensile behaviour. The results obtained for these configurations are also very similar to those observed for the composite involving carbon and glass fibres, but with the latter positioned on the tensile side. This proves the poor compression performance of the carbon fibres. Finally, the highest ILSS values were obtained for the composite involving carbon and glass fibres, while the lowest ILSS values were obtained for composites involving kevlar fibres. The recognized good adhesion of carbon and glass fibres to epoxy matrices and the poor adhesion of kevlar fibres justify the results obtained. Furthermore, it was observed that the fibre content and its positioning in the laminate affect both flexural strength and interlaminar shear strength, evidencing that these properties may be related. Creep and stress relaxation also showed lower values for carbon or glass under compression and kevlar under tension. These results were related to a higher ILSS and a higher stiffness. The effect of the fibres' content on these two properties didn't lead to the conclusion of the influence of molecular rearrangements.

6.1 Future works

This study was carried out at room temperature, but during service, aircrafts structures go through temperature and moisture variations. Therefore, making a research on the effect of these parameters on the viscoelastic behaviour of the same fibre-reinforced composites configurations as the ones used in this work would be an interesting subject. These experimental works should be supported by numerical studies in order to obtain cheaper and faster results. In this context, it is suggested to develop numerical tools capable of predicting the hybridization effect on viscoelastic behavior. It is also suggested that an optimization study of the number of layers be carried out to obtain a better viscoelastic performance of the laminates. A numerical tool can also be used to optimize this laminate layout.

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Appendix A

Appendix

A.1 Bending properties values

	Laminate	Bending stress [MPa]		Bending stiffness [GPa]		Bending strain [%]	
		Average	Std Dev	Average	Std Dev	Average	Std Dev
Group 1	8C	843.3	33.2	48.4	0.9	2.0	0.06
	2C+6G	596.1	25.1	27.7	2.8	2.5	0.08
	6G+2C	694.6	16.8	30.7	1.6	2.4	0.07
	6C+2G	652.9	27.6	37.4	4.4	2.2	0.1
	2G+6C	820.0	35.0	38.8	0.6	2.5	0.10
	4G+4C	785.2	20.5	34.8	1.9	2.6	0.08
	4C+4G	637.2	12.8	31.9	2.8	2.4	0.09
Group 2	8G	632.5	11.8	22.1	0.7	3.3	0.09
	2G+6K	500.6	14.0	23.9	1.8	2.4	0.22
	6K+2G	332.3	7.0	20.5	2.2	4.0	0.13
	6G+2K	696.5	41.2	23.3	1.5	3.4	0.10
	2K+6G	465.4	16.0	19.0	0.9	4.4	0.08
	4K+4G	354.1	13.1	19.9	1.5	4.6	0.30
	4G+4K	646.8	20.3	23.2	1.4	3.2	0.16
Group 3	8K	378.2	8.8	21.0	1.3	6.2	0.46
	6K+2C	399.0	20.1	29.1	3.5	3.8	0.3
	2C+6K	488.8	34.7	29.9	2.9	1.8	0.06
	2K+6C	629.4	32.2	24.2	1.8	2.6	0.19
	6C+2K	644.6	32.0	42.5	6.0	2.0	0.20
	4K+4C	471.4	18.3	25.6	1.8	3.4	0.18
	4C+4K	638.7	19.0	34.5	2.4	2.04	0.09

Table A.1: Bending properties of all hybrid composites