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TÍTULO DEL TFG: Development of a methodology for the characterization of long-fibre composite materials for crashworthiness applications using CAE

TITULACIÓN: Degree in Aerospace Systems Engineering

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Overview

Composite materials have received a great deal of attention in recent years because of their exceptional mechanical properties and light weight, which make them suitable for a variety of engineering applications. One of these applications is crashworthiness, which refers to the ability of a structure to absorb energy during a crash, thus protecting occupants and minimising damage to the vehicle. In this context, the development of a methodology for the characterisation of long fibre composite materials using computer-aided engineering (CAE) is of vital importance.

The use of CAE tools has revolutionised the process of design and analysis of engineering structures, offering significant advantages such as cost and time savings, increased accuracy and the ability to simulate complex loading scenarios. By harnessing the power of CAE, engineers can perform virtual testing and analysis of composite structures, enabling a better understanding of their behaviour and performance under crash conditions.

The goal of this research is to develop a comprehensive methodology for the characterisation of long fibre composite materials specifically tailored to crashworthiness applications. The methodology will include experimental tests previously performed in-house, together with numerical simulations using CAE techniques. By combining these two approaches, a comprehensive understanding of the material behaviour and its response to shock loading can be achieved.

The characterisation process will involve the selection of suitable composite materials, taking into account factors such as fibre type, matrix material and fibre volume fraction, which are known to significantly influence the mechanical properties of the composite. Experimental tests were used to obtain essential material properties such as tensile strength, compressive strength, shear strength and fracture toughness. These properties will serve as input data for the numerical simulations.

The CAE simulations will be carried out using the finite element method (FEM), which allows virtual modelling and simulation of complex structures. By creating

an accurate representation of the composite structure and applying realistic loading conditions, the material response can be predicted.

The developed methodology will be validated with experimental results. This validation process is crucial to ensure the accuracy and reliability of the methodology. Any discrepancies between experimental and simulated results will be analysed.

Título: Desarrollo de una metodología para la caracterización de materiales compuestos de fibra larga para aplicaciones de resistencia al impacto mediante CAE

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Resumen

Los materiales compuestos han sido objeto de gran atención en los últimos años por sus excepcionales propiedades mecánicas y su ligereza, que los hacen adecuados para diversas aplicaciones de ingeniería. Una de estas aplicaciones es la resistencia a los choques, que se refiere a la capacidad de una estructura para absorber energía durante un choque, protegiendo así a los ocupantes y minimizando los daños al vehículo. En este contexto, el desarrollo de una metodología para la caracterización de materiales compuestos de fibra larga mediante ingeniería asistida por ordenador (CAE) es de vital importancia.

El uso de herramientas CAE ha revolucionado el proceso de diseño y análisis de estructuras de ingeniería, ofreciendo ventajas significativas como el ahorro de costes y tiempo, una mayor precisión y la capacidad de simular escenarios de carga complejos. Aprovechando la potencia de CAE, los ingenieros pueden realizar pruebas y análisis virtuales de estructuras de materiales compuestos, lo que permite comprender mejor su comportamiento y rendimiento en condiciones de choque.

El objetivo de esta investigación es desarrollar una metodología completa para la caracterización de materiales compuestos de fibra larga específicamente adaptada a las aplicaciones de resistencia a los choques. La metodología incluirá pruebas experimentales realizadas previamente en la empresa, junto con simulaciones numéricas mediante técnicas CAE. Combinando estos dos enfoques, puede lograrse una comprensión exhaustiva del comportamiento del material y de su respuesta a las cargas de choque.

El proceso de caracterización implicará la selección de materiales compuestos adecuados, teniendo en cuenta factores como el tipo de fibra, el material de la matriz y la fracción de volumen de la fibra, que se sabe que influyen significativamente en las propiedades mecánicas del compuesto. Se realizaron ensayos experimentales para obtener las propiedades esenciales de los materiales, como la resistencia a la tracción, la resistencia a la compresión, la resistencia al cizallamiento y la tenacidad a la fractura. Estas propiedades servirán como datos de entrada para las simulaciones numéricas.

Las simulaciones CAE se llevarán a cabo mediante el método de los elementos finitos (FEM), que permite el modelado virtual y la simulación de estructuras complejas. Al crear una representación precisa de la estructura compuesta y aplicar condiciones de carga realistas, se puede predecir la respuesta del material.

La metodología desarrollada se validará con resultados experimentales. Este proceso de validación es crucial para garantizar la precisión y fiabilidad de la metodología. Se analizará cualquier discrepancia entre los resultados experimentales y los simulados.

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INTRODUCTION

This Final Degree Project aims to achieve an efficient modularisation of carbon fibre (CFRP) tests, optimising the time and workload of each test. To achieve this goal, tests will be modularised to make them more efficient and reusable. This means that multiple tests will be able to take advantage of the same files instead of needing numerous files for each test. Thus, when modifications need to be made, a single file will be accessed instead of multiple files. To achieve this goal, the project has been developed following a step-by-step methodology that has allowed for a systematic and comprehensive approach to the research.
In chapter 1, a general description of composite materials has been carried out, addressing aspects such as their definition, matrix and reinforcement composition, and the different manufacturing processes used for their production.

In chapter 2, the applications of these materials in the aerospace and automotive industries were explored, highlighting their relevance today. Within the composite materials of interest, special attention was given to carbon fibre reinforced polymers (CFRP).

In chapter 3, by means of an experimental campaign, the mechanical characterisation of the composites studied was obtained. Different types of tests were carried out in order to evaluate the properties of stiffness, strength, toughness, among others.

In chapter 4, the composites were numerically modelled using the finite element method (FEM). The LS-DYNA software was used to carry out simulations that allowed the behaviour of the materials to be analysed under different conditions and to validate the results obtained in the experimental tests. The modelling process was detailed, including the orientation of the fibres and the definition of the material properties in the software.

In chapter 5, the material chart 262 (*MAT_262: *MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO) was described. In this chapter, the definition of the properties of the chart and their relevance in the numerical simulation has been discussed in detail. Through this information, it is intended to provide a solid basis for the understanding and application of this property in the development of models and simulations.

In chapter 6, the results obtained from both experimental tests and numerical simulations were presented. A comparative analysis was performed and the correlation between the two data sets was evaluated. The modularisation proposed in this research will allow for a more systematic and structured approach to testing, providing significant benefits in terms of optimising time, reducing the risk of errors and improving the quality of the results.

The modularisation proposed in this research will allow for a more systematic and structured approach to testing, providing significant benefits in terms of optimising time, reducing the risk of errors and improving the quality of the results.

CHAPTER 1. COMPOSITES

1.1. General description

1.1.1. Definition

Composite materials, also known as composites, are an important class of materials with broad applications in many different industries. Composites are manufactured by combining two or more materials, each with unique properties, to create a product with superior properties compared to each material independently. These materials are used in a variety of industries, from aerospace to construction and automotive.

One of the materials in a composite is a reinforcing fibre, which can be made from a wide range of materials, including carbon fibre, fibreglass, and aramid fibre. The reinforcing fibre adds properties such as strength, stiffness, and durability to the composite. The other material is the matrix, which can be made from different materials, such as thermoset resins or thermoplastics. The matrix is used to bond the reinforcing fibres and provide the shape of the composite. In addition, the matrix can also provide properties such as corrosion resistance or high-temperature resistance.[1]

1.1.2. Matrix and reinforcements

In composite materials, the matrix and the reinforcement play key roles in determining the mechanical and physical properties of the resulting material. The matrix constitutes the continuous phase that encloses and supports the reinforcement, while the reinforcement consists of the discontinuous phase that confers strength and stiffness to the composite material.

The matrix can be made of different materials, such as thermosetting polymers, thermoplastics, metals, or ceramics, and is used to bind and transfer loads between the reinforcement fibres.

Thermoplastic polymers and thermosetting polymers are types of plastics that undergo different production processes and result in a variety of properties depending on the constituent materials and production method. The terms thermoplastic and thermoset refer to the way a material can be processed under a change of temperature.

A thermosetting resin is normally a liquid material at room temperature but hardens irreversibly when heated. Once cured, thermosetting resins retain their shape and cannot soften or melt under heat. These resins are known for their high strength and stiffness, as well as their ability to withstand high temperatures.[2,3]

A thermoplastic, on the other hand, is a resin that is solid at room temperature but becomes plastic and soft when heated. This means that they can be repeatedly melted and moulded into different shapes without undergoing irreversible chemical changes. Thermoplastics are known for their ease of processing, as they can be moulded by injection moulding, extrusion, or other forming methods.[4]

On the other hand, the reinforcement can be made of different materials, such as glass, carbon, aramid or metal fibres, and the choice of reinforcement depends on the desired mechanical properties of the final material. The reinforcement fibres provide superior mechanical properties to the composite material, such as tensile strength and stiffness, and are crucial to the performance of the material in its end use.

The right combination of both components can result in composite materials with superior properties, making them favourable for various applications in sectors such as aerospace, automotive and construction.

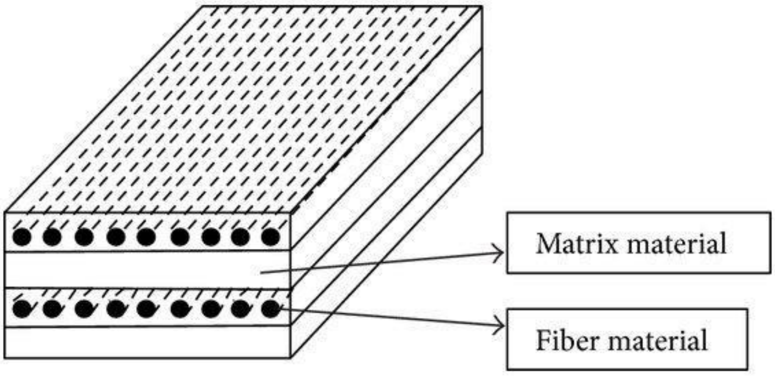


Figure 1. Composite material. [5]

1.1.3. Manufacturing processes for composite materials

1.1.3.1 Hand lay-up

Hand lay-up is a process in which fibres are cut to the desired length and manually placed in a mould in a predetermined sequence. The fibres may be pre-impregnated with resin or infused into the mould by resin injection or infusion.

Once the first layer of fibres is in place, a layer of resin is applied to bind the fibres together to form a composite layer. Additional layers of fibres and resin can be added to create a thicker and stronger composite part. After all the layers are stacked, the mould is covered with a release film and placed in a press to apply pressure and heat. The pressure and heat cause the resin to cure and harden, forming a solid composite part.

When the curing process is complete, the part is removed from the mould and cut or machined to the desired shape and size. Hand lay-up is suitable for parts with irregular or complex shapes.[6]

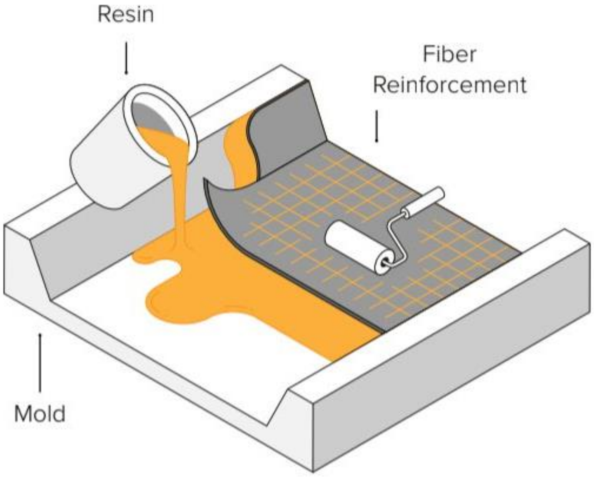


Figure 2. Hand lay-up. [7]

1.1.3.2. Prepreg lay-up

Prepreg placement, also known as prepreg composite manufacturing, is a method of manufacturing composite materials using fibre reinforcement materials that have already been impregnated with thermoset or thermoplastic resin.

In this process, pre-impregnated sheets are cut to the desired shape and placed in a mould. They are then subjected to heat and pressure to cure the resin and bond the prepreg layers into a rigid and durable structure.

This method of composite manufacturing offers high quality and repeatability in production, as the reinforcing materials are already impregnated with the correct amount of resin and are carefully handled to avoid contamination. In addition, the placement of prepregs allows for lightweight, high-strength parts with excellent surface quality and good dimensional tolerance.[8]

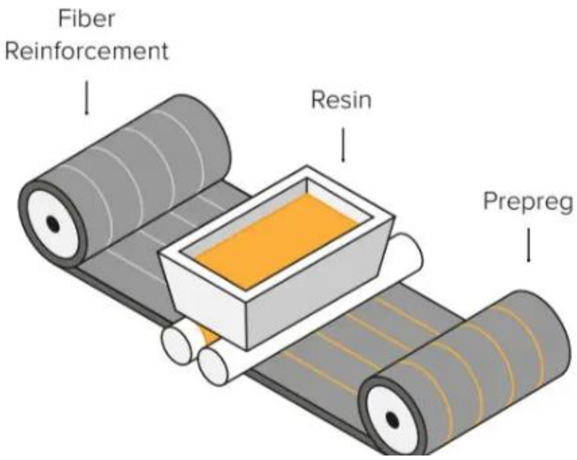


Figure 3. Prepreg lay-up. [7]

1.1.3.3. Filament winding

Filament winding is a method where fibre filaments are wound on a mandrel in a predetermined sequence and impregnated with resin as they are wound. The mandrel rotates as the filaments are wound, creating a three-dimensional shape.

Once winding is complete, the resin hardens, and the part is removed from the mandrel. The part can then be machined or trimmed to the desired shape and size.

Filament winding is suitable for manufacturing cylindrical or spherical shaped parts, such as liquid storage tanks and pressure vessels. It is an efficient and automated manufacturing method that allows for high accuracy in fibre placement.[9]

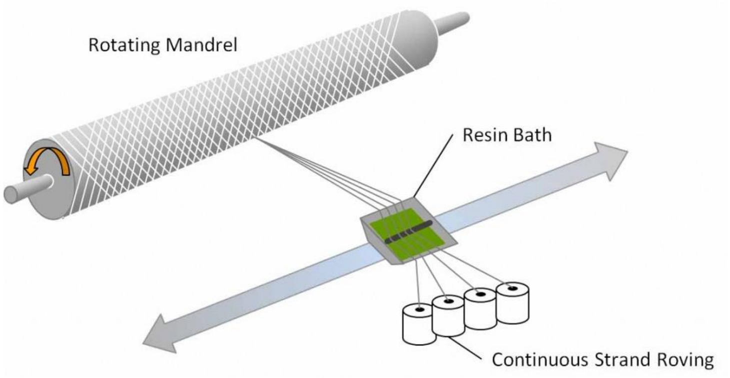


Figure 4. Filament winding. [1]

1.1.3.4. Resin transfer moulding

Resin transfer moulding involves placing a fibre preform in a mould and closing it with a cap. Resin is pumped through a pipe and injected into the mould through orifices, permeating the preform.

Pressure and vacuum are used to control the flow of resin and ensure its uniform distribution in the mould. Once the preform is impregnated, the mould is heated to cure the resin.

Once the resin has cured and hardened, the part is removed from the mould and trimmed or machined to the desired shape and size. Resin transfer moulding is a versatile method that can be used to manufacture large, complex shaped parts.[10]

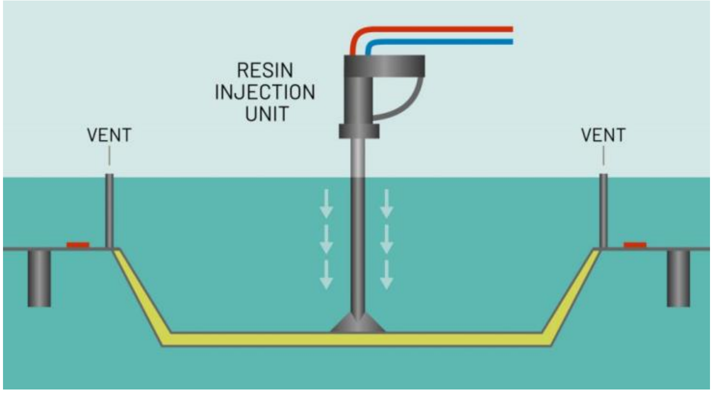


Figure 5. Resin transfer moulding. [11]

1.2. Applications of composite materials

Composite materials are present in our everyday life in diverse and impactful ways. Composites offer a unique combination of properties such as high strength and lightweight, which make them highly attractive for a wide range of applications.

1.2.1. Aerospace industry

Composite materials are widely used in the aerospace industry due to their high strength and stiffness in relation to their weight, which allows for the construction of lighter and more efficient structures. Some of the most common applications of composite materials in the aerospace industry include:[12,13,14,15]

- *Aircraft structures*: Composite materials are used in the manufacture of various components of aircraft structures, such as fuselages, wings and control surfaces. The use of these materials is aimed at reducing weight and improving fuel efficiency in aircraft.

- *Engine parts*: Composite materials are also used in the manufacture of engine components such as air ducts and engine support structures. These materials provide increased strength and stiffness, especially when exposed to high temperatures and heavy loads.

- *Cabin interiors*: Are used in the manufacture of aircraft cabin interiors, such as seats, panels, and linings. These materials offer increased durability and corrosion resistance.

- *Rockets and satellites*: In rocket and satellite manufacturing are used for their excellent strength and stiffness properties under extreme conditions and at low temperatures.

1.2.2. Automotive industry

Composite materials are used in various automotive components and systems, among others:[16,17,18]

- *Car bodies*: Composite materials are used in the manufacture of car bodies with the aim of reducing weight and thus increasing fuel efficiency. Carbon fibre is used to make exterior panels, such as the bonnet and doors.

- *Structural parts*: In the manufacture of structural components for automobiles, such as chassis beams and roll bars. Carbon fibre reinforced composites are used to improve the strength and stiffness characteristics of these parts.

- *Interior components:* In the manufacture of automotive interior components such as centre console panels and door panels. These materials offer increased durability and corrosion resistance.

- *Brake systems*: In elements of the braking system, such as brake discs and pads. The use of ceramic fibre reinforced composites improves both strength and durability, exceeding that of conventional materials.

- *Wheels*: In automotive wheels with the aim of reducing weight and improving performance. Carbon fibre wheels offer a lighter alternative to conventional alloy wheels, while maintaining superior strength and durability.

- *Exhaust systems*: In exhaust systems to achieve weight reduction and improved performance. Carbon fibre exhaust systems provide greater strength and durability compared to conventional exhaust systems, ensuring better overall performance.

CHAPTER 2. COMPOSITE FIBRES

The presence of fibres is essential in composite materials, which can be short, medium, or long depending on their length. Each type of fibre has unique mechanical properties that make it ideal for specific applications in composite materials. Therefore, the right choice of fibre length and fibre type is critical to achieve the desired mechanical properties in the final composite material.

2.1. Fibre size

2.1.1. Short fibres

The use of short fibre reinforcements is a common technique used to improve the mechanical properties of polymer composites. Short fibres, typically ranging from 0.1 to 10 mm in length, are specifically chosen to improve the stiffness, increase the tensile strength and reduce the weight and cost of composite materials.

Fibre orientation can be random or controlled, depending on the manufacturing process employed.

The choice of fibre orientation depends on the desired mechanical properties for the specific application. In some cases, a combination of random and controlled orientations may be used to achieve optimum properties in all directions.[19,20]

2.1.2. Medium fibres

Medium fibres, typically between 10 and 30 mm in length, have wide application in the manufacture of sheet moulding compounds (SMCs). SMCs are a specific type of composite material comprising a thermoset polymer matrix reinforced with fibres. The incorporation of medium fibres into SMCs offers numerous advantages, such as increased strength, stiffness, and impact resistance.
Another challenge posed by medium fibres is their tendency to create more complex and anisotropic structures compared to composites with short fibres. The alignment and orientation of medium fibres can be more difficult to control, leading to variations in the mechanical properties of the whole material.[1]

2.1.3. Long-fibres

Long fibre materials are a type of composite material that offer several advantages compared to short fibre materials, making them ideal for demanding applications in different industrial sectors. These materials are produced through extraction processes that result in a unidirectional and continuous fibre reinforcement. The length of the granule is equivalent to that of the fibre, typically in the range of 30mm to 50mm.

The use of long fibre materials is common in applications that require high performance, such as aerospace and automotive components, sporting equipment, and medical devices. This is because long fibre materials are more resistant, rigid, and have greater impact resistance. Although the extraction process can be costly and time-consuming, the resulting composite material offers superior mechanical properties, making it valuable for manufacturers.

The use of long fibre materials is crucial in the manufacture of composites to achieve high performance and quality in the final product. By understanding and optimizing the orientation of the fibres, manufacturers can produce composite materials that are even stronger, stiffer, and more durable, making them ideal for a wide range of applications. These materials are an efficient solution for improving the mechanical and physical properties of composite materials, allowing manufacturers to create high-quality products that meet their customers' needs.[21]

2.2. Fibre orientation

2.2.1. Unidirectional

Unidirectional carbon fibre is a type of carbon reinforcement in which all fibres are aligned in a single parallel direction. This arrangement ensures that there are no gaps between the fibres and that the fibres lie flat. As a result, the fabric has a concentrated density of fibres, which provides maximum longitudinal tensile strength.

Carbon fibre composites are strongest along the direction of fibre alignment, making them a non-isotropic material. By layering unidirectional layers in various angular orientations during the lamination process, strength in multiple directions can be achieved without compromising stiffness. In addition, during lamination, unidirectional fabrics can be combined with other carbon fibre fabrics to achieve different aesthetic or directional strength properties. Unidirectional fibres are available in extremely lightweight options, allowing parts to be constructed in a more controlled and precise manner.[22]

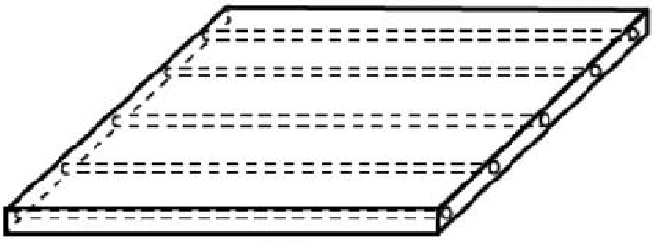


Figure 6. Unidirectional fibre. [23]

2.2.2. Woven

Woven polymer composites have excellent mechanical strength. Although their stiffness or strength may be lower than equivalent unidirectional (UD) composites, they possess superior impact resistance and dimensional stability, making them very attractive to the automotive industry in the manufacture and development of passive safety related components.

Woven polymer composites have found wide applications in the aerospace, military, and civil sectors due to their high fracture toughness, strength, modulus, heat resistance and good wear resistance. However, their marked anisotropy and inhomogeneity, together with processing problems such as fibre detachment from the matrix, fibre fracture and matrix cracking, pose problems in achieving high quality surface finishes, which can lead to failure of such parts.

A woven fibre composite is a type of textile composite in which the yarns are interwoven in two perpendicular directions and impregnated with a resin.[24]

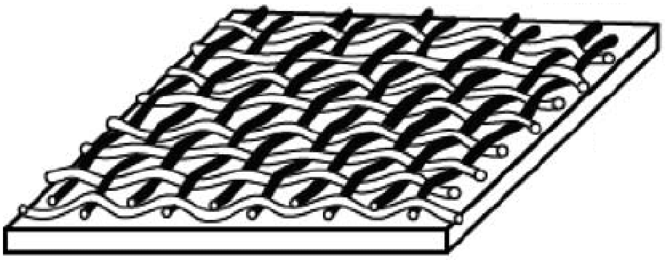


Figure 7. Woven fibre. [23]

2.3. Advantages and disadvantages of long fibre

2.3.1. Benefits and features

Some of the main advantages of the application of long-fibre composites are mentioned below.[25,26]

- *Corrosion Resistance*. Long-fibre does not rust, corrode, or rot, and are resistant to most chemicals. This quality has been applied in corrosive environments such as chemical processes and in water treatment industries.

- *High Specific Properties*. Long-fibre provides high resistance to high weights such as aluminium or steel. High strength and lightweight long-fibre can be used, for example, in the transportation industry where low weights are desired.

- *Dimensional Stability*. Dimensional stability is understood as the ability of a material to maintain its size under different conditions. Long-fibre has great dimensional stability under physical, environmental, and thermal stress.

- *Parts Consolidation and Tooling Minimization*. A single long-fibre moulding can replace a multi-part metal assembly, reducing assembly time, simplifying inventory, and lowering manufacturing costs.
- *High Dielectric Strength and Low Moisture Absorption*. Long-fibre materials have excellent electrical insulating properties and low moisture absorption. Therefore, they are used in primary support applications where these characteristics are required, such as circuit breaker housings.
- *Minimum Finishing Required*. Materials can be pigmented as part of the mixing operation or coated as part of the moulding process, often eliminating the need for painting.
- *Low to Moderate Tooling Costs*. The cost of tooling, in terms of moulding, is usually substantially lower than the cost of the multiple forming tools required to produce a similar finished piece of metal.
- *Design Flexibility*. Current applications vary widely. They range from commercial fishing boat hulls and decks to truck fenders, from television satellite dishes to traffic seats, and from outdoor lamp housings to seed hoppers.
- *High Crash performance***.** Long-fibre composites, especially when reinforced by fabric materials, show large Specific Energy Absorption (SEA) under impact events, which make them interesting for crash dissipation elements.

2.3.2. Disadvantages

The disadvantages of long-fibre materials can include:

- *Higher cost.* Long-fibre materials tend to be more expensive than conventional materials, which can increase the overall production cost of a product.
- *Complex processing.* The manufacturing of long-fibre materials may require complicated and expensive processes that can limit their use in certain applications.
- *Not easily recyclable.* Some long fibre materials, such as carbon fibre, pose problems for recycling, which can lead to disposal in landfills or incineration facilities.
- *Anisotropic properties.* Long fibre materials can exhibit anisotropic characteristics, which means that their properties can vary in different

directions. This variability can pose problems in designing and manufacturing parts with uniform properties in all directions.

2.4. Carbon fibre reinforced polymer (CFRP)

Carbon fibre reinforced polymer (CFRP) is a composite material that combines a polymer matrix with carbon fibres and stands out for its exceptional qualities.

One of the main advantages of CFRP is its outstanding strength-to-weight and stiffness-to-weight ratio. This means that it offers high strength and structural rigidity despite being a lightweight material. This property makes it the ideal choice for applications where high performance and significant weight reduction are required. In addition, carbon fibres have chemically inert properties, which means they are corrosion resistant and unaffected by aggressive chemicals. They are also excellent electrical and thermal conductors, making them ideal for applications requiring conductive properties.

In this project, we aim to exploit the advantages and unique characteristics of CFRP for application in different contexts.[27,28]

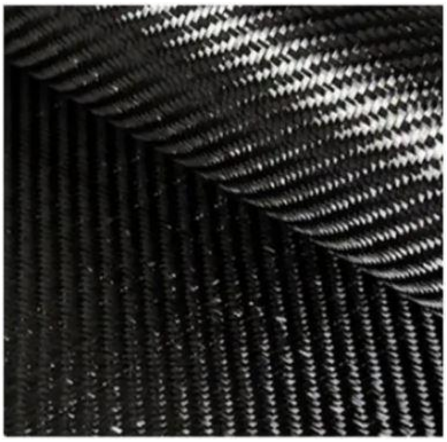


Figure 8. Carbon fibre. [29]

2.4.1. Carbon fibre vs Glass fibre

Carbon fibre and glass fibre are both reinforcing composite materials. Despite this similarity, the fundamental distinction between the two is that while carbon fibre is composed of carbon strands, glass fibre is made of molten glass strands.

Glass fibre finds applications in a variety of industries, from automotive components such as door and window frame profiles to railway seals and telecommunications radomes.

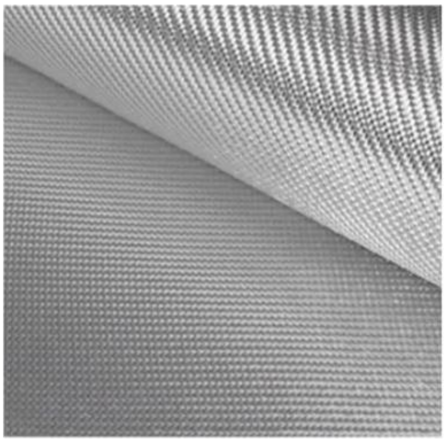


Figure 9. Glass fibre. [29]

Reinforcing fibres, which include glass, carbon, aramid and other natural and synthetic materials, are used in different forms and combinations to achieve specific properties. Glass fibre is often chosen for its affordability, excellent tensile strength (superior to most metals), thermal insulation, low coefficient of thermal expansion, and resistance to corrosion and weathering.

On the other hand, carbon fibre stands out for several reasons:

- *Strength*: Industrial carbon fibre is approximately 20% stronger than glass fibre, and its strength-to-weight ratio is almost double that of glass fibre.
- *Stiffness*: Carbon fibre is significantly less flexible than glass fibre, making it suitable for applications where stiffness is required.
- *Weight*: Both carbon fibre and glass fibre are lightweight materials compared to metals, but carbon fibre is typically 15% lighter than glass fibre.
- *Thermal expansion*: Carbon fibre does not shrink in cold climates, whereas glass fibre materials can. This thermal stability can be advantageous in extreme temperature conditions.
- *Corrosion resistance*: Both fibres show good resistance to chemical corrosion and abrasive environments.

The strength-to-weight and stiffness-to-weight ratio of carbon fibre, together with its thermal stability and corrosion resistance, make it a preferred choice in high-performance applications. However, glass fibre remains a popular and cost-effective choice in a variety of industries. The choice between these two materials depends on specific requirements and design considerations.[30,31]

CHAPTER 3. EXPERIMENTAL CAMPAIGN

In response to increasing market demand, manufacturers have responded by conducting tests under various conditions to evaluate the performance of composite materials in tensile, compressive, flexural and delamination situations.

These tests are used to understand the response of the composite material to applied forces and to determine its mechanical characteristics. The results obtained in these tests can be used to optimize product design, increase safety, and reduce production costs.

In order to ensure the quality and reliability of the test results, test standards established by ASTM, a leading organization in the development of technical standards for materials and products, are used. These standards ensure that tests are performed consistently and accurately, facilitating meaningful comparison of results between manufacturers and products.

As the evaluation process progresses, data from more comprehensive and costly tests is integrated, allowing for a more complete and accurate understanding of material characteristics. This gradual accumulation of information and knowledge is essential to optimise product design, improve product safety and efficiency, and reduce production costs, in line with the progressive and strategic Building Block Approach.

The CFRP campaign is primarily aimed at creating a material card intended for use in crash simulations. Therefore, it is of great interest to understand its behaviour in terms of failure crack propagation and delamination, among other phenomena that can manifest themselves during a crash event.

3.1. Building Block Approach

The Building Block approach consists of performing from a variety of more economical tests, which provide preliminary information and allow for an initial evaluation of product characteristics, to more complex assemblies. The initial tests, as known as Coupon Test, can include simple, quick, and less expensive tests, which provide an overview and help identify potential areas of concern.

However, it is recognized that these inexpensive tests may have limitations in terms of accuracy and detail. To overcome these limitations, a more comprehensive and higher cost assay is performed. These tests cover a wider range of conditions and provides a deeper understanding of the properties and behaviour of the material or product under study.

The key advantage of the Building Block approach lies in the optimization of available resources. By employing cheaper tests at an early stage, initial results can be obtained at a lower cost. This allows the identification of those products or materials that have the greatest potential and justify the investment in the more expensive and comprehensive assay.

This work is focused on the Coupon Test campaign. The Coupon Test campaign is divided in Intralaminar and Interlaminar tests.

3.2. Intralaminar tests

Intralaminar behaviour refers to events occurring within a single layer or lamina of the material. Intralaminar failure denotes the development of cracks within the plane parallel to the direction of reinforcement. Various factors, such as fibre orientation, the existence of defects or cracks in the individual layer and the applied load, can influence intralaminar behaviour.[32]

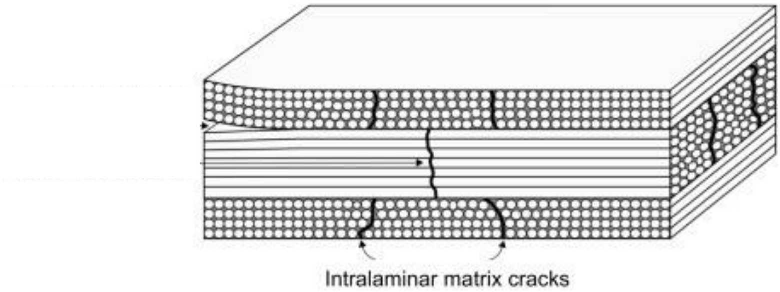


Figure 10. Intralaminar crack. [32]

In this project, tests have been carried out to analyse some cases of intralaminar failures in carbon fibre. Understanding the behaviour of the different layers in composite materials is necessary to predict their strength and durability.

3.2.1. Tensile test

A carbon fibre tensile test is a test used to evaluate the tensile strength of a carbon fibre composite material. This type of test is important because tensile strength is one of the most critical properties for structural materials, especially in applications where the material is expected to withstand tensile loads.

During the test, a carbon fibre sample is clamped in a testing machine and subjected to a uniaxial tensile load in each direction (in this case 0° and 90°). The load is applied gradually until the maximum load is reached, and the deformation that occurs in the specimen during the test is recorded.

From the data recorded during the test, various mechanical properties such as modulus of elasticity, tensile strength and strain at failure can be calculated. These properties are important for understanding the tensile strength of the material and its ability to withstand loads in structural applications.

It is important to note that the results of a carbon fibre tensile test can vary depending on a number of factors, such as fibre orientation, material quality and applied strain rate. Therefore, multiple tests are performed to ensure its safe and effective use in structural applications.

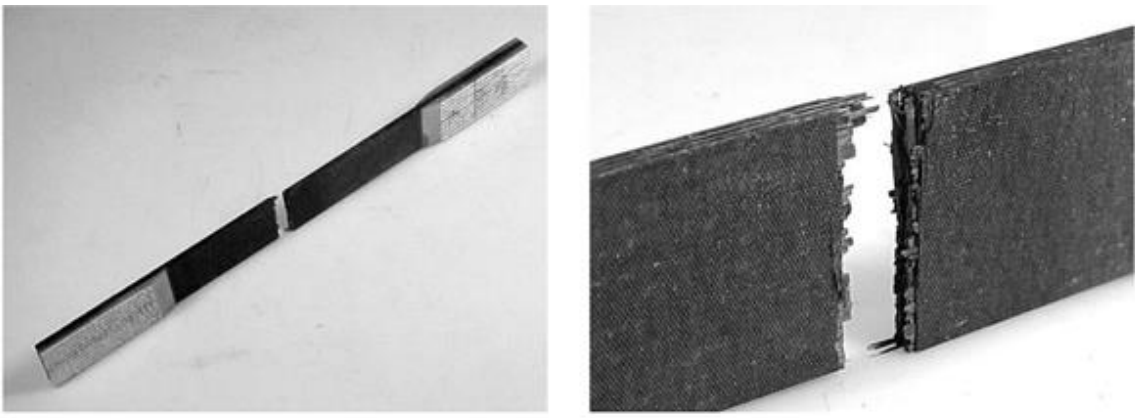


Figure 11. Carbon fibre sample. [33]

This test uses an electromechanical machine MTS INSIGHT 300 (INSIGHT300) with a maximum capacity of 300 kN and a load cell MTS Mod. 569331-01 working at 100% range is used for the test. The system uses hydraulic grippers. The gripping pressure used in the tests was 6.89 MPa (1000 psi). The test speed was 2 mm/min as indicated by the standard ASTMD3039.

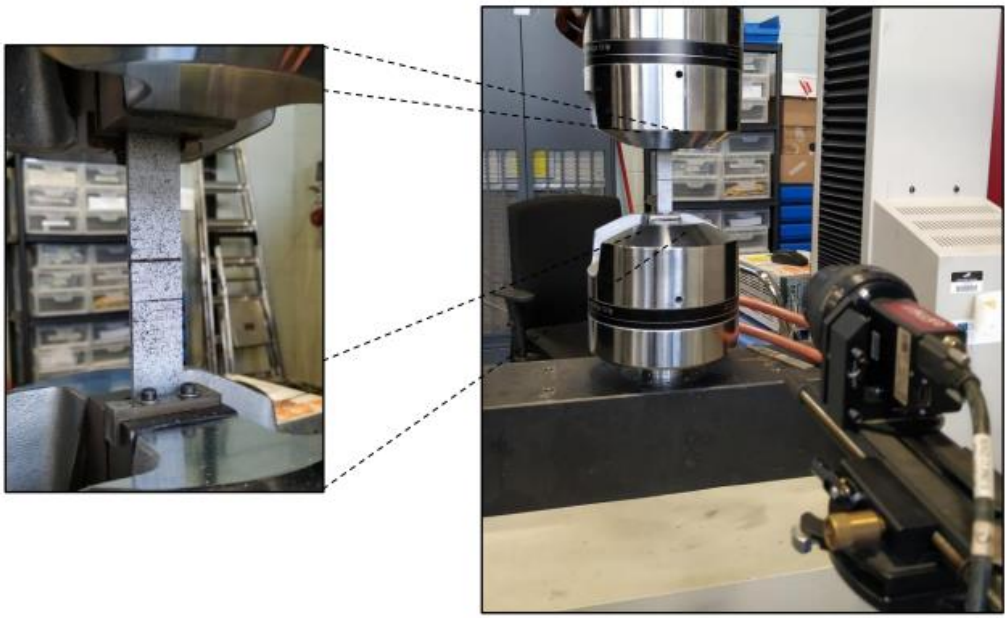


Figure 12. Tensile test.

3.2.2. Compression test

A carbon fibre compression test is a test where the compressive strength of a carbon fibre composite material is evaluated.

During the test, a sample of carbon fibre material (one specimen with its fibres oriented at 0° and one with its fibres oriented at 90°) is placed between two platens in a compression testing machine. The load is applied gradually until the material fails or until a predetermined level of deformation is reached. The test results are used to determine the maximum stress the material can withstand before failure under compression.

Also, as above, multiple tests must be performed.

The data obtained from the carbon fibre compression test can also be used to calculate other mechanical properties such as elastic modulus, Poisson's ratio and yield strength.

This test uses the electromechanical testing machine MTS Insight 100 kN with a 100 kN load cell calibrated to 100 % is used in the tests. It was equipped with compression plates and the ASTMD6641M test standard fixture. The tightening torque for clamping the specimens was 11 Nm.

Figure 13. Compression test.

3.2.3. Compact compression and compact tension tests

Carbon fibre compression and tensile tests are two tests used to evaluate fracture toughness.

During the compact tension test, a specimen is placed in a testing machine with a loading mechanism applied in the axial direction. The specimen is subjected to a uniaxial tensile load while the fracture develops at the centre of the specimen.

Similarly, during the compact compression test, a carbon fibre specimen is placed between two platens and compressed axially with a gradually applied load. The specimen has a wedge-shaped opening at one end to ensure that the test focuses on the crack produced at the notch of the specimen. The relative displacement between the 2 sides of the opening is measured.
The fracture toughness of both is computed with a Data Reduction Method from the force with respect to the opening measurement.

The results of both tests are important to understand the material's capacity to support loads in both directions and its energy dissipation during failure under compression and tension.

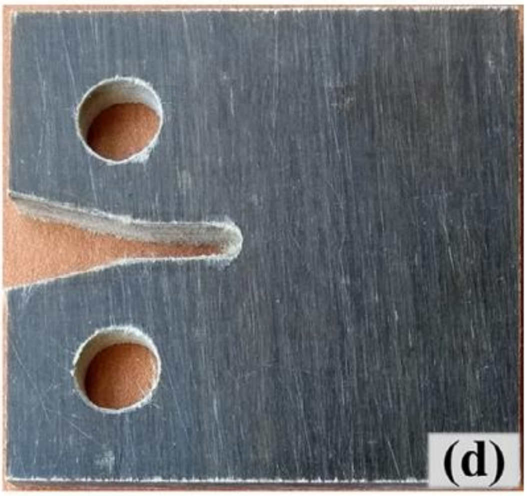


Figure 14. Compact compression sample. [34]

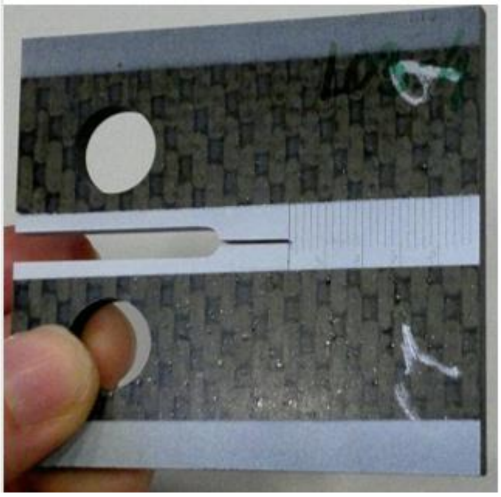


Figure 15. Compact tension sample.

The test uses the electromechanical test machine INSIGHT was used in testing with a load cell of 100 kN. The opening relative was measured with a COD as well as with machine displacement.

The data acquisition system (QUANTUMX/01) was used to read the values of force, machine displacement and COD.

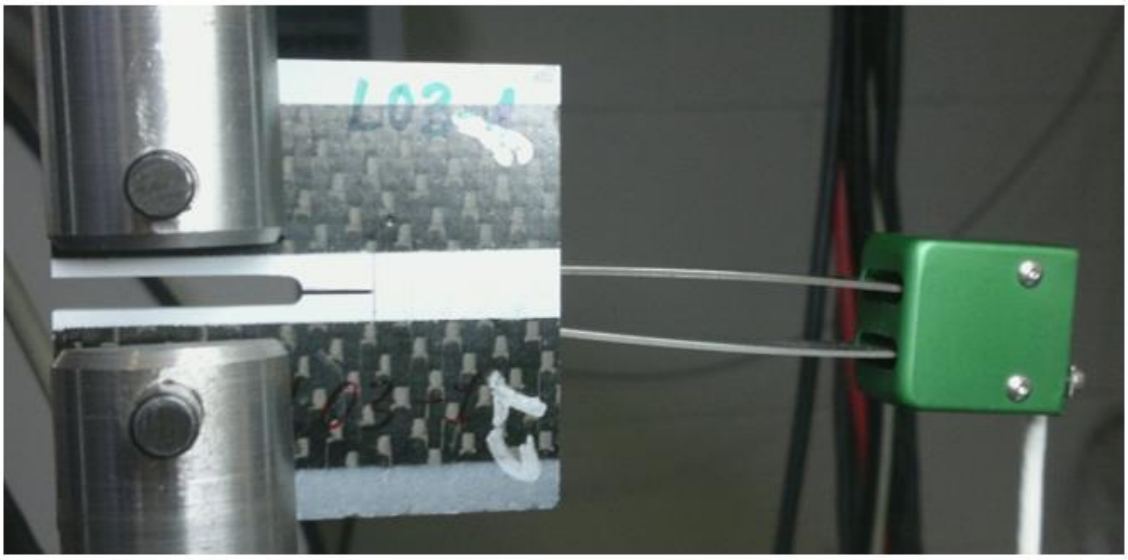


Figure 16. Compact compression/tension test.

3.2.4. Open holes tests

This test evaluates the fracture toughness of a carbon fibre composite material with holes in its structure.

During the test, a carbon fibre sample is used with a hole drilled in its centre, which can be of different diameters (between 2mm to 16mm). The specimen is fixed in a testing machine and subjected to a gradually applied uniaxial tensile or compressive load. Fracture initiates at the edge of the hole and propagates towards the centre of the specimen.

The results of the open hole test are important for assessing the ability of the material to resist fracture in the presence of holes and for determining the sensitivity of the material to the presence of holes in its structure.

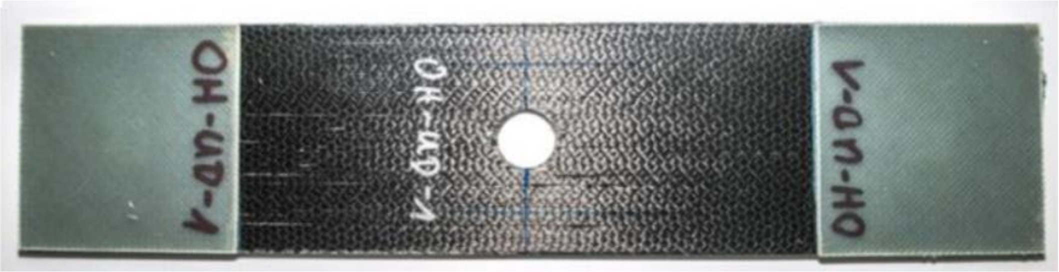


Figure 17. Open hole sample. [35]

The test uses the electromechanical test machine INSIGHT was used in testing with a load cell of 100 kN. The displacement was measured with a COD as well as with machine displacement.
The data acquisition system (QUANTUMX/01) was used to read the values of force, machine displacement and COD.

Figure 18. Open hole test.

3.2.5. Bending test

The carbon fibre bending test measures the strength and stiffness of a carbon fibre composite material under bending loads. During the test, a rectangular carbon fibre specimen is placed on two supports and a load is applied to the centre of the specimen to bend it. The load is applied gradually until the specimen breaks or the maximum load is reached. The load and strain are recorded at different points on the specimen to determine the strength and stiffness of the material.

This test is important because bending is one of the main loads that structural materials must withstand in many applications, such as aircraft wings. The results of the carbon fibre bending test are used to evaluate the material's ability to withstand bending loads and to design structures that can withstand these loads without damage.

In addition, this test is also useful to identify defects in the material, such as areas of low carbon fibre density or air inclusions, which can weaken the specimen and reduce its strength and stiffness under bending loads.

Figure 19. Bending sample.

The test is carried out on a 3-point bending assembly in accordance with the standard ISO14125:1998. In this test a force is applied to the specimen from above. The equipment used was:

- Electro mechanic test machine: MTS Insight 100 kN
- Load cell: MTS 10 kN
- Test fixture: "Utillatge ENF" with a span of 80 mm

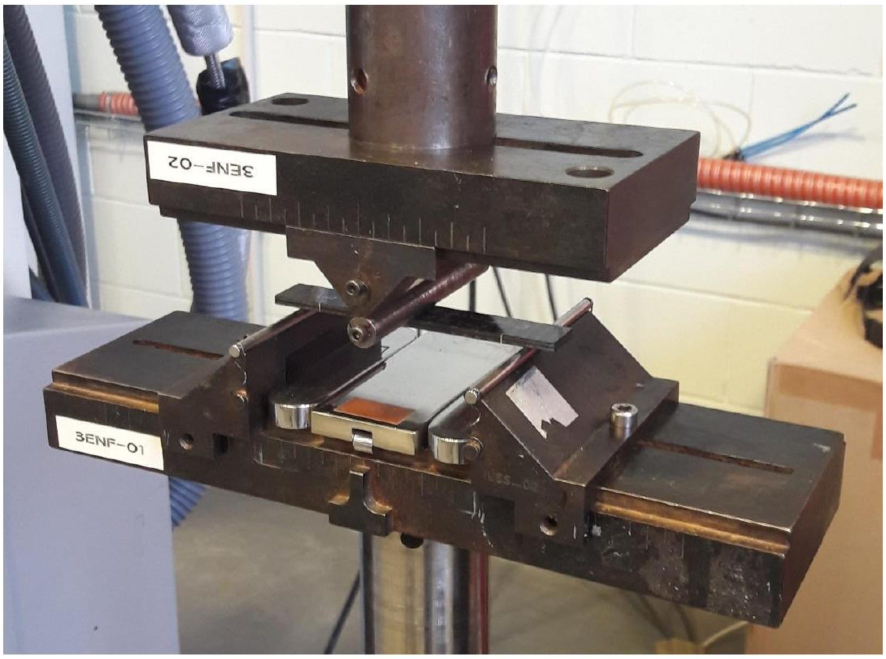


Figure 20. 3-point bending test.

3.2.6. In-plane shear test

A carbon fibre in-plane shear test is a test that examines the ability of carbon fibre composite materials to resist in-plane shear loads in which the fibres of the material are oriented at ±45°. During this test, a tensile force is applied to the sample until it deforms or fractures.

During the test, the amount of load required to induce deformation in the material is recorded, and the response of the sample is monitored as the load is applied. The data obtained is used to determine the stiffness and strength of the composite material against shear in the plane of the fibres.

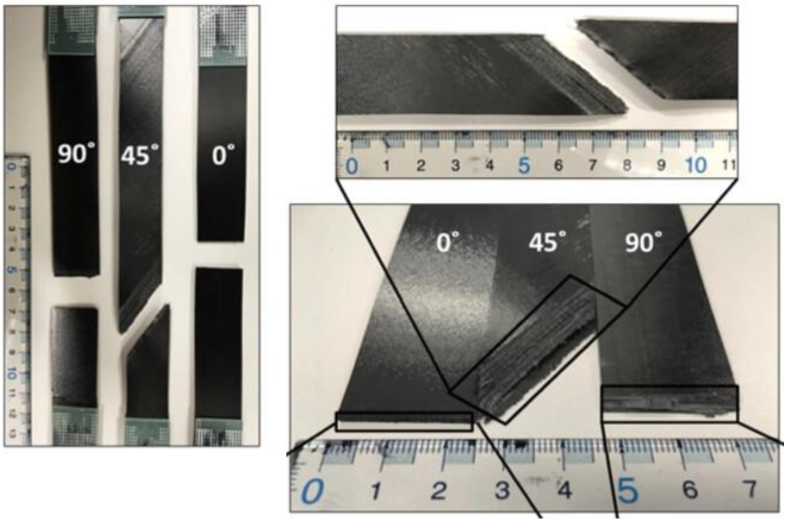


Figure 21. 90 degrees, In-plane shear (45 degrees) and 0 degrees samples. [36]

This test is of particular importance in the aerospace industry, since carbon fibre composites are widely used in the construction of aircraft structures and are subjected to in-plane fibre shear loading during flight. In addition, this test is used in the manufacture of automotive parts, boats, bicycles, and other products requiring high strength and stiffness.

Figure 22. In-plane shear test.

3.3. Interlaminar tests

Interlaminar failure, also known as delamination, is where the plies of the structure progressively separate. This failure mode is critical because traditional laminates lack reinforcement fibres in the "through-thickness" direction, making the interlayer interfaces the weakest element of the composite material.

Delamination can lead to a loss of structural integrity and can be caused by a variety of factors, such as impact, fatigue, or poor manufacturing processes. As composite materials become more popular in various industries, it is crucial to understand and mitigate interlaminar failure to ensure the safety and reliability of structures.[32]

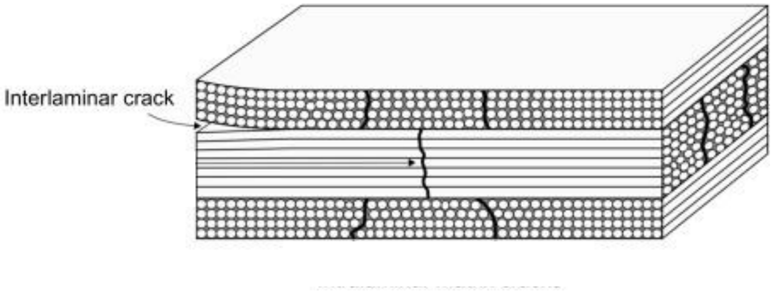


Figure 23. Interlaminar behaviour. [32]

3.3.1. Double Cantilever Beam (DCB or Mode I)

The double cantilever beam (DCB or Mode I) delamination test is a technique commonly used to evaluate the interlaminar strength of carbon fibre composite materials. This test is performed by creating a controlled crack between two layers of a composite laminate. The sample is then subjected to a bending load to separate the layers of material along the crack. The force required to propagate the crack is recorded and used to determine the delamination resistance of the material.

The DCB test is important because delamination can significantly weaken the structure of the material and reduce its strength and stiffness. This test is used to evaluate the material's ability to resist delamination and to design composite materials that can withstand delamination loads without failure. In addition, this test can be used to determine the effect of various factors, such as fibre orientation and material thickness, on the interlaminar strength of the material.

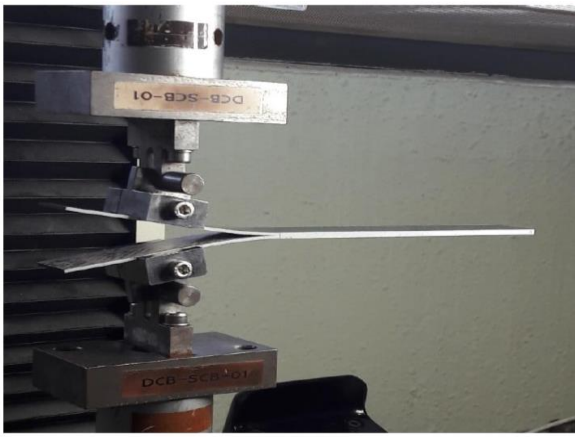


Figure 24. DCB sample.

The test was carried out according to the standard test ISO15114:2014. The following equipment was used in testing:

- Test machine: INSIGHT5
- Load cell: 5 kN used at 100 % range
- Test fixture: Mode II tooling (Utillatge C-ELS)

Figure 25. DCB test.

3.3.2. Compression after Edge-on Loading and Shear (C-ELS or Mode II)

The Compression after Edge-on Loading and Shear (C-ELS or Mode II) test is a technique used to evaluate the interlaminar strength of carbon fibre composite materials under compressive loading. This test is performed by applying a shear load to the edge of a laminated composite specimen, which generates an interlaminar delamination along the length of the specimen.

The C-ELS test is used to assess the material's ability to resist delamination and to design composite materials that can withstand delamination loads without failure.

This test is an important tool for assessing the structural integrity of carbon fibre composite materials under compressive loads and for improving the understanding of the factors that affect the interlaminar strength of the material.

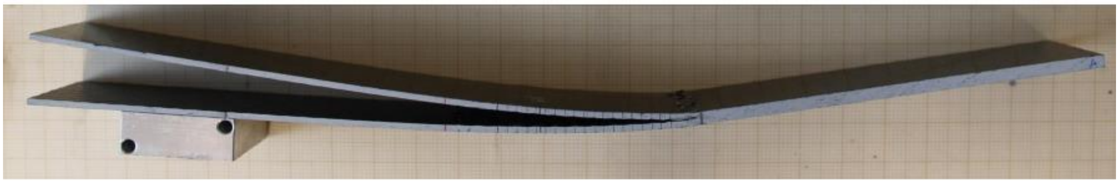


Figure 26. C-ELS sample.

The test was carried out according to the standard test ISO15114:2014.
The following equipment was used in testing:

- Test machine: INSIGHT5
- Load cell: 5 kN used at 100 % range
- Test fixture: Mode II tooling (Utillatge C-ELS)

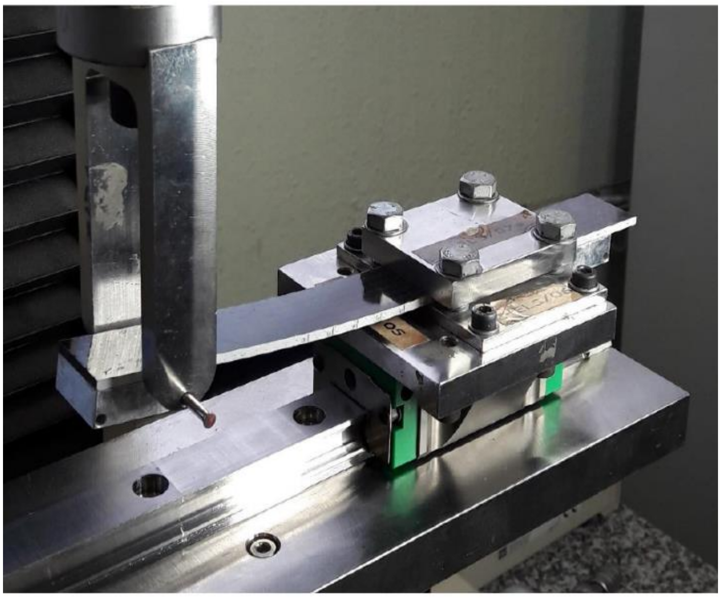


Figure 27. C-ELS Woven test.

CHAPTER 4. NUMERICAL MODELLING

4.1. Finite Element Method (FEM)

The finite element method (FEM) is a numerical technique widely used to analyse the behaviour of complex structures and systems. In this method, the structure is divided into a large number of small, simple elements, such as squares or triangles, which are connected together to form a mesh. Each element is modelled mathematically with equations describing its behaviour, and the combination of all these elements allows the structure to be represented in its entirety. The solution of the engineering problem using the finite element method consists of establishing and solving a set of deterministic algebraic equations using a computer.

The FEM uses a set of points called nodes, which define the finite elements and create a mesh that represents the geometry of the system to be simulated. These nodes are the intersection points between each element and its adjacent elements. By assigning a stiffness or elasticity matrix to each element, it is possible to calculate the displacements at the nodes. Once the displacements are known, the deformations can be determined and, using the constitutive equations, the stresses can be calculated.

In this way, the problem is "discretised" by transforming the continuous model into a set of discrete elements, the union of which forms the complete system. This implies that the problem cannot be solved exactly, but the method provides an approximation, which will become more accurate as the number of elements into which the model is divided increases.[37]

4.1.1. In automotive

The Finite Element Method (FEM) is widely used in the automotive industry for the simulation and analysis of the mechanical behaviour of vehicle components. FEM is used to evaluate the strength, stiffness, vibration, and thermal behaviour of various vehicle parts, such as the chassis, suspension, engine, braking system and bodywork.

In the field of passive safety, the impact of a collision on the vehicle body can be simulated and evaluated to determine how it will deform and absorb the energy. It is also used to optimise the structure of the car and its protective systems (seat belts, airbags, etc.) and to study the types of injuries that occupants may suffer during a collision.

Using these analyses helps engineers identify problem areas and improve vehicle strength and durability. The software introduces meshing modules to analyse the problem set and check the results obtained. results. The results can be represented in printed form as stress contour maps, deflection plots and output parameter plots.

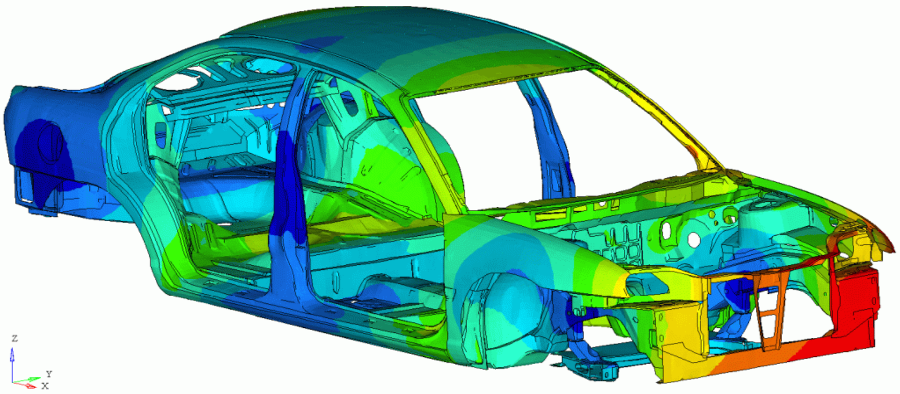


Figure 28. Car model in FEM. [37]

Stiffness analysis consists of linear models, where simple parameters are available and the material is assumed not to deform plastically, and non-linear models, which consist of stressing the material beyond its elastic capabilities by varying with the amount of deformation.

FEM enables fast and efficient design changes without the need to manufacture and test expensive physical prototypes. In summary, FEM is a tool used in the automotive industry to improve vehicle safety, efficiency and performance while reducing development time and costs.

4.1.2. In aeronautics

In the aircraft industry, engineers use FEM to evaluate the strength and stiffness of various aircraft parts, such as the fuselage, wings, turbines, blades and control system components. In addition, FEM analysis is used to simulate airflow around the aircraft, which helps to improve fuel efficiency and reduce aerodynamic drag.

FEM also allows the analysis of material fatigue, which is important for determining the service life of aircraft components. In addition, the thermal behaviour of aircraft components is assessed by FEM, which is crucial for determining the resistance to high temperatures and designing appropriate cooling systems.

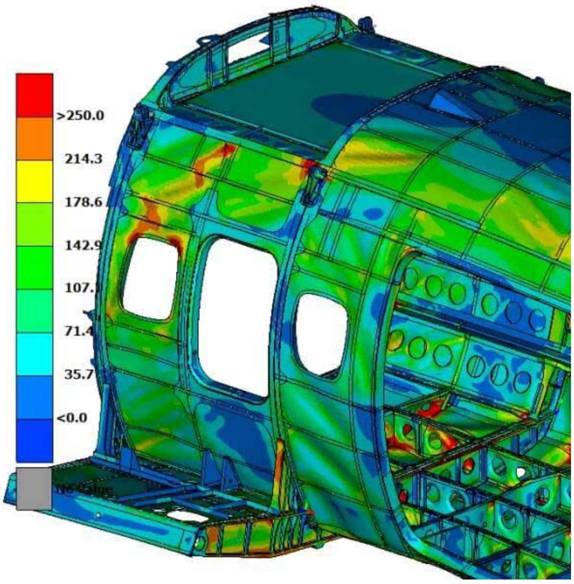


Figure 29. Aircraft fuselage model in FEM. [38]

4.2. LS DYNA

LS-DYNA is a finite element simulation solver used to analyse the behaviour of complex structures and systems under static and dynamic loads. This tool is oriented towards the simulation of complex systems. It is widely used in the automotive industry for impact testing and in the aerospace industry to simulate and prevent structural failures.

LS-DYNA is capable of simulating large deformations and damage to the structure, allowing engineers to assess the safety and performance of designs prior to fabrication.

For the automotive industry, LS-DYNA is used to analyse cases of head impacts, frontal impacts, side impacts (quasi-static and dynamic), roof crush, seat belt anchorage, rear impacts, among others.

As a result, automotive companies and their suppliers can test and optimise their virtual prototypes for design approval at the first physical certification test, saving time and money.[39,40]

4.2.1. Crashworthiness

Crashworthiness refers to the ability of an automobile and its internal systems to protect occupants in the event of a crash. Effective crashworthiness designs must carefully address all potential sources of injury and strive to minimise or mitigate them to the greatest extent possible within specified design impact limits. This includes considerations of various aspects such as the adequacy of seating and restraint systems, the effectiveness of energy absorption mechanisms, the presence of potentially harmful objects in the vicinity of occupants, and post-crash factors such as fire prevention and the availability of adequate escape routes.

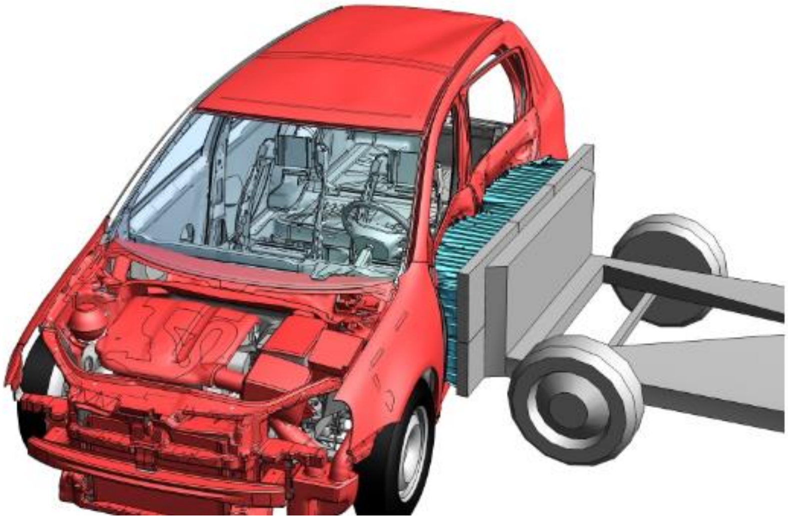


Figure 30. Side impact crashworthiness case. [41]

Passive safety plays a key role in the automotive industry, and in developing new innovative components and products, high priority is given to the protection of drivers, passengers, and pedestrians.

To assess crashworthiness, several criteria can be analysed, such as the deformation patterns of the vehicle structure, the acceleration experienced by the vehicle during impact and the probability of damage predicted by human body models.

In this context, impact resistance becomes of utmost importance for the industry, and computational simulation, particularly the LS-DYNA software, is the most widely used for safety and crash studies.[42,43,44]

4.2.2. Properties needed for carbon simulation

In the characterization campaign, experimental tests are used to measure the mechanical properties of the material. The results of this campaign will be used as input in the virtual development of composites. Composite materials are attempted to be solved by implementing the LS-Dyna material libraries. To define the laws of material behaviour the following properties are required:[45]

- Elastic Modulus and Poisson Ratio for the different directions
- Strength for all the mechanisms (damage initiation parameters)
- Plastic Definition for In-plane shear
- Fracture Toughness for all mechanisms

Where, the material directions are:

- A: Longitudinal direction (Fibre direction for a UD material)
- B: Transverse direction (Matrix direction for a UD material)
- C: Through-thickness direction (Perpendicular direction to the ply plane)

And the material mechanisms are:

- Intralaminar:

  - Longitudinal tension (Fibre tension for a UD material)
  - Longitudinal compression (Fibre compression for a UD material)
  - Transverse tension (Matrix tension for a UD material)
  - Transverse compression (Matrix compression for a UD material)
  - In-plane Shear

- Interlaminar:

  - Delamination mode I (DCB)
  - Delamination mode II (C-ELS)

4.2.2.1. Intralaminar characteristics

The tensile test (ASTM D3039) measures the strength and elasticity of carbon fibre in the direction of its fibres.

The compression test (ASTM D6641) is used to measure the elastic modulus and determine the strengths in the principal ply directions of carbon fibre specimens.

Compact Tension and Compact Compression tests are used to measure the fracture toughness of fibre-related mechanisms. As there are no related standards for these properties for composite materials, characterization procedures used for metallic materials have been adapted. However, a drawback is observed when CT and CC methodologies are applied to composite laminates: there is a risk of premature failure due to buckling at the back of the specimen. To avoid this, an anti-buckling system was included in the test set-up.

The In-plane shear test (ASTM D3518) is used to measure both the elastic modulus and elastoplastic law of shear mechanisms in carbon fibre specimens.

4.2.2.2. Interlaminar characteristics

The DCB (ASTM D5528) and C-ELS (ISO 15114) tests are commonly used to characterise fracture toughness in the pure modes of crack propagation: mode I (Normal) and mode II (Shear), respectively.

4.3. Modelling

Carbon fibre modelling is a process for understanding and simulating the behaviour of carbon fibre reinforced composite materials. This technique uses mathematical and numerical models to predict how the composite material will behave under different loads and environmental conditions, allowing these materials to be designed and optimised for specific applications.

Carbon fibre modelling uses computer simulation techniques to analyse the response of the composite material to different types of loading, such as tensile, compressive and delamination. Experimental models are built and used to validate and adjust the model parameters.

By simulating the mechanical behaviour of the composite material in different scenarios, the number of physical tests required can be reduced, saving time and costs in the design and development process. In addition, carbon fibre modelling improves the understanding of the composite material and therefore optimises its performance in a wide range of applications, such as aerospace and automotive, among others.[46]

4.3.1. Orientation

The orientation of the carbon fibres is a critical factor in modelling, as it significantly affects the behaviour of the composite material under different loads. In carbon fibre modelling, each layer is modelled as a unidirectional layer of carbon fibre with its own orthotropic elastic properties and its own material coordinate system.

In each layer, the direction of the fibres, and thus the main direction of the composite's strength, is determined and thus influences how stresses and strains are distributed in the composite when it is subjected to a load. The orientation of the fibres also affects the strength and stiffness of the composite in different directions.[47]

4.3.2. Laminate

A laminate is composed of multiple thin layers of carbon fibres impregnated in a resin matrix, thus forming a composite material. These layers are arranged in a specific sequence, each oriented in different directions to provide strength and stiffness in multiple directions.

It is assumed that the laminate has a perfect bond between the layers and that the interfaces are infinitely thin and do not deform under shear. Displacements are continuous across the ply boundaries, avoiding any separation between the plies. In this way, the laminate acts as a single layer with special properties that make it a fundamental structural element.

When the laminate is thin, a straight line initially perpendicular to the mid-surface of the laminate, known as the mid-surface normal, is considered to remain straight and perpendicular to the mid-surface even when the laminate is deformed, whether by bending, compression or shear. This implies that the line does not bend or deform during the deformation of the laminate, which makes it possible to accurately predict its mechanical behaviour.

In most applications requiring the use of composite materials, multiple laminate layers are used, as a single layer has highly anisotropic properties (varying in different directions within the plane of the laminate) and is too thin (typically fractions of a millimetre).

In this study, unidirectional, bidirectional, or woven laminates have been considered. The fibre orientation angles are 0º, 0º and 90º, 90º and +-45º.[48]

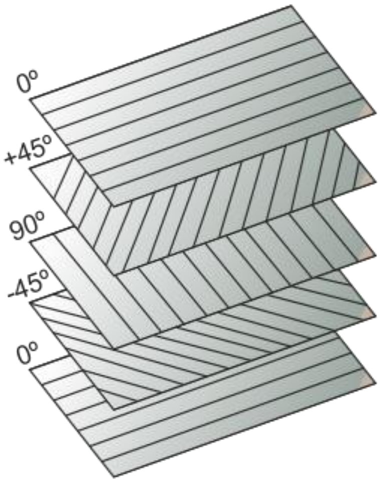


Figure 31. Laminate. [48]

4.4. Numerical campaign models

4.4.1. Initial status

In the context of this project, we identified certain limitations in existing models that required attention and improvement. One of the main challenges was that all the information of each FE model was contained in a single file, which means that it was not modular. This lack of modularity made it difficult to interconnect common items, such as specific properties, between different models.

These limitations had several disadvantages:

- Any change or modification required adjustments to all models, which was time-consuming and increased the risk of errors.
- The presence of common elements defined in different models created uncertainty and made it difficult to ensure coherence and consistency of results.
- Risk of models using different approximations, which could affect the accuracy and reliability of the analyses performed.
- Difficulty in editing and updating the models, which had a negative impact on the efficiency and flexibility of the process.

Hence, one of the main goals of this work is to make the FE Models as modular as possible to highly improve the workflow.

Material Engineering Portal (MEP), an ongoing company-internal software that requires modularisation to enable efficient model management and proper interconnection of common elements. Through the improvements performed in this work, it is expected to overcome previous disadvantages and provide a more flexible, accurate and reliable working environment.

4.4.2. Includes

The FE Models of CFRP coupon tests are divided into different modules containing the necessary information to obtain proper simulation results.

Each module is defined in a text file, called Include file, that in case of LS-Dyna can have a .k, .key or .dyn extension. Each Include file holds a part of the FE Model that can be commonly used in different FE Models.

Finally, a text file, named Main file, calls all the necessary Include files to obtain proper results simulation. There is one Main file per Coupon test model.

The use of Includes files provides a more efficient and organized management of the necessary information for the simulation. This facilitates the replication of tests and the exchange of data between different projects.

The list of Include files defined in the models are shown below:

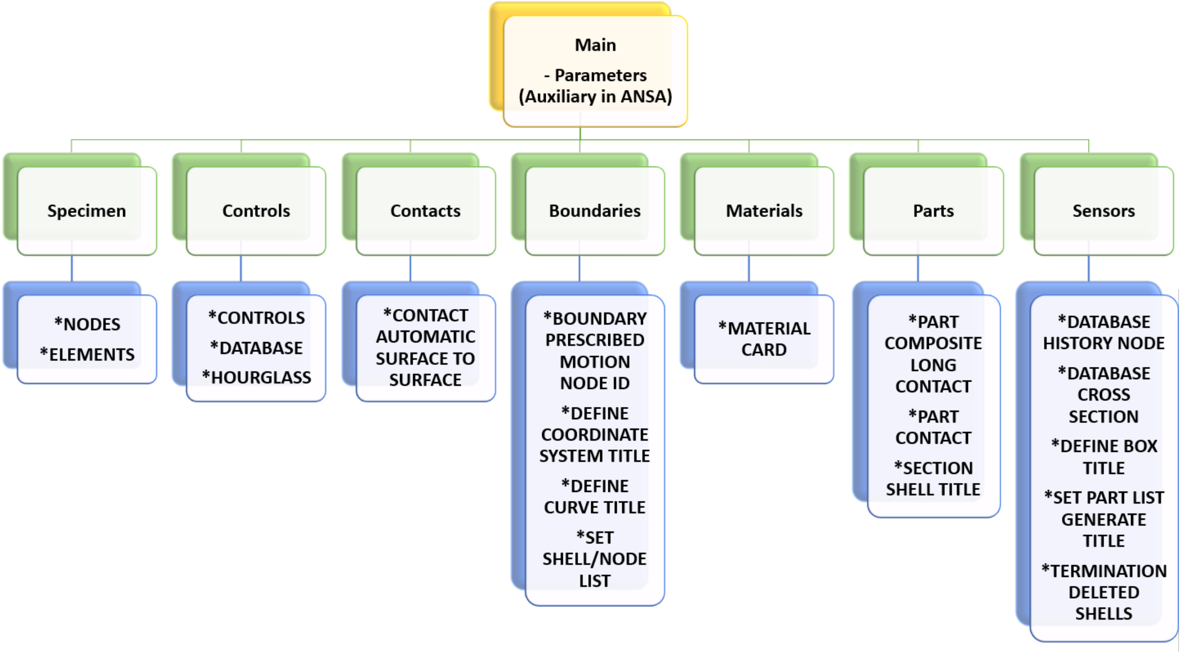


Figure 32. Includes's tree.

- *Controls and Databases.* The Control and Databases include file contains the controls cards that are used to define parameters and solution options in the analysis. These cards govern aspects such as solution accuracy, numerical integration methods, time limits, result output, among others. It also contains the databases setting that are necessary to obtain output files containing results information. This file is standard for all tests.

- *Sensors.* The Sensor include file contains the defining of the model outputs, i.e., this file will define at which points of the specimen the forces are to be measured (*DATABASE_CROSS_SECTION_SECTION_PLANE_ID) and which points of the specimen are used to measure displacements (*DATABASE_HISTORY_NODE).

- *Parts.* The Parts include files contain detailed information about the orientation, the number of layers and the thickness of the material (*PART_COMPOSITE_LONG_CONTACT). These files help structure and modularize the definition of different Stacking sequences, making it easier to reuse them in different Coupon test which are performed with the same Lay-up.

- *Materials*. Material includes files allow for the definition and characterization of different types of materials based on their specific properties(*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO_TITLE). These files include parameters such as density, elastic modulus, Poisson's modulus, among others. The use of these files provides advantages in terms of organization, reusability, and flexibility, as it facilitates the management of material data, property updates, and consistent application of material models in different simulations. This file is standard for all tests.

- *Specimen*. The Specimen includes files contain detailed information about the geometry (*NODES and *ELEMENTS) that make up a specimen used in a simulation. These files describe the connectivity between the elements, the coordinates of the nodes, the material properties, and other relevant details for the specific specimen. These files facilitate an accurate description of the specimen and are used to automatically generate the necessary mesh for the simulation.

- *Boundaries*. The Boundaries includes are files that contain information about the boundary conditions used in a simulation. These files describe the physical limits or constraints applied to the model, such as prescribed displacements and movement restrictions, i.e., which points will be fixed, and which will move (*SET_NODE_GENERAL_TITLE).

- *Contacts.* The contact includes are files that contain information about contact interactions between different components in a simulation model (*CONTACT_AUTOMATIC_SINGLE_SURFACE_ID).

4.4.3. Testing models

4.4.3.1. Tensile test 0º

The tensile test is simulated by gradually applying an increasing axial load to the model in the direction of the fibres at 0º. As the load is applied, the deformations of the composite material are recorded and analysed. The simulation allows visualizing how the 0º carbon fibres stretch and resist the tensile load. Stress-Strain curves can be obtained, representing the material's behaviour during the test. This provides information about the maximum tensile strength, yield stress, and other relevant parameters.

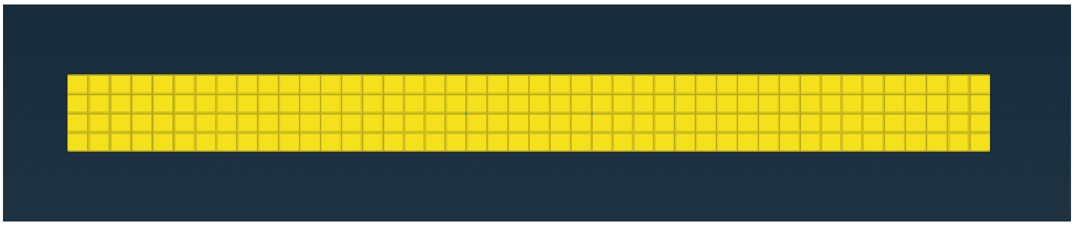


Figure 33. Tensile test 0º.

4.4.3.2. Tensile test 90º

In this type of test, a gradually increasing axial load is applied in the direction perpendicular to the fibres, which are oriented at 90º. During the simulation, the deformations of the composite material are recorded and analysed. This allows us to visualize how the carbon fibres at 90º resist the tensile load. Stress-Strain curves are generated, representing the material's behaviour during the test. These graphs provide valuable information about the maximum tensile strength, yield stress, and other relevant parameters for the material.

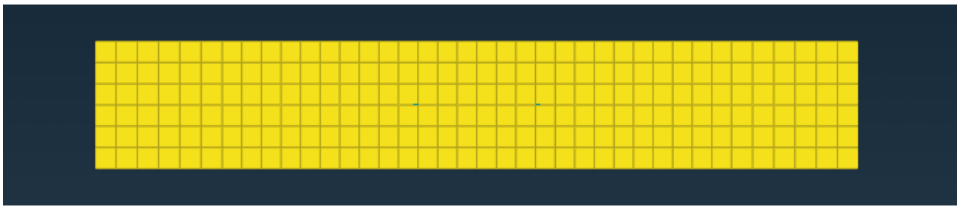


Figure 34. Tensile test 90º.

4.4.3.3. Compression test 0º

During the compression test of carbon fibre with fibres oriented at 0°, a gradually increasing axial load is applied in the opposite direction to the fibre orientation. Deformations of the composite material are recorded and analysed during the simulation. This allows for the observation of how the 0° carbon fibres compress and withstand the compressive load. Load-deformation curves can be generated to represent the material's behaviour during the test. These curves provide information about the maximum compressive strength, stiffness, and other relevant parameters for the specific material.

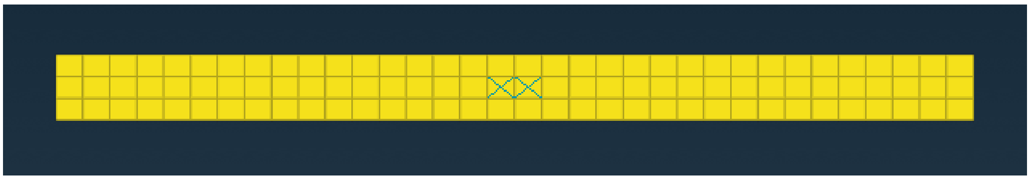


Figure 35. Compression test 0º.

4.4.3.4. *Compression test 90º*

In the compression test of carbon fibre with fibres aligned at 90º, a gradual axial load is simulated in the direction perpendicular to the fibres. During the simulation, the deformations of the composite material are recorded, and the obtained results are analysed. This allows visualization of how the 90º carbon fibres compress and withstand the compressive load. Load-deformation curves can be generated, representing the material's behaviour during the test. These curves provide information on maximum compressive strength, stiffness, and other relevant parameters.

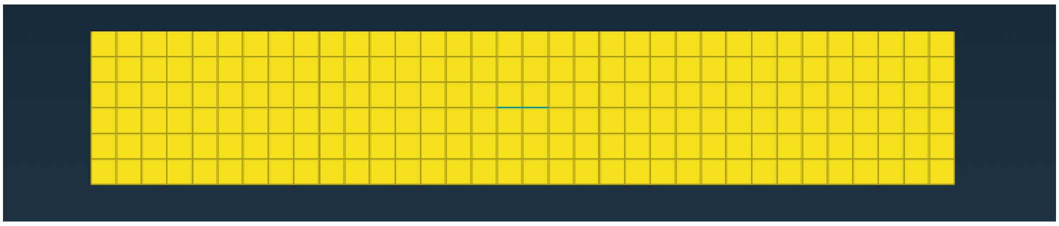


Figure 36. Compression test 90º.

4.4.3.5. *In-plane shear test*

In the in-plane shear test of carbon fibre with fibres at +45º/-45º, a gradual application of shearing stress parallel to the plane of the fibres is simulated. During the simulation, the deformations of the composite material are recorded, and the obtained results are analysed. This allows for the observation of how the +45º/-45º carbon fibres resist and deform under shearing stress. Stress-strain curves can be obtained, representing the material's behaviour during the test. These curves provide information on in-plane shear strength, stiffness, and other relevant parameters for the tested material.

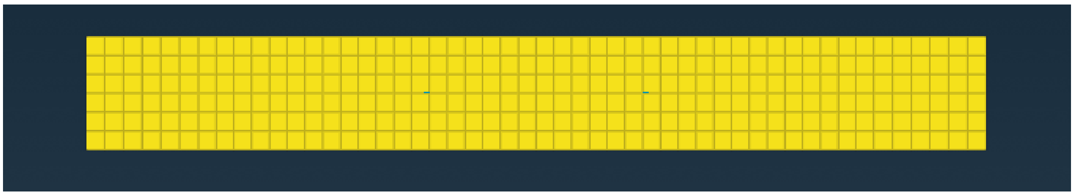


Figure 37. In-plane shear test.

4.4.3.6. *Compact tension test*

In the compact tension test of carbon fibre with fibres at 0º and 90º, a simulation is conducted where an axial force is applied (in the y-axis direction) to a sample with a geometry that includes two holes where the specimen is gripped by the machine. During the simulation, deformations of the composite material are recorded, and the obtained results are analysed. This type of test allows for evaluating the fracture resistance and the material's ability to withstand crack propagation. Force-displacement curves are used to characterize the behaviour of the sample during the test. These curves provide valuable information about the fracture resistance and toughness of carbon fibre in different fibre orientations.

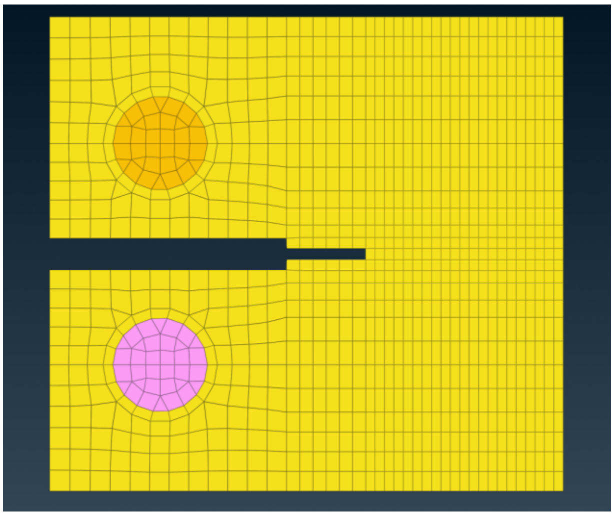


Figure 38. Compact tension test.

4.4.3.7. Compact compression test

The compact compression test on carbon fibre with 0º and 90º fibres is used to assess the carbon fibre’s ability to withstand compressive loads. In this test, a carbon fibre specimen is used with fibres arranged in two directions: one aligned parallel to the load (90º) and the other perpendicular to it (0º). The main objective is to determine the carbon fibre’s capacity to withstand compression in different fibre orientations. By obtaining load-deformation curves, the material's behaviour during the test can be analysed. These curves provide valuable information about the fracture resistance and toughness of carbon fibre in different fibre orientations.

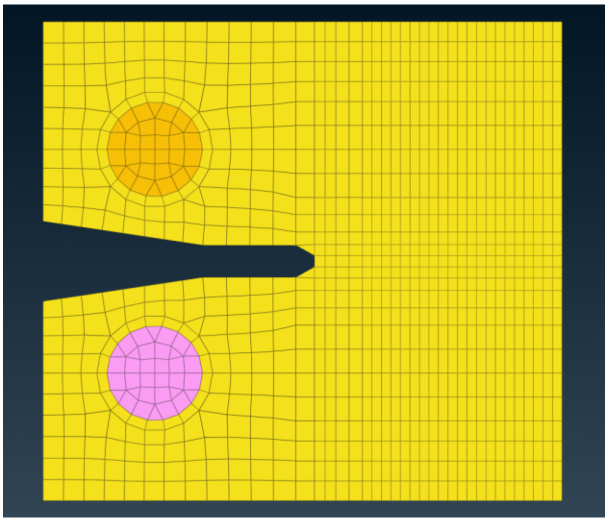
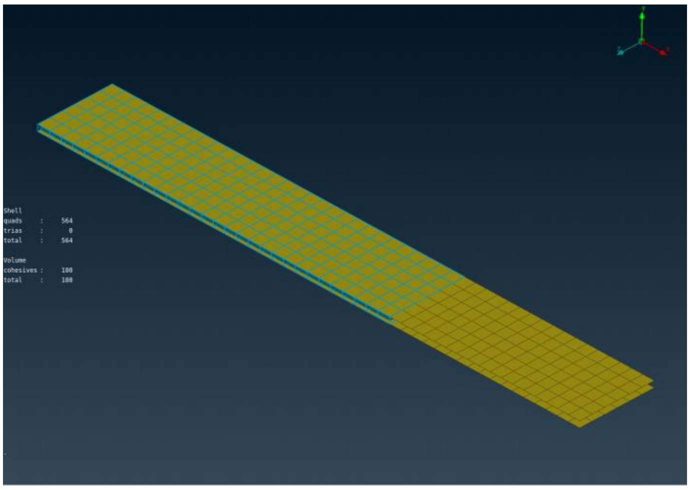


Figure 39. Compact compression test.

4.4.3.8. Mode I (DCB) test

During the simulation of the Mode I test (DCB) with 0° oriented fibres, a uniaxial tensile load is applied to both faces of the DCB, while they are bonded by a cohesive material. This induces crack opening. The load is applied gradually or at a constant rate. By simulating the Mode I test (DCB) with fibres oriented at 0°, information on the behaviour of the matrix interface and the fracture toughness in this specific direction can be obtained.



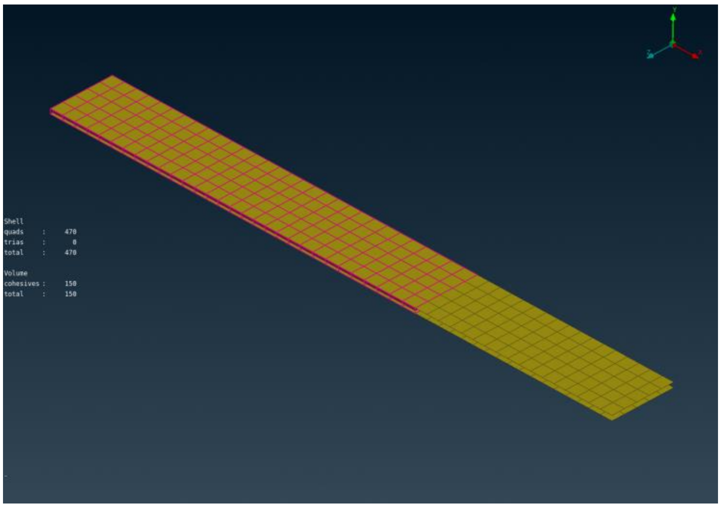
```
Shell
quads     :   564
trias     :     0
total     :   564

Volume
cohesives :   100
total     :   100
```

Figure 40. DCB sample.

4.4.3.9. Mode II (C-ELS) test

The simulation of the Mode II test (C-ELS) for carbon fibre with 0° oriented fibres involves subjecting a composite specimen to shear loading at its bond interface. This sample is placed in an arrangement with the top and bottom faces overlapped by a cohesive material, where a crack will initiate. Throughout the simulation, the deformation occurring in the crack region is carefully monitored and analysed to assess the fracture toughness of the material. The results of this analysis provide valuable insight into the behaviour of carbon fibres oriented at the 0° interface when subjected to shear loading, giving information on the strength and performance of the bond in this specific orientation.[49]



```
Shell
quads     :   470
trias     :     0
total     :   470

Volume
cohesives :   150
total     :   150
```

Figure 41. C-ELS sample.

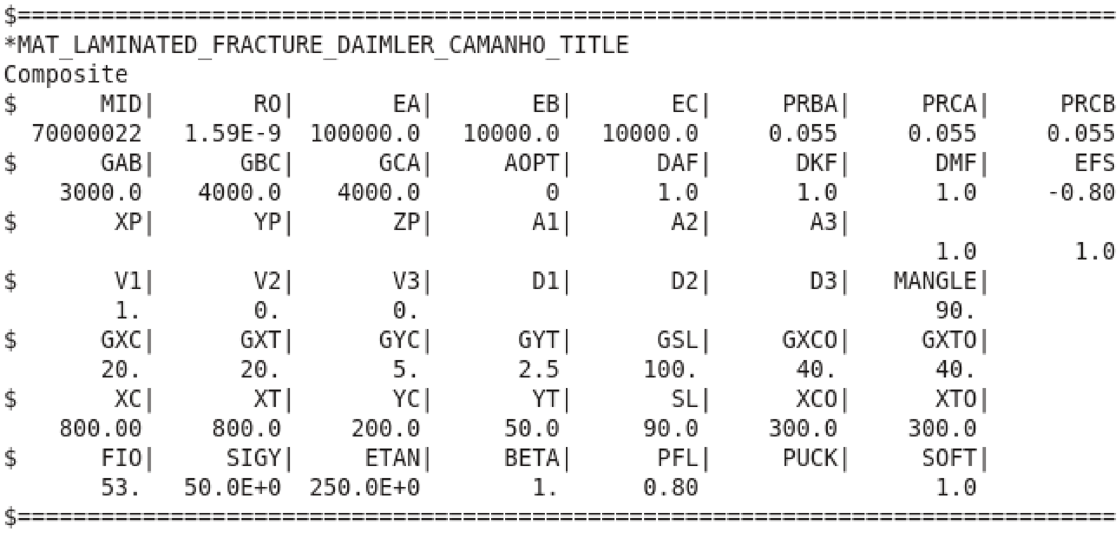
CHAPTER 5. MATERIAL CARD 262

5.1. MAT_262: *MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO

Material 262 is a widely used model to simulate the behaviour of fibre-reinforced laminated composite materials. This orthotropic continuous damage model accurately captures failure phenomena and allows an accurate representation of the material response. It considers in-plane shear behaviour, which is essential for understanding the stress and strain distribution. Implemented in several numerical simulation elements, Material 262 offers flexibility for structural analysis.

The Material 262 card is indispensable in carbon fibre testing as it provides a detailed description of material properties, ensures reproducibility of tests and facilitates accurate comparison of results. It includes Young's modulus, Poisson's ratio, shear modulus, fracture toughness, bulk density, material axis options and many other parameters, providing a complete understanding of material behaviour.

Access to a comprehensive Material 262 data sheet enables informed material selection for each test, ensuring specific requirements are met. This improves the quality and reliability of test results in the carbon fibre field. In addition, citing the Material 262 data sheet in scientific publications establishes a solid basis for validation and verification of results. Researchers can support their claims, promote reproducibility of experiments, and enable verification of results within the scientific community.[50]



```
$===============================================================================
*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO_TITLE
Composite
$     MID|       RO|       EA|       EB|       EC|     PRBA|     PRCA|     PRCB|
  70000022  1.59E-9 100000.0  10000.0  10000.0    0.055    0.055    0.055
$     GAB|      GBC|      GCA|     AOPT|      DAF|      DKF|      DMF|      EFS|
    3000.0   4000.0   4000.0        0      1.0      1.0      1.0    -0.80
$      XP|       YP|       ZP|       A1|       A2|       A3|
                                                                1.0      1.0
$      V1|       V2|       V3|       D1|       D2|       D3|   MANGLE|
        1.       0.       0.                                    90.
$     GXC|      GXT|      GYC|      GYT|      GSL|     GXCO|     GXTO|
       20.      20.       5.      2.5     100.      40.      40.
$      XC|       XT|       YC|       YT|       SL|      XCO|      XTO|
    800.00    800.0    200.0     50.0     90.0    300.0    300.0
$     FIO|     SIGY|     ETAN|     BETA|      PFL|     PUCK|     SOFT|
       53.  50.0E+0 250.0E+0       1.     0.80               1.0
$===============================================================================
```

Figure 42. Material 262 card example.

Variable name	Description
MID	Material identification
RO	Mass density
EA	Young's modulus in longitudinal direction
EB	Young's modulus in transverse direction
EC	Young' modulus through-thickness direction (perpendicular to ply)
PRBA	Poisson's ratio BA
PRCA	Poisson's ratio CA
PRCB	Poisson's ratio CB
GAB	Shear modulus AB
GBC	Shear modulus BC
GCA	Shear modulus CA
AOPT	Material axes option
DAF	Flag to control the tensile failure on longitudinal fibre
DKF	Flag to control the compression failure on longitudinal fibre
DMF	Flag to control matrix failure on transverse matrix
EFS	Maximum effective strain for element layer failure
V1, V2, V3	Component of vector v for AOPT=3
MANGLE	Material angle in degrees for AOPT=0 and AOPT=3
GXC	Fracture toughness for longitudinal fibre compressive failure mode
GXT	Fracture toughness for longitudinal fibre tensile failure mode
GYC	Fracture toughness for transverse compressive failure mode
GYT	Fracture toughness for transverse tensile failure mode
GSL	Fracture toughness for in-plane shear failure mode
GXCO	Fracture toughness for longitudinal fibre compressive failure mode
GXTO	Fracture toughness for longitudinal fibre tensile failure mode
XC	Longitudinal compressive strength
XT	Longitudinal tensile strength
YC	Transverse compressive strength
YT	Transverse tensile strength
SL	Shear strength
XCO	Longitudinal compressive strength
XTO	Longitudinal tensile strength
FIO	Fracture angle in pure transverse compression
SIGY	In-plane shear yield stress
ETAN	Tangent modulus for in-plane shear plasticity
BETA	Hardening parameter for in-plane shear plasticity
PFL	Percentage of layers which must fail before crash front
PUCK	Inter-fibre-failure criterion
SOFT	Softening reduction factor for material strength crash front elements

Table 1. Material card properties.

5.2. Material card definition

As a first step of the work, the material properties obtained from the characterisation tests are introduced in the definition of the coupon card. In this case, the first state is obtained. This is done in order to evaluate the mechanical properties of the material in the MAT_262 model and to detect possible unwanted couplings between the damage mechanisms affecting the constitutive laws of the material.

In the next stage, the affected constitutive laws are adapted to minimise the effect of the couplings and to obtain the final material card. The aim is to adequately describe the material behaviour for the different tests at work and to provide reliable and stable results for the crash simulations. Specimens are simulated under automotive conditions, using a monolayer model and a large in-plane element size.

Once the MAT_262 card achieves an adequate level of correlation in coupon tests, its performance in component-related tests is tested. Differences between coupon test and real service conditions are analysed, especially in failure modes and damage evolution. The effects of these differences on the material constitutive laws are evaluated and modifications are introduced in MAT_262 to improve the correlation in component tests and in service conditions.

That is, the final development of the CAE material card is based on the following methodology:

- The initial definition of the material card using the material properties.
- The correction of possible drawbacks in the application of the material laws.
- The consideration of differences between coupon and component materials in terms of manufacturing processes such as:

    - Increased layer thickness in CFRP components.
    - Fibre misalignment during the VARI process.

This methodology is enriched by IDIADA's experience at component level.

CHAPTER 6. RESULTS

6.1. Introduction

The comparison of FEM results with experimental data obtained in laboratory tests under real conditions is of paramount importance in carbon fibre development. This comparison allows validation of the accuracy, reliability and predictivity of the FEM. It also allows the identification of any discrepancies between the FEM and the experimental results. The identification of these discrepancies allows adjustments and improvements to be made to the experimental tests to increase their accuracy.

It is important to note, however, that this project does not focus specifically on its development. Instead, it focuses on the verification and validation of existing models, using experimental data to support their accuracy and applicability.

With this approach, it is expected to improve the workload in carbon fibre related projects, as well as its application in MEP software, which may have significant implications for future product design and development.

6.2. Correlation methodology

The correlation of carbon fibre results involves following different methods and phases, such as pre-processing, calculation, and postprocessing. These stages are essential for collecting and preparing data, performing necessary calculations, and ultimately analysing and comparing the obtained results.

6.2.1. Pre-processing phase

During the pre-processing stage, the selection or definition of materials is performed in the program's data library, and the mesh (the specimen or set of nodes and elements of the model) is prepared. This involves determining the type, distribution, and size of the elements, as well as selecting boundary conditions, loads, and other options that may affect the result. This phase is crucial for establishing the initial parameters of the model and ensuring an appropriate representation of the system under study. In this study, the ANSA software version 23.1.1 has been used to perform the pre-processing stage.

6.2.2. Calculation phase

The calculation stage consists in submitting the FEM of the different tests in the IDIADA cluster. The calculation machine runs LS-Dyna solver to compute the nodes displacements and elements stress-strains applying the boundaries conditions and other parameters defined in the model.

The most important item of the calculation is the material card which define the material law and material parameters of the FEM.

From this stage we can obtain the data requested as output in the FEM, such as of the displacement generated in the specimen and the force/displacement curves.

6.2.3. Post-processing phase

In the post-processing phase, the results obtained in the calculation are visually represented and analysed in graphs.

This stage is carried out using the Meta software version 23.1.1, which can be used to obtain additional information on the behaviour of the analysed system, such as deformations, stresses, among others.

In addition, during this stage, files called "sessions" were designed for each test, in which a simplified code was incorporated to speed up the user's tasks. Through these "sessions", the corresponding graphs can be executed instantaneously, eliminating the need to manually select the measurements in each axis, the units, or the normalisation of the values, among other configurations.

6.3 Result analysis

In the obtained results in this study, the values of engineering stress and engineering strain were used instead of the true values. The choice to use engineering stress and strain is based on several considerations.

Firstly, the use of engineering stress and strain is simpler and more convenient in many cases. These values are calculated using basic measures of force and length, making their determination and application in calculations and analysis easier. Additionally, engineering stress and strain are widely employed in the design and analysis of structures and components as they provide a conservative estimation of the material's response. This means that an additional safety margin can be ensured in designs by considering potential variations and nonlinear behaviours of the material.

Finally, due to the confidentiality of the company and the protection of sensitive data, the specific values obtained in the graphic results of this work will not be presented in this document. Instead, the normalized values corresponding to the values of engineering stress [MPa], engineering strain [-], applied force [kN] and displacement [mm] will be presented. For this reason, the plots of the absolute value of the relative error have also been made as a second comparison between the simulation (CAE) and the real tests.

Results with real values will be shown only in the presentation.

6.3.1. Tensile 0º

During this test, noticeable trends in test behaviour are observed. Initially, a significant error is evident in the minimum test, reaching up to 20% for the value of 0, in contrast to the curve corresponding to the maximum test, which presents an error close to 5%. As we progress, the curves tend to stabilise; the stiffness remains constant and repeatable for both samples, with the curve corresponding to the maximum test being slightly higher. At the end of the analysis, the minimum test curve experiences a substantial increase in error due to premature failure of the specimen, producing a 27% discrepancy with respect to the simulation curve. It is important to note that both curves show higher deformation in the real experiments, while the simulation exhibits higher stiffness.

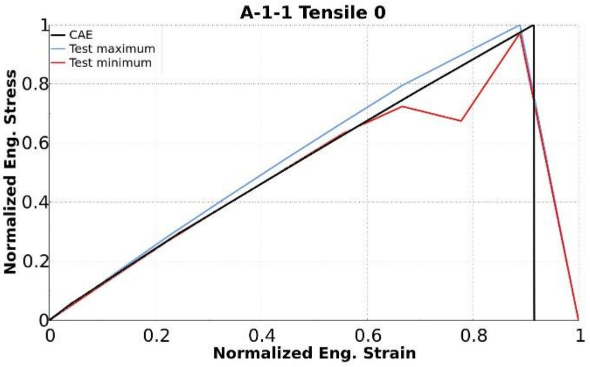


Figure 43. Tensile test graph at 0º.

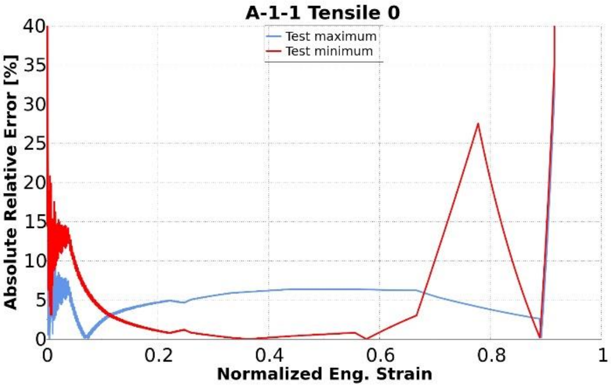


Figure 44. Absolute relative error graph.

6.3.2. Tensile 90º

At the beginning of certain tests, a non-linear behaviour is observed, possibly attributable to the properties of the adhesive bonding the CFRP to the aluminium tabs. Subsequently, both tests reach a stabilisation phase, with the minimum test showing an error of approximately 8%, while the maximum test shows an error of around 4%. These results suggest that there are variations in the stiffness of the material, which exceed previous expectations.

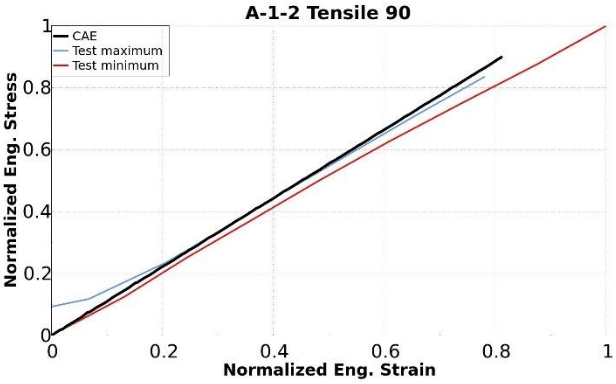


Figure 45. Tensile test graph at 90º

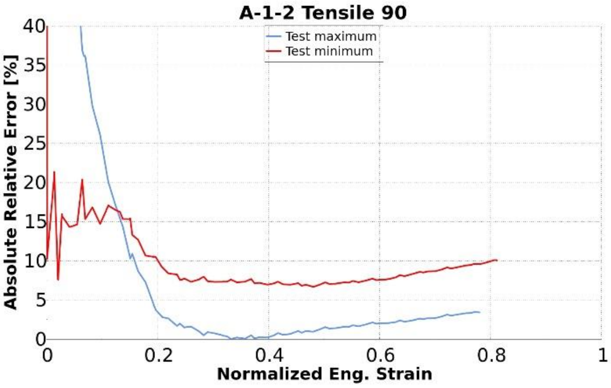


Figure 46. Absolute relative error graph.

6.3.3. Compression 0º

The tests exhibit a slight variability in stiffness and toughness. In the minimum test, we observe a lower stiffness compared to the CAE simulation, resulting in an absolute relative error of 13%. In the case of the maximum test, we note that the toughness is lower than the simulation due to an anticipated fracture in the specimen, generating an absolute relative error of 7%.

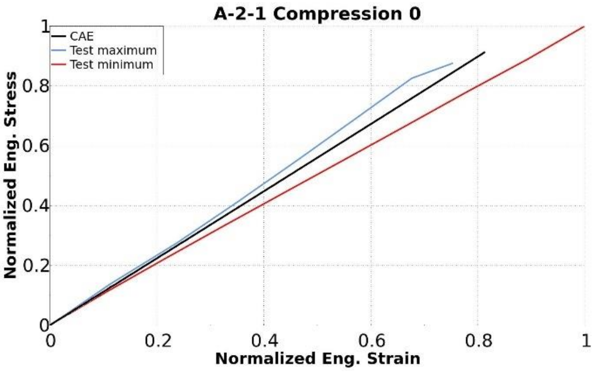


Figure 47. Compression test graph at 0º.

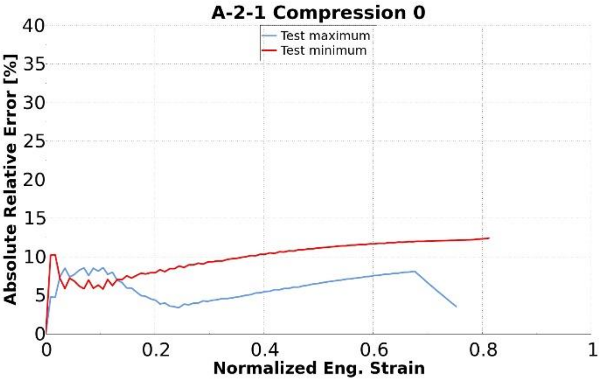


Figure 48. Absolute relative error graph.

6.3.4. Compression 90º

The samples exhibit notable differences in their behaviour. In the minimum test, an elastic response is manifested up to the failure point, where a 15% error is recorded in the proximity of the breaking point. On the other hand, the maximum test shows plasticity before failure, reaching an error of 15% at the 0.4 point, where the specimen begins to fracture.

It is important to note that in some specimens, it is not possible to fully reproduce the non-linear behaviour due to intrinsic limitations of the material used, specifically the absence of plasticity in the direction of the matrix.

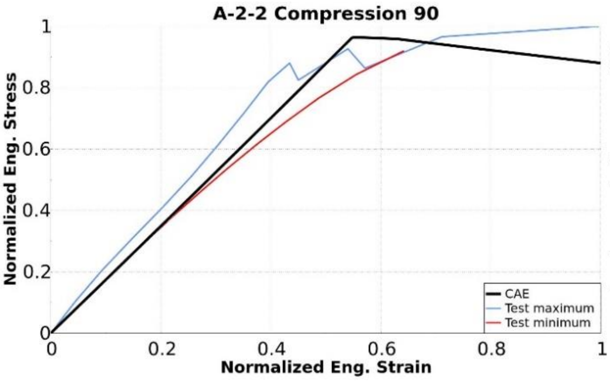


Figure 49. Compression test graph at 90º.

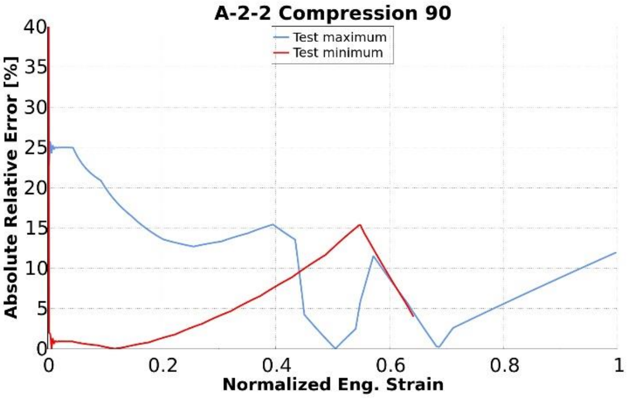


Figure 50. Absolute relative error graph.

6.3.5. In-plane shear

A good repeatability observed in the elastoplastic part of the test. The maximum strength of the material has not been obtained, since norm specifies that test should be stopped at 5% strain.
The way the material deforms cannot be correctly represented by the linear definition of plasticity in MAT_262. To ensure that simulations in large deformation situations (such as shocks) are accurate, the yield stress is initially increased. Then, the slope is adjusted so that the stress reached at 5% strain corresponds properly with the experimental results.

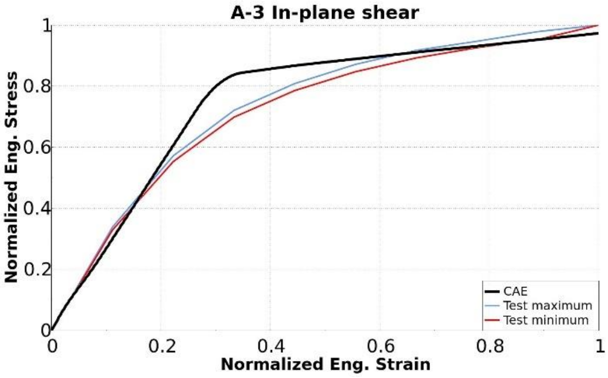


Figure 51. In-plane shear test graph.

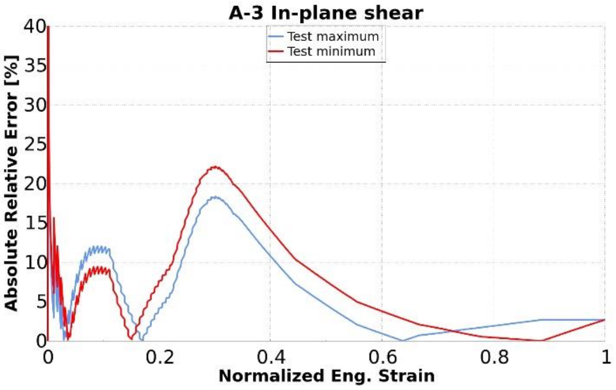


Figure 52. Absolute relative error graph.

6.3.6. Compact tension

Tests show good repeatability at different times. However, some scatter is observed in the non-linear behaviour before failure showing errors ranging from 2% and increasing at the end of the curves up to 40%. The simulation correlates well in general for the whole valid test range. However, the onset of the non-linear behaviour is a little above in the numerical simulations due to limitations in the definition of the shear law.

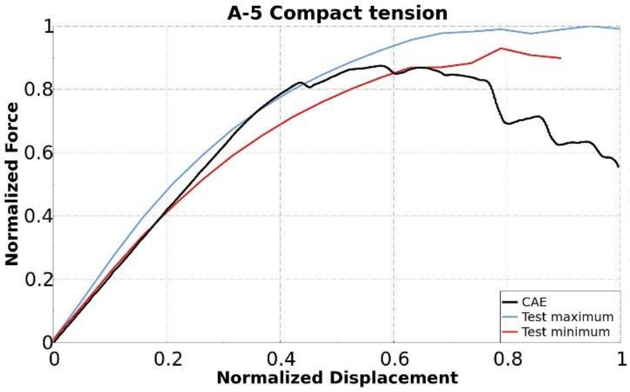


Figure 53. Compact tension test graph.

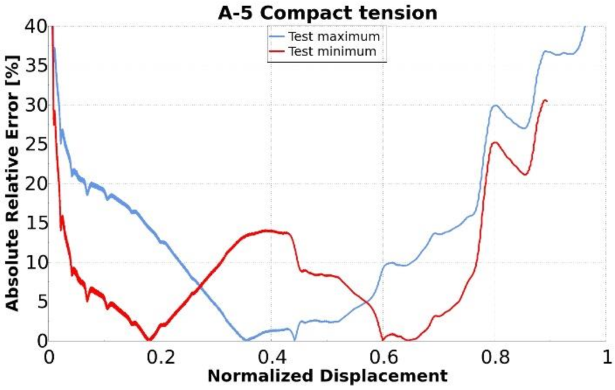


Figure 54. Absolute relative error graph.

6.3.7. Compact compression

In this test, a remarkable variability in the behaviour of the specimens up to fracture is evident, which translates into considerable discrepancies in their elastoplastic characteristics. It is important to point out that a substantial error has been recorded, reaching up to 50% in the case of the minimum test. The possible explanation for this variation could lie in the presence of vibrations that significantly influence the results obtained. This can be improved by placing an anti-buckling device on the specimens.

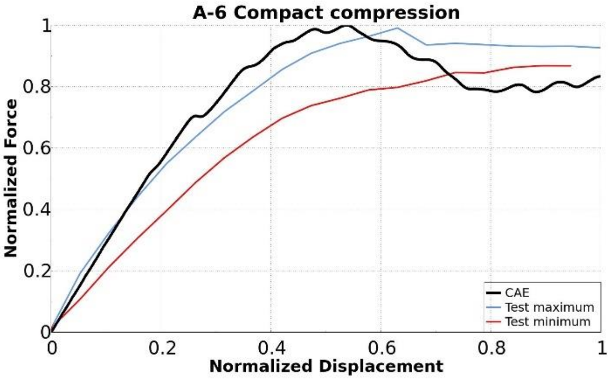


Figure 55. Compact compression test graph.

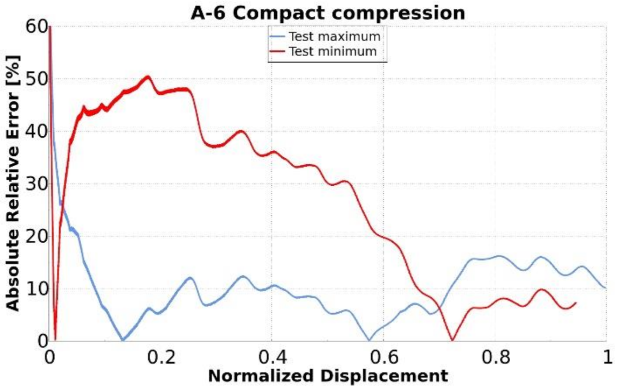


Figure 56. Absolute relative error graph.

6.3.8. DCB (Mode I)

During the DCB tests, large differences in the results occurred due to the unstable propagation of the “stick-slip” phenomenon due to the adhesive on the surface of the specimen. The “stick-slip” phenomenon is an undesirable behaviour observed on the moving specimen, as it does not move continuously and uniformly, but sticks momentarily (stick) and then releases (slip) repeatedly as it moves. This results in an intermittent movement rather than a smooth and continuous slip.

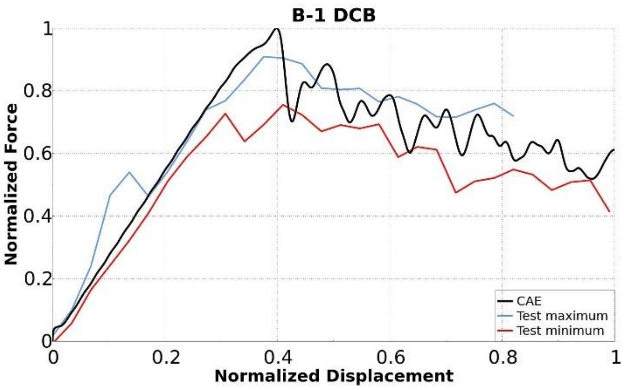


Figure 57. DCB (Mode I) test graph.

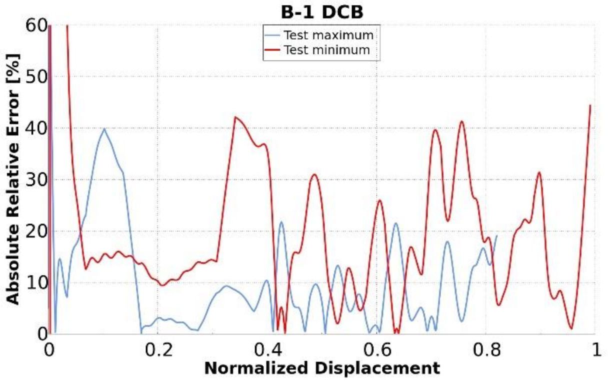


Figure 58. Absolute relative error graph.

6.3.9. C-ELS (Mode II)

Significant variability in the elastic behaviour of the specimens has been observed, with differences ranging from 1% to 27%. In addition, the stiffness recorded in this test is below expectations, which can be attributed to the high-test speed applied during the experimental phase.

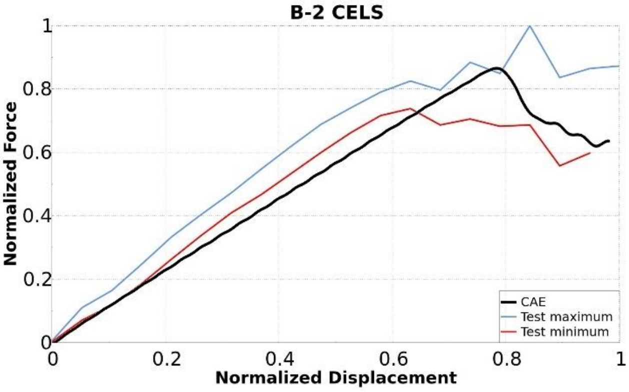


Figure 59. C-ELS (Mode II) test graph.

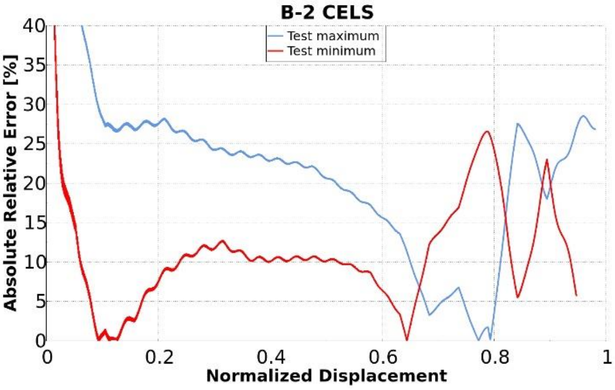


Figure 60. Absolute relative error graph.

CONCLUSIONS

In this Final Degree Project, a characterization methodology for carbon fibre (CFRP) test models has been addressed, and its efficiency has been enhanced through modularization.

The primary objective of this project has been to establish a CFRP testing methodology that optimizes the time and workload of individual tests. To achieve this, each test has been modularized for enhanced practicality and reusability. This implies that multiple tests can utilize the same inclusion files, avoiding the need for numerous files per test. Consequently, users can make modifications by accessing a single file, streamlining the process. To realize this, a structured and systematic approach has been developed to better understand the distinct components and steps involved in testing.

Firstly, efforts were directed towards standardizing sample preparation procedures by organizing and modularizing inclusion files to ensure correct usage and reliable outcomes. A detailed analysis of each test (simulation and real) used for assessing the mechanical properties of CFRP was performed.

Furthermore, special emphasis was given to Material Law 262, a fundamental component in characterizing and evaluating carbon fibre materials (CFRP).

Lastly, significance was also placed on interpreting and analysing test data through correlating experimental and CAE simulation tests, leading to the following conclusions:

- Tensile tests at 0 and 90 degrees demonstrate notable trends, with initial errors stabilizing over time. Particularly, the 0-degree tensile test highlights a significant error due to premature failure in the minimum test, underscoring the importance of understanding sample behaviour.
- Compression tests at 0 and 90 degrees exhibit slight variations in stiffness and toughness, suggesting factors initially unconsidered, such as adhesive properties and anticipated fractures.
- In-plane shear displays repeatability in the elastoplastic region.
- Compact tension tests display good repeatability but nonlinear behaviour before failure limits predictability. In Compact compression, sample variability and vibrations affect result consistency.
- The DCB test reveals the influence of the "stick-slip" phenomenon, while C-ELS demonstrates limitations in stiffness and elastic behaviour, raising concerns about reliability at high testing speeds.

In summary, this work has advanced the characterization and evaluation of CFRP materials, offering a more efficient and structured testing methodology. These findings and contributions are expected to serve as a foundation for future research and development within the company.

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