João Miguel Ramalheiro Martins Barata Duarte

Composite panels subjected to multi-impacts at different energy levels

Submitted in Partial Fulfilment of the Requirements for the Degree of
Master in Mechanical Engineering in the speciality of Production and Project

July/2018

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UNIVERSIDADE DE COIMBRA

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DEPARTAMENTO DE
ENGENHARIA MECÂNICA

Composite panels subjected to multi-impacts at different energy levels

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Desempenho de painéis compósitos sujeitos a multi-impactos de diferentes níveis de energia

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Coimbra, July, 2018

“Every end has a new beginning”

Unknown Author

ACKNOWLEDGEMENTS

The realization of this dissertation was only possible thanks to the support of some people whom I cannot forget to thank.

At first, I must thank to my advisors, Professora Doutora Ana Paula Amaro and Professor Doutor Paulo Reis, for their support, guidance and encouragement. I learned a lot from you and I'm sure I grew up as a future professional.

My thanks to my parents, my brother, and all my family, for all the support and trust over these five years. You are my mainstay in life, and I know you will continue to be.

A big thank you to my colleagues of the "sala da tese" for these insane five months of work. We shared our problems and victories in this last academic journey, and you made that work seem easier and a bit more fun. Ângela, Toni, Gonçalo, Ponte, Jonas, Miguel, Sara and Tomás, a big thank you.

My thanks to the colleagues with who I shared this five years of classes, tests, dinners, "Queimas", and a great friendship. Toni, Filipe, Gonçalo and Miguel, thank you. A special thank you to Gonçalo Carvalho for being a good surprise in my life, and my most loyal buddy in this journey, we arrived here together!

To the people that made part of the most challenging and amazing experience of these five years, to the friends I made in Split, a big thank you. Alina, Bernardo, Camarneiro, Ponte, Nuno and Pedro, you are very special to me.

A big thank you to the people that helped to make of this last year the most challenging, fun and rewarding one. I've grown a lot with all of you, and I'm sure it will be difficult to find a group that works so well and with so much motivation. Thank you to all the members of BEST Coimbra, who are now my friends. BEST, easy to join, hard to leave, impossible to forget.

Finally, my thanks to all my "old" friends from Lousã, for all the friendship and support in all these years. As much as life changes, our friendship stays strong.

To all of you, I'm really grateful.

Abstract

Composites are known by their good mechanical properties and low weigh when compared to traditional materials. Because of it, they are used in many applications, like: aircraft/space sector, automotive sector, medical applications and in many sports.

Composites applied to the fuselage of airplanes, for example, are subjected frequently to low velocity multi-impacts, resultant from collision with birds, rocks or even ice stones. The low-energy impacts affect significantly the residual strength of those materials, and the damage resultant is difficult to detect. Therefore, the main goal of the present work is to study the effect of multi-impacts on laminated composites, and to obtain models that are able to estimate the fatigue life in Glass Fibre Reinforced Composites (GFRP).

Composite laminates subjected to multi-impacts with constant energy level have already been studied by many authors, but multi-impacts with different/variable energy levels represent a topic that was not studied yet. Therefore, this subject sustains this work. For this purpose, experimental tests were performed, where the results of multi-impacts with the same energy level are express by a curve “energy versus number of impacts to failure”, similar to the S-N curves used in fatigue. In terms of multi-impacts with variable energies, the samples were subjected to sequences of impacts with two different blocks composed by different energy levels. The first block represents one third of the fatigue life estimate by the curve obtained with constant energies, and the second one was applied up to failure (full perforation).

Finally, the impact fatigue life was estimated based on the E–N curve to the appropriated energy, using a linear cumulative damage rule, and the predictions were compared with experimental results. It is possible to conclude that the linear cumulative damage rule is not applicable to predict the fatigue life in multi-impact tests with variable energy levels for GFRP.

Keywords Low velocity impact, Mechanical testing, Multi-impact, Polymer matrix composites (PMCs).

Resumo

Os materiais compósitos são conhecidos pelas suas boas propriedades mecânicas e baixo peso, quando comparados com os tradicionais materiais que estes substituem. Por estas razões, podem ser utilizados nas mais diversas áreas, tais como: sector da aviação/espaço, sector automóvel, medicina, e em muitas aplicações desportivas.

Os compósitos utilizados nas fuselagens dos aviões, por exemplo, são frequentemente sujeitos a multi-impactos de baixa velocidade, resultantes da colisão com pássaros, pedras ou mesmo granizo. Os impactos de baixa energia afetam significativamente as tensões residuais destes materiais, e o dano causado é de difícil deteção. Assim sendo, o objetivo principal deste trabalho é estudar o efeito de multi-impactos em compósitos laminados, e também obter modelos capazes de estimar a vida á fadiga em compósitos reforçados por fibra de vidro.

Multi-impactos com níveis de energia constantes em materiais compósitos laminados é um tema já estudado por vários autores, mas multi-impactos com níveis de energia variáveis é um tópico que ainda não foi estudado. Portanto, o tema sustenta este trabalho. De modo a cumprir esse propósito, foram realizados ensaios experimentais, em que os resultados dos multi-impactos com nível de energia constante são expressos pela curva "energia em função do número de impactos até á rotura", semelhante ás curvas S-N usadas em fadiga. No que diz respeito aos multi-impactos com energias variáveis, as placas foram sujeitas a sequências de impactos, divididos em dois blocos diferentes com níveis de energia distintos. O primeiro bloco corresponde a um terço da vida á fadiga, estimada pela curva obtida com energia constante, e o segundo é aplicado até á rotura (perfuração total).

Por fim, a vida á fadiga por impacto foi estimada com base na curva E-N para a energia pretendida, através da utilização de uma lei de dano linear cumulativa, e as previsões foram comparadas com os resultados experimentais. É possível concluir que, para compósitos de matriz polimérica reforçados com fibras de vidro, essa lei não é fiável para prever a vida á fadiga em ensaios de multi-impacto com níveis de energias variáveis.

Palavras-chave: Compósitos de matriz polimérica, Impactos de baixa velocidade, Multi-impacto, Testes mecânicos.

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SIMBOLOGY AND ACRONYMS

Simbology

C – Damage fraction

E – Energy

Acronyms

DAS – Data Acquisition System

DEM – Departamento de Engenharia Mecânica

FCTUC – Faculdade de Ciências e Tecnologia da Universidade de Coimbra

GFRP – Glass Fibre Reinforced Polymer Composites

IBS – Impact Bending Stiffness

PMCs -Polymer Matrix Composites

1. INTRODUCTION

The utilization of composite materials goes back to the 1500s B.C., but their utilization has been increasing enormously since the World War II, where the bigger advance in research and production of these materials began. The importance of this type of material is related to their better mechanical properties and low weight when compared to traditional materials. They are used in many different fields, aircraft industry, marine industry, renewable energies, space applications, medical applications, etc.

In real life, materials aren't normally subject to ideal conditions of work, they are vulnerable to a lot of unpredictable situations depending on their utilization. Impact events are an example of that, and on composite materials they are really common. Per example, cars can be hit by gravel coming with acceleration from a truck in front of them. Airplanes are commonly hit by birds, hail, or even small rocks when they land or take off. All these impacts have different energies, and the damage caused is normally not visible to the naked eye, therefore it must be studied so it can be predicted.

The aim of this work is to study the behaviour of composite materials when these are subjected to multi-impacts with different energy levels. Events of repeated impacts on composites have already been studied, but not when the impact energy used to break the material changes during tests. The number of multi-impacts studies on composites has been increasing in recent years, showing the relevance of this type of study to scientific community.

The impact test choose is drop weight impact test. In the begging the objective will be to find a model that relates the number of impacts to failure with a constant impact energy. The model will be used to predict the number of impacts to failure when different impact energies are applied. At the end, tests with different energy levels will be made, and the results will be compared to the ones predicted from the model.

The material used in tests is a glass fibre-reinforced polymer (GFRP) composite with E-Glass fibres and a polyester matrix. GFRP are the most widely used polymer matrix composites, and the key reasons for that are their low price and the fact of being the first significant structural composite to be developed.

This dissertation is divided in 5 chapters, and this is the Introduction.

In chapter 2 a literature review is done about composite materials, their applications, and about multi-impact events on composites, among others.

The chapter 3 is related with experimental procedure and the material used in tests. There is given information about the material and its manufacturing process, the necessary equipment, and some of the analysed data.

Chapter 4 is where the results of the tests are presented and discussed.

In the last chapter include the conclusions about the experimental tests and are presented proposals for future work.

2. LITERATURE REVIEW

2.1. Introduction

In this chapter it will be explained what are the composite materials, there classifications and applications. It will also be presented the composite in study during the experiments of this thesis and their possible applications. In the end, reference will be made to multi-impact on composite materials and the research that has been done until now.

2.2. Composite materials

There is no universally accepted definition for composite material [1], but a comprehensive definition can be: any multiphase material that features significant proportions of properties of all constituent phases in order to obtain a better combination of properties [2]. For engineering applications proposes the definition can be: a composite is an artificially made material [2], results from the combination of two or more materials that have different physical and chemical properties, and are insoluble in each other [1].

The uses of composites started thousands of years ago (1500 B.C.) in Egypt and Mesopotamian, where settlers start using a mixture of mud and straw to create buildings, making it more strong and resistant. Near 1200 A.C. Mongols created a bow made of composite material, they used wood, bone and “animal glue”. Nevertheless, the big advance in research and production of composite materials begun with the World War II (1939-1945), in result of need of lightweight and stronger materials for military aircraft. The Figure 2. shows the evolution of the relative importance of composite materials, based on that is possible to understand that the importance of this type of material is increasing and will continue in the next years, especially for aeronautical and naval applications [3].

The composite materials industry is growing really fast, now focused in renewable energy applications, searching for bigger, stronger, and lighter parts. The future passes through the areas of nanomaterials and bio-based polymer composites [3].

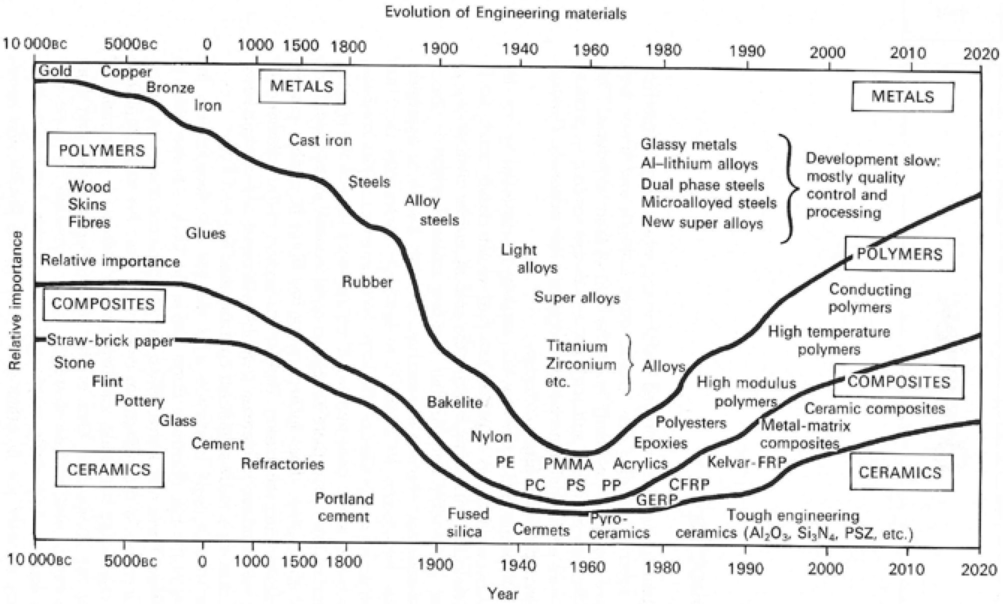


Figure 2.1. Schematic diagram presenting the relative importance of the four classes of materials in mechanical and civil engineering as a function of time (time scale is nonlinear) [4].

Composite materials are known for being lighter, stronger and more durable than the traditional materials. Most of it are created to improve combinations of mechanical characteristics as toughness, stiffness, ambient resistance and high-temperature strength. For example, a carbon-fibre reinforced composite part can be five times stronger, and present only one fifth of the weight of the same part made with 1020 grade steel [5]. Composites are also known for their design flexibility, due to the many types of this materials that can be moulded into complex shapes. The biggest disadvantage of this materials is the cost, despite the efficiency of the products when comparing to traditional ones, the raw materials are usually expensive [6].

2.3. Classification of composite materials

Most composites are composed by two phases, matrix and reinforcement. The matrix is the continuous phase, it surrounds and binds the reinforcement, that in most of materials are fibres or particles, of other material.

The tests needed to fulfil the objectives of this thesis will be made with a Glass Fibre-Reinforced Polymer (GFRPs), a composite material with a matrix of unsaturated polyester resin reinforced with glass fibres, also known as Fibreglass Reinforced Polyester.

This composite material has a lot of characteristics that make it a commonly used composite: it is strong, lightweight, non-corrosive, have design flexibility, is maintenance free and cheap. Per unit of weight, this material is among the strongest commercial materials, being stronger than concrete or steel [7].

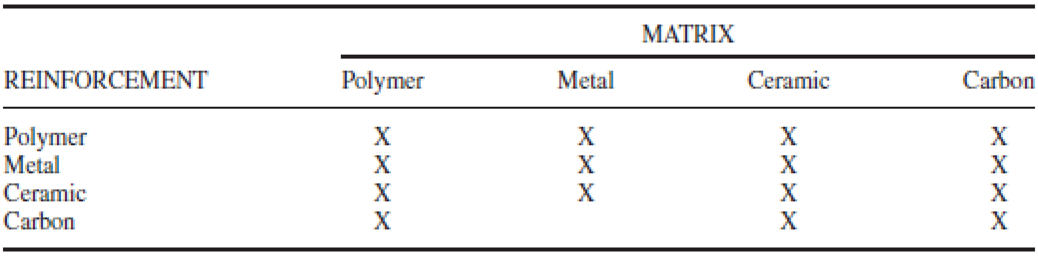
2.3.1. Matrix

The main functions of the matrix of a composite material are [8]:

- Protect the reinforcement from the environment;
- Keep the cohesion between the reinforcement;
- Distribute the load by the reinforcement in case of rupture.

A common way of classifying composite materials is by the type of matrix material. Solid materials can be separated into four classes: ceramics, metals, polymers, and carbon, considered in a separated category due to its unique features [9]. So, the four main categories of composite materials are: ceramic matrix composites (CMCs), metal matrix composites (MMCs), polymer matrix composites (PMCs) and carbon matrix composites (CAMCs). Nowadays the most widely used type of composites are PMCs. In Table 2.1 is presented the type of combinations possible to be made between the different materials.

Table 2.1. Possible combinations of materials to make composites. [9].



	MATRIX			
REINFORCEMENT	Polymer	Metal	Ceramic	Carbon
Polymer	X	X	X	X
Metal	X	X	X	X
Ceramic	X	X	X	X
Carbon	X		X	X

Polymer matrices of composite materials are normally viscoelastic materials, relatively weak, and have how stiffness. Are mainly the fibres who give the strength and stiffness to this type of composite materials. Polymer matrices can be divided in two big classes, depending on the type of polymer used: thermosets or thermoplastics resins.

Thermosets resins are the most used matrix materials for structural applications, and generally are more resistant to solvents and corrosive environments than thermoplastics. Other properties are resistance to heat and high temperatures, excellent adhesion, fatigue strength and excellent finishing. This resin passes through a curing process at elevated temperatures, where resin cures permanently by irreversible cross linking [10], it makes the material rigid and impossible to be reformed [9].

Thermoplastics resins don't cure permanently, meaning that can be reformed and reshaped. The resin remains solid at room temperature, but it can be heated and reshaped, by a physical process, unlike the thermoset resins. These resins are more complex to process when making a composite material than thermoset resins, and are also inadequate for structural applications.

Some of the most common resins used are unsaturated polyesters, epoxies, and vinyl esters; the least used resins are the polyurethanes and phenolics [10]. The most used resin in glass fibre reinforced composites is unsaturated polyester, a thermoset resin [5].

Polyester resins can be classified has saturated or unsaturated resins. More than 75% of all polyester resins used in the world are from unsaturated polyester. This happens because of their characteristics, it's dimensional stable, has an affordable cost, it's easy to handle, process and fabricate. It can also be fire retardant and corrosion resistant. All of this makes unsaturated polyester resins the best choice considering a balance between performance and structural capacities [10]. In Table 2.2 are presented some typical properties of these resins.

Table 2.2. Typical mechanical properties of Polyester Resins [10].

	Tensile Strength (MPa)	**Modulus of Elasticity (GPa)**	**Density (g/cm^3)**	**Compressive Strength (MPa)**	**Flexural Strength (MPa)**
Polyester resins	40-85	1.3-4.5	1.1-1.4	140-410	205-690

2.3.2. Reinforcements

When talking about reinforcements, the discontinuous part, composite materials can be divided in three main categories: particle-reinforced, fibre-reinforced and structural (Figure 2.2).

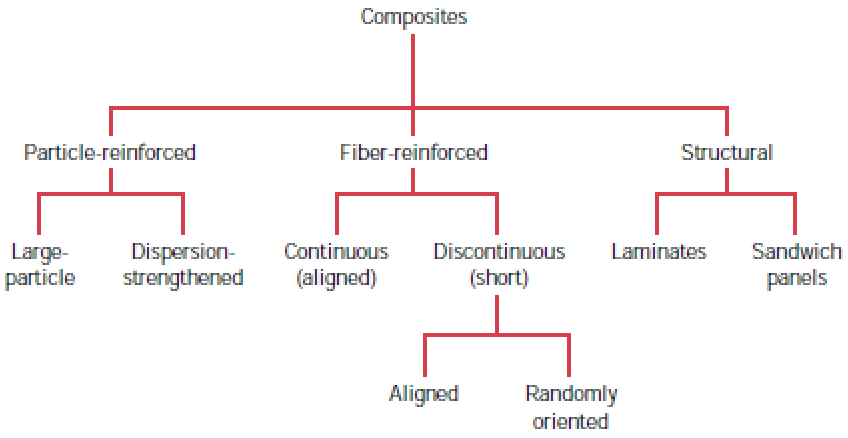


Figure 2.2. Scheme that shows the classification of reinforcements of composite materials [2].

The most common reinforcements used in composite materials are particles and fibres (aligned continuous or discontinuous). The structural composites result from the combination of composites with homogeneous materials.

In fibre-reinforced composites, the reinforcement (the fibres) are the main reason to the great importance they achieved and to the improvement in their properties, when compared to traditional materials they replace. The most important fibres for mechanical engineering applications are the glass fibres, carbon fibres, several types of ceramics, and high-modulus organics [9].

Glass fibres are made from glass, first it’s heathen until it molten, then it’s forced to pass through superfine holes, creating thin glass filaments. These fibres are then woven into large material pieces [11]. There are three main types of this fibres, E-glass, S-glass, and C-glass. The first one is specially for electrical applications, the second one for high strength parts, and the C-glass for high corrosion resistance purposes. The most widely used reinforcement is the E-glass, which can be produced from silica sand, limestone and other minerals, materials easy to obtain from raw materials like sand [5].

The original purpose of E-glass fibres was to provide isolation for electrical wires, but later it was found that these fibres have an excellent fibre forming capabilities, one of the many reasons for being widely used nowadays. Other reasons for this massive utilization are these properties of E-glass fibres: low cost, high production rates, non-flammable, relatively low density, impact resistance, and high strength [12]. Some mechanical properties of typical E-glass fibres are presented in Table 2.3.

Table 2.3. Mechanical properties of typical E-Glass fibres [10].

	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Density (g/cm^3)	Elongation (%)
E-Glass fibres	3445	72.3	2.58	4.8

2.3.3. Fibre orientation and stacking

When related to fibre orientation and stacking, two of the most common types of fibre-reinforced composites, are the laminates and the sandwich composites.

Laminates composites are made from a combination of laminas, resulting in a multiple-plie structure. The stacking and ply orientation depend on the application required to the material, and can change from ply to ply. The layers of this composite material are normally bounded by a resin in the thickness direction, in which each layer is made of fibres embedded in the matrix [13].

Each laminate composite has a description, where appears the orientation of each lamina, the number of laminas for each orientation, and the geometric sequence of the laminate orientations.

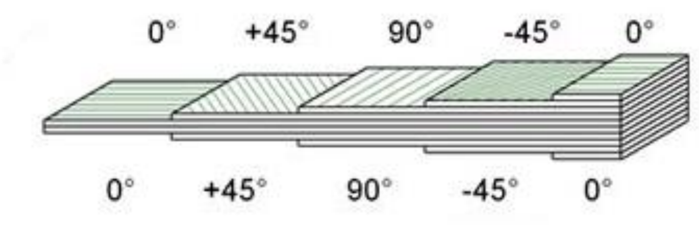


Figure 2.3. Representation of the different layers in a laminate composite [14].

In the Figure 2.3 it’s possible to see a composite laminate with ten layers with different orientations. The description of this laminate can be [0/-45/90/+45/0/0/+45/90/-45/0], or simplifying, [0/-45/90/+45/0]$_S$, in which the subscript ‘s’ means that the laminate is symmetric.

Sandwich composites are made putting a light material with good compressive strength in the middle of two counter-plates with high strength. The final structure is light and with good stiffness [8].

2.4. Applications of composite materials

Composites materials can't be considered the best type of material for every application; besides their strengths they also have weaknesses, both presented in the next paragraphs.

Strengths:

- Weight reduction, comparing to the materials they are replacing. The main reason to choose a composite material is the specific strength/stiffness;
- High strength, in result of the combination of properties from different materials;
- Better durability, leading to less need of maintenance. A good example of that is the excellent corrosion resistance in maritime applications;
- Design flexibility. Composites are made to suit a specific design for an application, adding specific materials to help in that.

Weakness:

- Low toughness comparing to traditional materials;
- Service temperature is limited.

One of the oldest composites still in use is concrete, a mix of small stones or gravel with cement and sand. This composite was improved by adding metal bars, which lead to an increase of its tensile strength besides the good compressive strength of concrete [6]. This improved concrete is called reinforced concrete.

Like it was said before, of all four classes of materials, polymer matrix composites (PMC) are the dominant type of composite materials [9]. This class of composite materials is present in almost all people daily lives, and some of the most common uses are:

- Aircraft industry;
- Marine industry;
- Sports equipment;
- Automotive components;
- Military equipment's;
- Renewable energy industry;
- Constructions materials;

- Space industry;
- Medical applications;
- Oil and gas industry.

Composites have been used in marine applications since several decades ago, and the racing yachts are the marine structure that uses more composite materials. The main objective is to achieve big velocities and have big resistance to impact, which can be obtain with a low weight and maximum stiffness structure. The composites which are more used in this application are the carbon fibre reinforced composites.

In the oil and gas industry, composite materials are being used in a lot of applications, such as protection, pressure vessels, equipment and transportation pipes. The piping systems used in oil transportation needs to resist to crude oil, high pressures and sea water (for offshore applications). The properties that composite materials can offer, like high service temperatures, good chemical resistance or good mechanical properties lead to their application in oil transportation pipes [5].

One of the most known applications of composite materials is in the aircraft industry, especially on airplanes fuselage. The airplane Boeing 787 is a good example of this, having 50% of is airframe made with composite materials, like is presented in the scheme of Figure 2.4. The change from the typical materials, like aluminium alloys, to composites, allowed to reduce the weight of the aircraft in 20%. Almost half of the composites used are carbon fibre reinforced plastic composites [15].

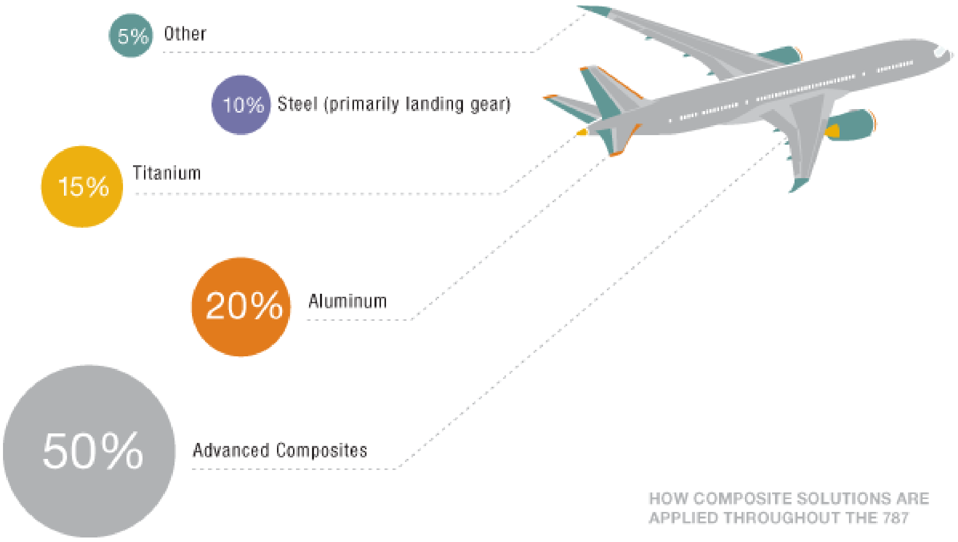


Figure 2.4. Scheme of the materials from which the airplane Boeing 787 is made [15].

The research of composite materials continues, and nanomaterials and bio-based polymers are some of the areas of greatest interest for researchers.

Every year, almost 2 million tons of unsaturated polyester resin components are produced worldwide [16]. It can be used for sports equipment, car bodies, swimming pools, surfboards, boat hulls, etc.

In aviation and aerospace, per example, this material can be used to produce engine cowlings, luggage racks and antenna enclosures. It can also be used in medical applications, like instrument enclosures or X-ray beds, due to X-ray transparency. This material is also used in wind energy applications, almost every wind turbine blade is made of a Glass-Fibre Reinforced Polymer.

2.5. Multi- Impact on Composite Materials

Due to their superior specific strength and stiffness, FRP composites have been widely used in structural applications subjected to quasi static loading. However, in aerospace, pipelines, or military applications, per example, these structures can be subjected to high strain rates loadings coming from impact events. When this happens, the behaviour of composite structures is normally poorer and more fragile than ductile materials such as metals [17].

Impact events are usually classified using one of these three characteristics, by velocity of impact, height of the drop weight or impact energy.

Although there is no official agreement in the classification of impacts, most of the authors agree that it can be divided in two categories: low velocity impacts and high velocity impacts. The transition between these two types is also not clear, and the opinions of the authors diverge. According to [18] low velocity impacts happen for velocities lower than 10 m/s. On the other hand, [19] stated that this type of impact occurs for impact speeds smaller than 100m/s.

The low velocity impacts are considered one of the most dangerous loads on composites materials, they can seriously affect the performance of these materials and are also difficult to detect visually [20]. With these impacts different types of damage can occur: matrix cracking, fibre-matrix deboning or fibre fracture. Nevertheless, the most common consequence of low impact events in composite materials is the delamination between layers with different orientations [21].

Compressive and tensile strength are two of the most affected properties by these events. Compressive strength is affected by the delamination phenomenon, being considered a design limitation parameter. Normally, premature buckling happens has a consequence of internal delaminations, which leads to a drop of the compressive strength. Tensile strength also shows a decrease when an impact load exists, but is much less noticeable than compressive one [21].

The energy of an impact load is normally absorbed by internal damage mechanisms, result of an interaction of many damage types, preventing the appearance of exterior signs of damage perceptible by visual inspection [21].

High velocity impacts are easier to detect, and a single impact can be enough to break the structure. A bullet impact is a good example of a high velocity impact event. The damage made by these are visible without any special technique, what makes easier their detection and quick reparation [8].

To evaluate the behaviour of a material when subjected to impact events, an experimental procedure is required, and to apply it a specified device is also needed. There are two main typed of impact tests, pendulum and drop weight tests.

In pendulum tests a sample is used in the vertical position and a hammer is released from a known high and it will crush into the specimen. The main objective of this test is to calculate the energy lost in breaking the sample. Izod, Charpy (Figure 2.5) and tensile impact are some of the most common pendulum tests. Simple impact tests, like these ones, are useful, but don’t provide enough information about what’s happening to the sample test during the impact. In the case of composites, per example, that can fail internally and don’t show any damage externally, the information provided by these tests can be misleading [22].

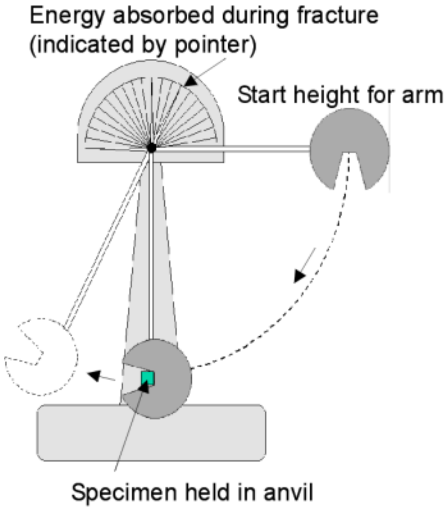


Figure 2.5. Charpy test scheme [23].

In drop weight tests (Figure 2.6) a weight is drop in a vertical direction, guided by a mechanism during the free fall. Both energy and velocity of impact can be changed for the impact event. Some drop weight machines can provide information such as impact energy, load, displacement or velocity versus time. Drop weight impact tests have some advantages over other type of impact tests [22]:

- Can be used in moulded samples, moulded parts, etc;
- Doesn't have a preferential direction of failure due to be a unidirectional test. The failure appears in the weakest point of the test sample and spread from there;
- The specimens can be considered failures even without breaking. The failure can be defined by deformation, crack initiation, or complete fracture, depending on the specifications needed.

Drop weight tests are considered the best simulation procedures of functional impact events, and consequently closer to real life environments.

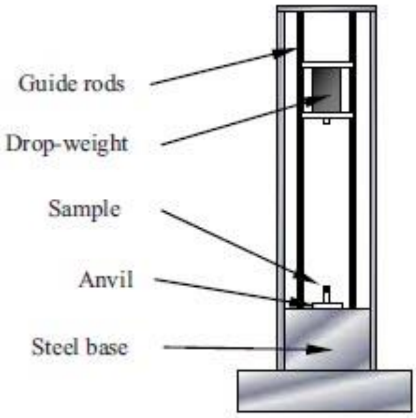


Figure 2.6. Drop weight test machine scheme [24].

Nowadays almost all impact tests are instrumented, this means that load, deformation and velocity during the entire period of impact event can be continuously recorded as a function of time. This is achieved using electronic sensing instrumentation, and can be applied to both test types explained above.

Multi-Impact tests are characterized by consecutive impacts in a sample of material to be tested, and in each impact several properties can be measured and compared between impacts, such as damage area, energy absorbed, maximum load, maximum displacement, etc. These tests allow to predict the behaviour of a certain material or piece when subjected to multi impacts.

The interest of the scientific community in the theme of multi-impact in composite materials has been increasing in recent years. This can be understood in the graph presented in Figure 2.7, where number of citations per year of articles about multi-impact in composites is presented. The number of citations has been increasing in the last years, and a big ride can be observed between 2012 and 2016.

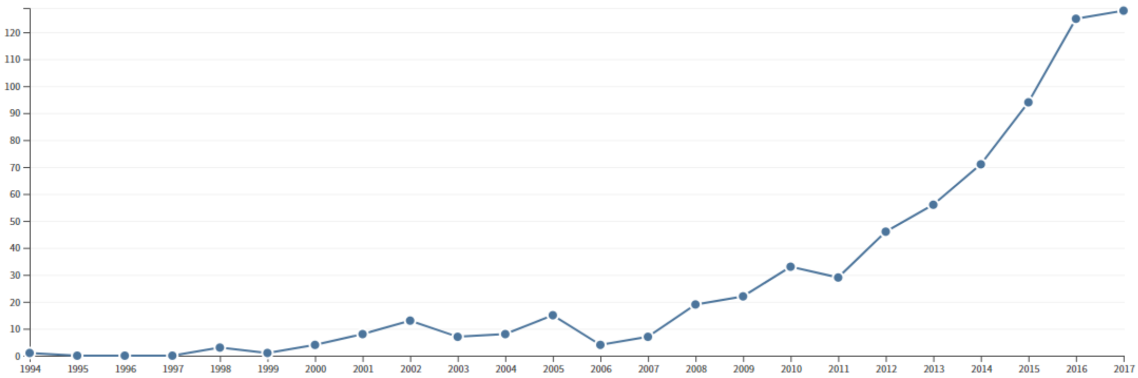


Figure 2.7. Graphic showing the number of articles cited about multi-impact composites, between 1994 and 2017 [25].

How it was shown, multi-impact fatigue test in composites is a theme studied by a lot of researchers, but almost all of them are multi-impact events with the same level of energy. This means that all the consecutive impacts applied in the sample of study has the same energy.

On the other hand, multi-impact fatigue with different energy levels is something that, to the author knowledge, was done just by [21]. This type of test is similar to the one referred above, the only difference is that the energy applied changes between consecutive impacts.

According to [21] the damage in the specimen increases with the value of the higher impact event in each sequence. It was proved that a single impact of 3 J in the GFRP composite in study was more detrimental when comparing to a cumulative damage made by the multi-impact events with the sum of total energy of 3J. It was also proved that the energy dissipated by the damage spread increases with the value of impact energy.

Table 2.4. Research done by the author related to multi-impact fatigue tests on composites.

Author (s)	Title	Ref.
Abir, M. R., Tay, T. E., Ridha, M., & Lee, H. P.	Modelling damage growth in composites subjected to impact and compression after impact	[26]
Ahmad, F., Hong, J. W., Choi, H. S., & Park, M. K.	Hygro effects on the low-velocity impact behavior of unidirectional CFRP composite plates for aircraft applications.	[27]
Amaro, A. M., Reis, P. N. B., & Neto, M. A.	Experimental study of temperature effects on composite laminates subjected to multi-impacts.	[20]
Amaro, A. M., Reis, P. N. B., de Moura, M. F. S. F., & Neto, M. A.	Multi-Impact Response of Composite Laminates with Open Holes.	[28]
Amaro, A. M., Reis, P. N. B., de Moura, M. F. S. F., & Neto, M. A.	Influence of multi-impacts on GFRP composites laminates.	[21]
Amaro, A. M., Reis, P. N. B., Santos, J. B., Santos, M. J., & Neto, M. A.	Effect of the electric current on the impact fatigue strength of CFRP composites.	[29]
Ashcroft, I. A., Casas-Rodriguez, J. P., & Silberschmidt, V. V.	Mixed-mode crack growth in bonded composite joints under standard and impact-fatigue loading.	[30]
Azouaoui, K., Azari, Z., & Pluvinage, G.	Evaluation of impact fatigue damage in glass/epoxy composite laminate.	[31]

Azouaoui, K., Benmedakhene, S., Laksimi, a., Azari, Z., & Pluvinage, G	Impact fatigue damage of glass/epoxy plates predicted from three parameters model	[32]
Azouaoui, K., Ouali, N., Ouroua, Y., Mesbah, A., & Boukharouba, T.	Damage characterisation of glass/polyester composite plates subjected to low-energy impact fatigue.	[33]
Azouaoui, K., Rechak, S., Azari, Z., Benmedakhene, S., Laksimi, A., & Pluvinage, G.	Modelling of damage and failure of glass/epoxy composite plates subject to impact fatigue.	[34]
Barber, B. W., & Radford, D. W.	Impact-fatigue behavior of composite tube/metal end fitting bonded joints.	[35]
Beheshty, M. H., & Harris, B.	A constant-life model of fatigue behaviour for carbon-fibre composites: the effect of impact damage.	[36]
Beheshty, M. H., Harris, B., & Adam, T.	An empirical fatigue-life model for high-performance fibre composites with and without impact damage.	[37]
Butler, R., Almond, D. P., Hunt, G. W., Hu, B., & Gathercole, N.	Compressive fatigue limit of impact damaged composite laminates.	[38]
Coelho, S. R. M., Reis, P. N. B., Ferreira, J. A. M., & Pereira, A. M.	Effects of external patch configuration on repaired composite laminates subjected to multi-impacts.	[39]
de Vasconcellos, D. S., Sarasini, F., Touchard, F., Chocinski-Arnault, L., Pucci, M., Santulli, C., … Sorrentino, L.	Influence of low velocity impact on fatigue behaviour of woven hemp fibre reinforced epoxy composites.	[40]
Deka, L. J., Bartus, S. D., & Vaidya, U. K.	Multi-site impact response of S2-glass/epoxy composite laminates.	[41]
Dhakal, H. N., Zhang, Z. Y., Bennett, N., & Reis, P. N. B.	Low-velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites: Influence of impactor geometry and impact velocity	[42]
Ding, Y. Q., Yan, Y., & McIlhagger, R.	Effect of impact and fatigue loads on the strength of plain weave carbon-epoxy composites.	[43]
Dubary, N., Taconet, G., Bouvet, C., & Vieille, B.	Influence of temperature on the impact behavior and damage tolerance of hybrid woven-ply thermoplastic laminates for aeronautical applications.	[44]
Farrar, C., Hemez, F., Park, G., Sohn, H., Robertson, A., & Williams, T.	Developing impact and fatigue damage prognosis solutions for composites.	[45]
Feng, D., & Aymerich, F.	Finite element modelling of damage induced by low-velocity impact on composite laminates.	[46]
Feng, Y., He, Y., Tan, X., An, T., & Zheng, J.	Investigation on impact damage evolution under fatigue load and shear-after-impact-fatigue (SAIF) behaviors of stiffened composite panels.	[47]

Freeman, B., Schwingler, E., Mahinfalah, M., & Kellogg, K.	The effect of low-velocity impact on the fatigue life of Sandwich composites.	[48]
Garnier, C., Lorrain, B., & Pastor, M.-L.	Impact damage evolution under fatigue loading by InfraRed Thermography on composite structures.	[49]
Garnier, C., Pastor, M.-L., Lorrain, B., & Pantalé, O.	Fatigue behavior of impacted composite structures.	[50]
Jang, B. P., Kowbel, W., & Jang, B. Z.	Impact behavior and impact-fatigue testing of polymer composites	[51]
KATERELOS, D. G., PAIPETIS, A., & KOSTOPOULOS, V.	A simple model for the prediction of the fatigue delamination growth of impacted composite panels.	[52]
Kim, S. J., & Hwang, I. H.	Prediction of fatigue damage for composite laminate using impact response.	[53]
Koo, J.-M., Choi, J.-H., & Seok, C.-S.	Evaluation for residual strength and fatigue characteristics after impact in CFRP composites.	[54]
Kostopoulos, V., Baltopoulos, A., Karapappas, P., Vavouliotis, A., & Paipetis, A.	Impact and after-impact properties of carbon fibre reinforced composites enhanced with multi-wall carbon nanotubes.	[55]
Lee, M., Cha, M. S., & Kim, N. H.	Multi-scale modeling of composites subjected to high speed impact.	[56]
Lhymn, C.	Impact fatigue of PPS/glass composite - microscopy	[57]
Lhymn, C.	Impact fatigue of PPS/glass composites	[58]
Margueres, P., Meraghni, F., & Benzeggagh, M. L.	Comparison of stiffness measurements and damage investigation techniques for a fatigued and post-impact fatigued GFRP composite obtained by RTM process.	[59]
May, M., Nossek, M., Petrinic, N., Hiermaier, S., & Thoma, K.	Adaptive multi-scale modeling of high velocity impact on composite panels.	[60]
Melin, L. G., & Schön, J.	Buckling behaviour and delamination growth in impacted composite specimens under fatigue load: an experimental study.	[61]
Mitrovic, M., Hahn, H. T., Carman, G. P., & Shyprykevich, P.	Effect of loading parameters on the fatigue behavior of impact damaged composite laminates.	[62]
Montero, M. V., Barjasteh, E., Baid, H. K., Godines, C., Abdi, F., & Nikbin, K.	Multi-Scale Impact and Compression-After-Impact Modeling of Reinforced Benzoxazine/Epoxy Composites using Micromechanics Approach.	[63]
Ouroua, Y., Azouaoui, K., Mesbah, A., Ouali, N., & Boukharouba, T.	Some insights into the impact fatigue damage behaviour in laminated composites.	[64]
Ray, D., Sarkar, B. ., & Bose, N. .	Impact fatigue behaviour of vinylester resin matrix composites reinforced with alkali treated jute fibres.	[65]

Ren, Y., Qiu, L., Yuan, S., & Su, Z.	A diagnostic imaging approach for online characterization of multi-impact in aircraft composite structures based on a scanning spatial-wavenumber filter of guided wave.	[66]
Roy, R., Sarkar, B. K., & Bose, N. R.	Impact fatigue of glass fibre–vinylester resin composites.	[67]
Roy, R., Sarkar, B. K., & Bose, N. R.	Behaviour of E-glass fibre reinforced vinylester resin composites under impact fatigue.	[68]
Roy, R., Sarkar, B. K., Rana, A. K., & Bose, N. R.	Impact fatigue behaviour of carbon fibre-reinforced vinylester resin composites.	[69]
Russo, P., Langella, A., Papa, I., Simeoli, G., & Lopresto, V.	Thermoplastic polyurethane/glass fabric composite laminates: Low velocity impact behavior under extreme temperature conditions.	[70]
Santos, R. A. M., Reis, P. N. B., Santos, M. J., & Coelho, C. A. C. P.	Effect of distance between impact point and hole position on the impact fatigue strength of composite laminates.	[71]
Santos, R. A. M., Reis, P. N. B., Silva, F. G. A., & de Moura, M. F. S. F.	Influence of inclined holes on the impact strength of CFRP composites.	[72]
Sarkar, B. K., & Ray, D.	Effect of the defect concentration on the impact fatigue endurance of untreated and alkali treated jute–vinylester composites under normal and liquid nitrogen atmosphere.	[73]
Shi, Y., Pinna, C., & Soutis, C.	Modelling impact damage in composite laminates: A simulation of intra- and inter-laminar cracking.	[74]
Sınmazçelik, T., Arıcı, A. A., & Günay, V.	Impact–fatigue behaviour of unidirectional carbon fibre reinforced polyetherimide (PEI) composites.	[75]
Sohn, M. ., Hu, X. ., Kim, J. ., & Walker, L.	Impact damage characterisation of carbon fibre/epoxy composites with multi-layer reinforcement.	[76]
Soliman, E. M., Sheyka, M. P., & Taha, M. R.	Low-velocity impact of thin woven carbon fabric composites incorporating multi-walled carbon nanotubes.	[17]
Sun, B., Hu, D., & Gu, B. (2009).	Transverse impact damage and energy absorption of 3-D multi-structured knitted composite.	[77]
Tai, N. ., Yip, M. ., & Lin, J.	Effects of low-energy impact on the fatigue behavior of carbon/epoxy composites.	[78]
Tai, N. H., Ma, C. C. M., Lin, J. M., & Wu, G. Y.	Effects of thickness on the fatigue-behavior of quasi-isotropic carbon / epoxy composites before and after low energy impacts	[79]
Taraghi, I., Fereidoon, A., & Taheri-Behrooz, F.	Low-velocity impact response of woven Kevlar/epoxy laminated composites reinforced with multi-walled carbon nanotubes at ambient and low temperatures.	[80]
Uyaner, M., Kara, M., & Şahin, A.	Fatigue behavior of filament wound E-glass/epoxy composite tubes damaged by low velocity impact.	[81]

Whitlow, T., & Sathish, S.	Characterization of multi-layered impact damage in polymer matrix composites using lateral thermography.	[82]
Yuanjian, T., & Isaac, D. H.	Combined impact and fatigue of glass fiber reinforced composites.	[83]
Jefferson Andrew, J., Arumugam, V., Saravanakumar, K., Dhakal, H. N., & Santulli, C.	Compression after impact strength of repaired GFRP composite laminates under repeated impact loading.	[84]
David-West, O. S., Nash, D. H., & Banks, W. M.	An experimental study of damage accumulation in balanced CFRP laminates due to repeated impact.	[85]
Hosur, M. V., Karim, M. R., & Jeelani, S.	Experimental investigations on the response of stitched/unstitched woven S2-glass/SC15 epoxy composites under single and repeated low velocity impact loading.	[86]
Richardson, M. O. W., & Wisheart, M. J.	Review of low-velocity impact properties of composite materials.	[87]

The research done to sustain this experimental study is presented in Table 2.4, where all the 65 articles related to the issue in study are presented. From all these articles, the most relevant ones were choosing to be presented throughout this Masters dissertation.

3. MATERIALS AND EXPERIMENTAL PROCEDURE

3.1. Introduction

This chapter intends to present all the materials, procedures and equipment used in the experimental analysis. The main objective of this work, as explained before, is to study the behaviour of composite materials subjected to multi impacts with different energy levels.

3.2. Test Samples (E-Glass/Polyester Laminate Composite)

The specimens are made of a glass fibre reinforced composite with E-Glass fibres reinforcement in a matrix of polyester resin. The volume fraction of E-Glass fibre is ??? and it's present in ?? layers. This material was prepared in ????? and processed in agreement with manufacturer recommendations.

The process to obtain this laminate composite was ???, and the steps taken were: ???. The stacking sequence of this laminate is [90,0,90,0], and some of their mechanical properties are presented in Table 3.1.

Table 3.1. Mechanical properties of E-Glass/Polyester Laminate Composite.

The test plates were cut from a bigger piece, resulting in samples with dimensions of 100 x 100 x 2.4 mm3, which can be seen in Figure 3.1.

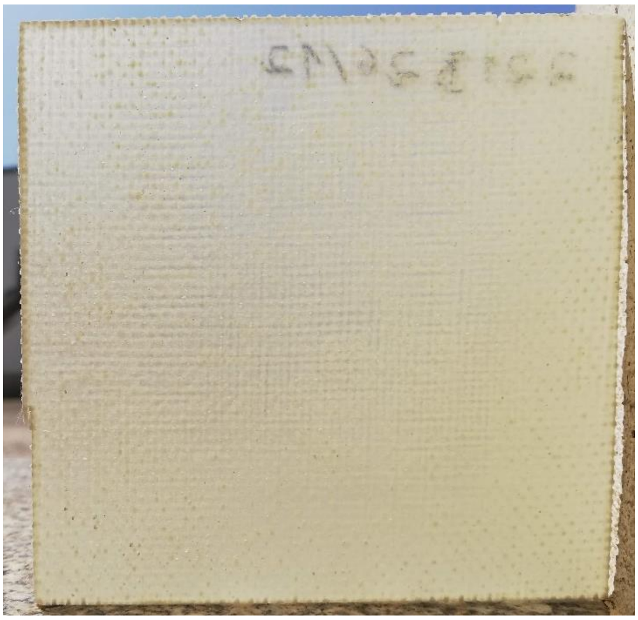


Figure 3.1. Photography of a test piece used in the experimental tests.

3.3. Impact Tests Machine

All the impact tests were performed in an impact machine by weight drop, property of DEM (FCTUC), which is placed in their facilities. The machine is CEAST 9340, presented in Figure 3.2 a), developed by INSTRON®, which can deliver energy in the range of 0.30 – 405 J [88]. This impact energy depends on the height and weight of the impactor. The data acquisition system available, showed in Figure 3.2 b), allows to obtain time, load, displacement, energy and velocity throughout the impact.

a) **b)**

Figure 3.2. Equipment: a) Impact test machine CEAST 9340, and b) Data Acquisition System (DAS), both property of DEM (FCTUC).

During the tests the weight of the impactor was always the same, and what changed was the height, allowing to obtain different impact energies, which is presented in Table 3.2. The test samples were simply supported in a circular support of 70 mm of diameter, where the impactor strokes at the centre of the sample obtained by centrally supporting the 100 x 100 mm2 specimen. The mass of the impactor was 3.4 Kg and its diameter 10 mm. Every test was done at room temperature (23ºC).

Table 3.2. Impact characteristics.

Energy [J]	Height of impactor [mm]	Impact Velocity [m/s]
3	0.090	1.330
4	0.119	1.530
5	0.149	1.710
6	0.180	1.880
8	0.240	2.170
10	0.301	2.430

3.4. Analysed Data

3.4.1. Number of Impacts

The first goal of this work is to find a valid model to relate the number of impacts to failure with the impact energy. This is achieved using three test plates for each level of energy (4J, 6J, 8J and 10J), and applying impacts to failure. The number of impacts is then registered and all this data is used, with the help of a linear cumulative damage rule, to find a valid model that relates impact energy with number of impacts.

In the study done in [33] and [69] the authors created a curve similar to S-N classic fatigue curve, with the impact energy as a function of the failure impact number. In [33], was conclude that this curve follows the classical fatigue behaviour, following a power law.

One of the objectives of this dissertation is to understand if the model created using a linear cumulative damage rule is reliable to demonstrate the behaviour of composites when subjected to multi-impacts of different energy levels.

After obtaining the model based on the linear cumulative damage rule, multi-impacts with different energy levels will be applied to the samples, and the results will be compared to the theoretical prediction.

3.4.2. Area of Damage

After certain impact tests, some samples were inspected to evaluate the shape and size of the visible damaged zone. The glass-laminated plates are translucent, so it is possible to observe, measure and photograph the projection of the damaged area in counter-light using a powerful light source.

The specimens were framed in a window so that all the light could fall upon them. Then they were photographed and the visible damaged zone measured using a calliper, presented in Figure 3.3.

Figure 3.3. Calliper measuring visible damaged zone.

The area of damaged zone was approximated to a parallelepiped, because it's easier to measure with the calliper. The error obtain with this approximation in each measurement will be similar, so the comparation between the different value of areas will be reliable. When comparing this parameter along the impacts, the objective is to compare the evolution of it and not its exact size.

The damaged area increases with number of impacts, but after certain number of impacts it does no increase significantly [86]. According to [33], the damaged area grows considerably for a high number of impacts when the energy of impact is low (3.5J and 4J), and it grows rapidly for a low number of impacts when the energy of impact is high (≥ 5J). It was observed that the area of damage as function of impact number presents a linear evolution when in presence of cyclic impact events, and also that the higher the impact energy, the bigger is the slope of the straight line which relates them.

4. RESULTS AND DISCUSSION

Figure 4.1 shows the profile of typical curves obtained for different impact energies.

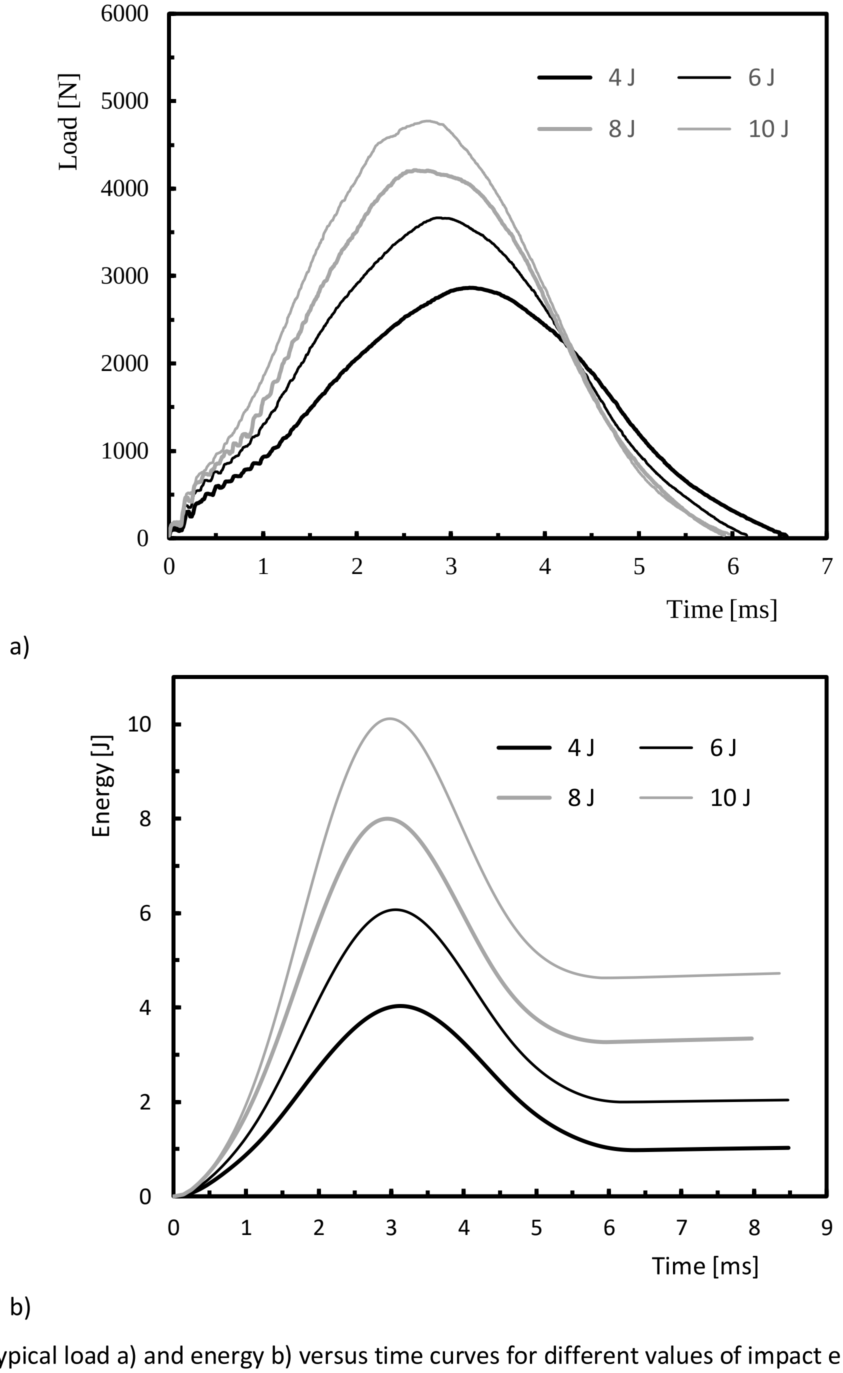


Figure 4.1. Typical load a) and energy b) versus time curves for different values of impact energy, for the 1st impact.

Figure 4.1 a) presents typical load versus time curves for the first impact when four different impact energies are applied. The behaviour of this curves is typical and agrees with those reported in literature [21], [55], [76], [86]. It's perceptible that the load increases up to a maximum value followed by a drop corresponding to the impactor rebound. Both maximum load and slop of the curve increase with the increasing of the impact energy.

Figure 4.1 b) represents a typical energy versus time curves for different values of impact energy. After the peak of maximum energy exists a plateau, and its beginning indicates the contact loss between the impactor and the specimen [20], [21], [28]. The difference between the maximum energy value and the energy defined by the plateau is the elastic energy, energy retained by the impactor and used to rebound after impact [55]. This property will be presented as a percentage of the impact energy applied.

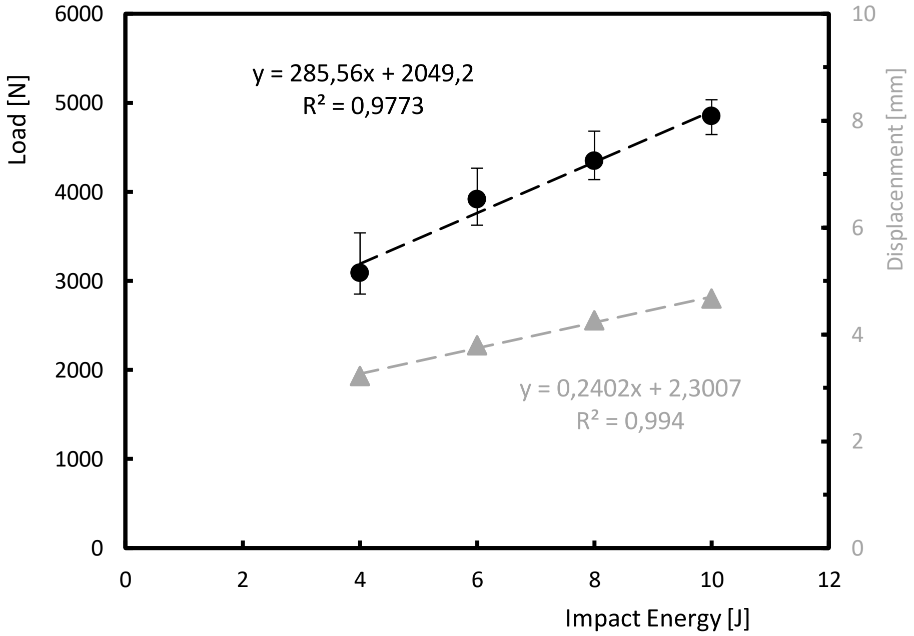


Figure 4.2. Load and displacement versus impact energy for the 1st impact.

Figure 4.2 shows the maximum load and maximum displacement values against the impact energy. Both parameters increase linearly with the impact energy, which can be fitted by linear equations, as shown in figure. This behaviour observed for the maximum load was also observed by Sohn et al. [76], but for higher impact energies. Studies developed by Dubary et al. [44], using higher impact energies, also shows the same behaviour for the maximum displacement, but not for the maximum load, and it occurs because this evolution just happens for lower energy levels.

Error bars presented in Figure 4.2 represent the maximum and minimum values obtained from the three tests performed for each condition. It is possible to conclude that the dispersion observed is very low, especially in terms of displacement, where the bars are not visible due to their reduced dispersion. The standard deviation obtained range from 0.9% for the maximum displacement observed for 6 J, and 10.4 % that is related to the maximum load obtained for 4 J.

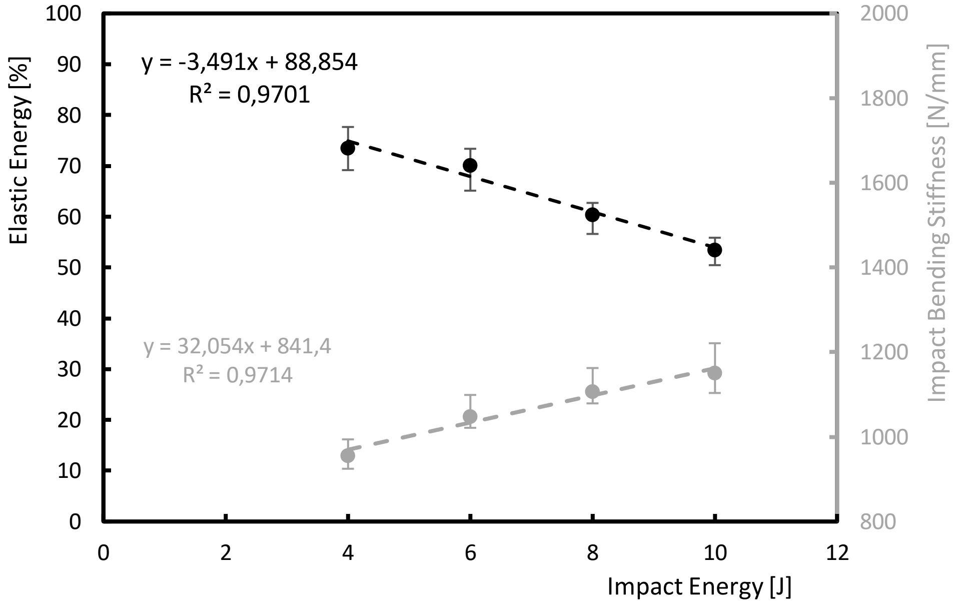


Figure 4.3. Elastic energy and impact bending stiffness (IBS) versus impact energy for the 1st impact.

Elastic energy, the energy that is dissipated by the plate test at the impact, shows a linear evolution with the impact energy (Figure 4.3), presenting a decrease with the increasing values of impact energy due to higher damages introduced [39], [84], [90]. For an impact energy of 4 J, the elastic energy is about 73.5%, while for 10 J it is 53.5% of the impact energy value. This behaviour is typical of composite materials, like it is shown by the literature [20], [21], [39], [55]. The standard deviation of these results present values between 1.1% and 7.1% for 10 J and 6 J impact, respectively.

Impact bending stiffness (IBS) is known as an important property for evaluation of damage resistance of a composite [20], [39], [85], [90]. The slope of the ascending section of the load-displacement plot is the bending stiffness, and it varies with the composite configuration [85]. According to Figure 4.3 this property seems to change with the impact energy, increasing directly with its value. For 4 J the IBS is 956.61 N/mm and it increases to 1150.67 N/mm for 10 J. The values of standard deviation range from 38.6% for 4 J to 50.7% for 10 J.

Both elastic energy and impact bending stiffness can be used to understand the damage evolution of a composite subjected to impact events. For the first impact, like it was referred before, these properties vary in an opposite tendency with the impact energy.

Finally, the contact time of impact was also recorded, and the values obtained are between 6.5 ms for 4 J and 5.9 ms for 10 J.

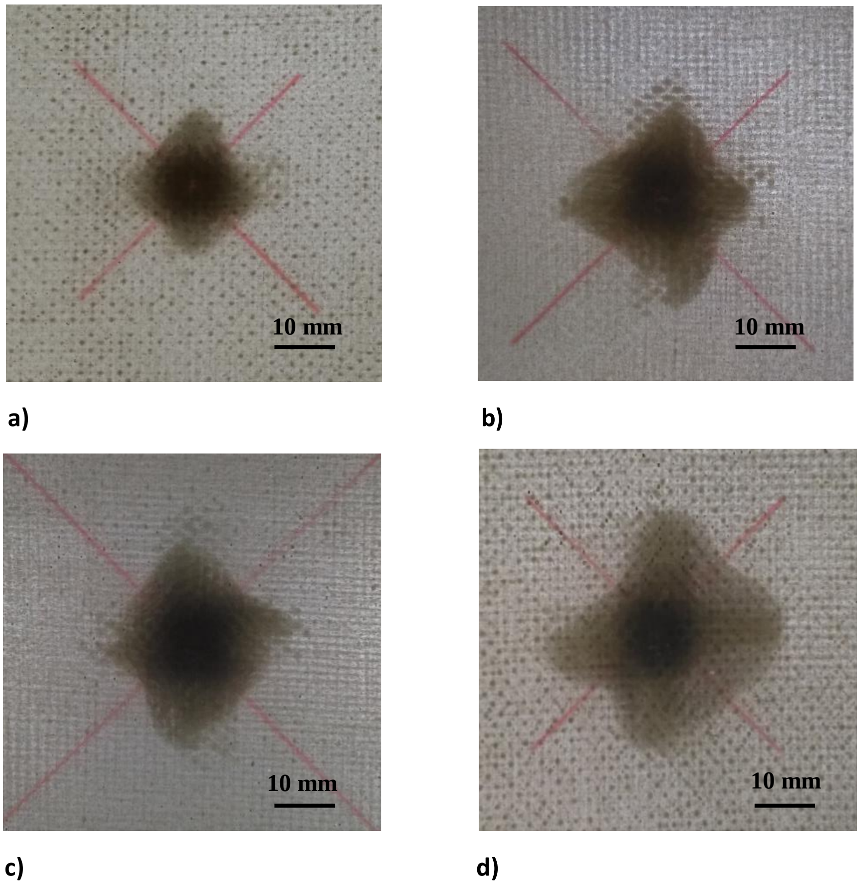


Figure 4.4. Typical damage observed in the test samples after the 1st impact for an impact energy of: a) 4 J; b) 6 J; c) 8 J; d) 10 J

Figure 4.4 presents the area of the damage observed in the first impact for different energies. It is possible to observe an increasing of the damage for higher impact energies, what is in good agreement with literature [33], [44], [55], [86]. The damaged area for the first impact of 4 J is around 498.5 mm^2, and about 1252.0 mm^2 for 10 J.

In order to obtain the impact fatigue life, the samples were subjected to multi-impacts with the same energy level. The final failure is considered when full perforation (when the impactor completely moves through the sample) occurs.

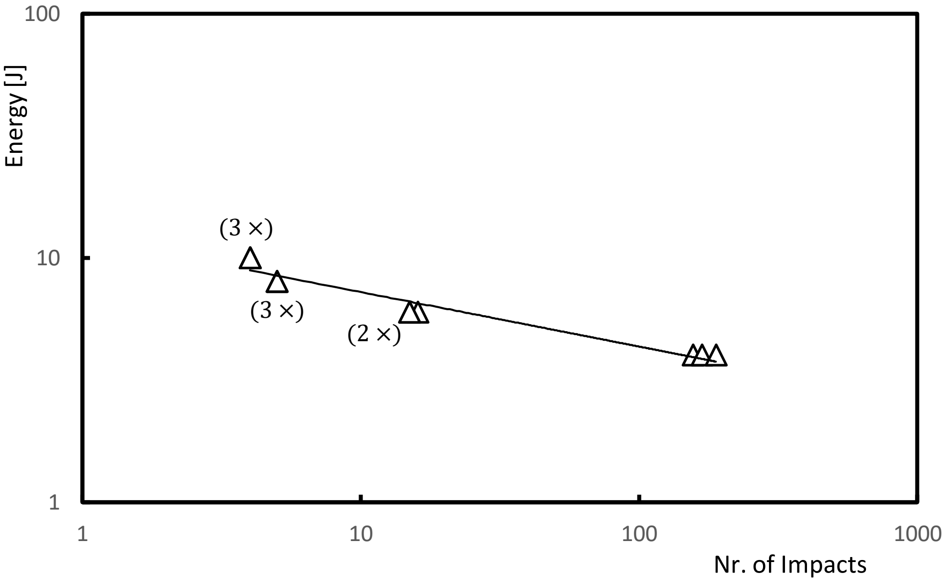


Figure 4.5. Impact energy versus number of impacts to failure.

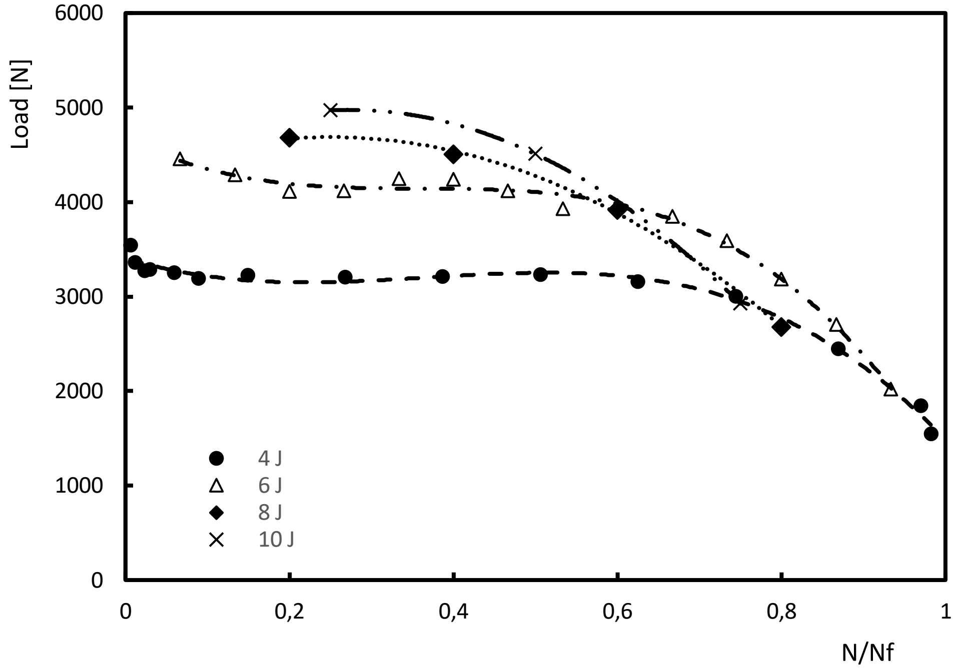
Figure 4.5 shows the impact energy versus number of impacts to failure, with both scales logarithmized. This representation is based on the typical fatigue S-N curves, where the stress is substituted by the impact energy. The number of impacts to failure varies inversely with the impact energy, and this behaviour is according with the literature [33], [39], [44], [64], [68].

The impact energy versus number of impacts can be express by the equation (4.1), with R=0.9703:

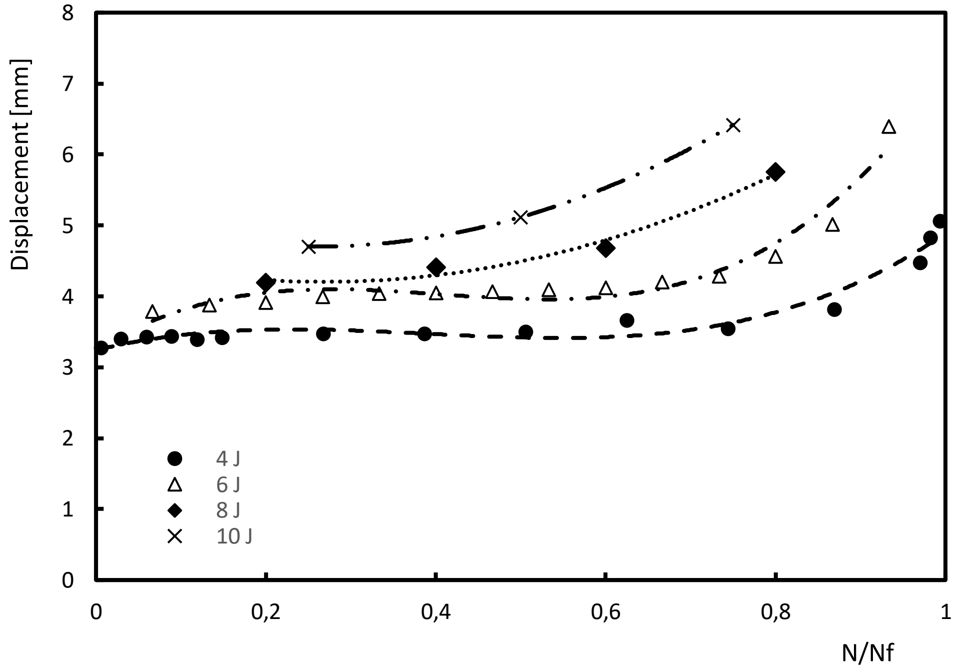
$$E = 12.138 \times N_f^{-0.223} \tag{4.1}$$

where, E is the impact energy and N_f the number of impacts to failure.

Similar to the analysis done for the first impact, the same parameters were analysed in a dimensionless format (N/N_f), where the N is the number of impacts at any given instant of the test and N_f is the number of impacts to failure. The last impact isn't presented because full perforation occurred.



a)



b)

Figure 4.6. Maximum impact load (a) and maximum displacement (b) versus N/N_f.

Figure 4.6 represents the effect of the multi-impacts on the maximum load and maximum displacement. It’s possible to observe, for all impact energies, that the maximum load decreases with the number of impacts, while the maximum displacement increases, which is in good agreement with open literature [8], [20], [28], [34], [39]. Curves for 4 J and 6 J can be fitted by polynomial of order three, presenting three stages, as consequence of damage accumulation [20], [34], [39]. Curves for 8 J and 10 J can be fitted by a polynomial of order two, showing fast evolution, due to the severity of the damage.

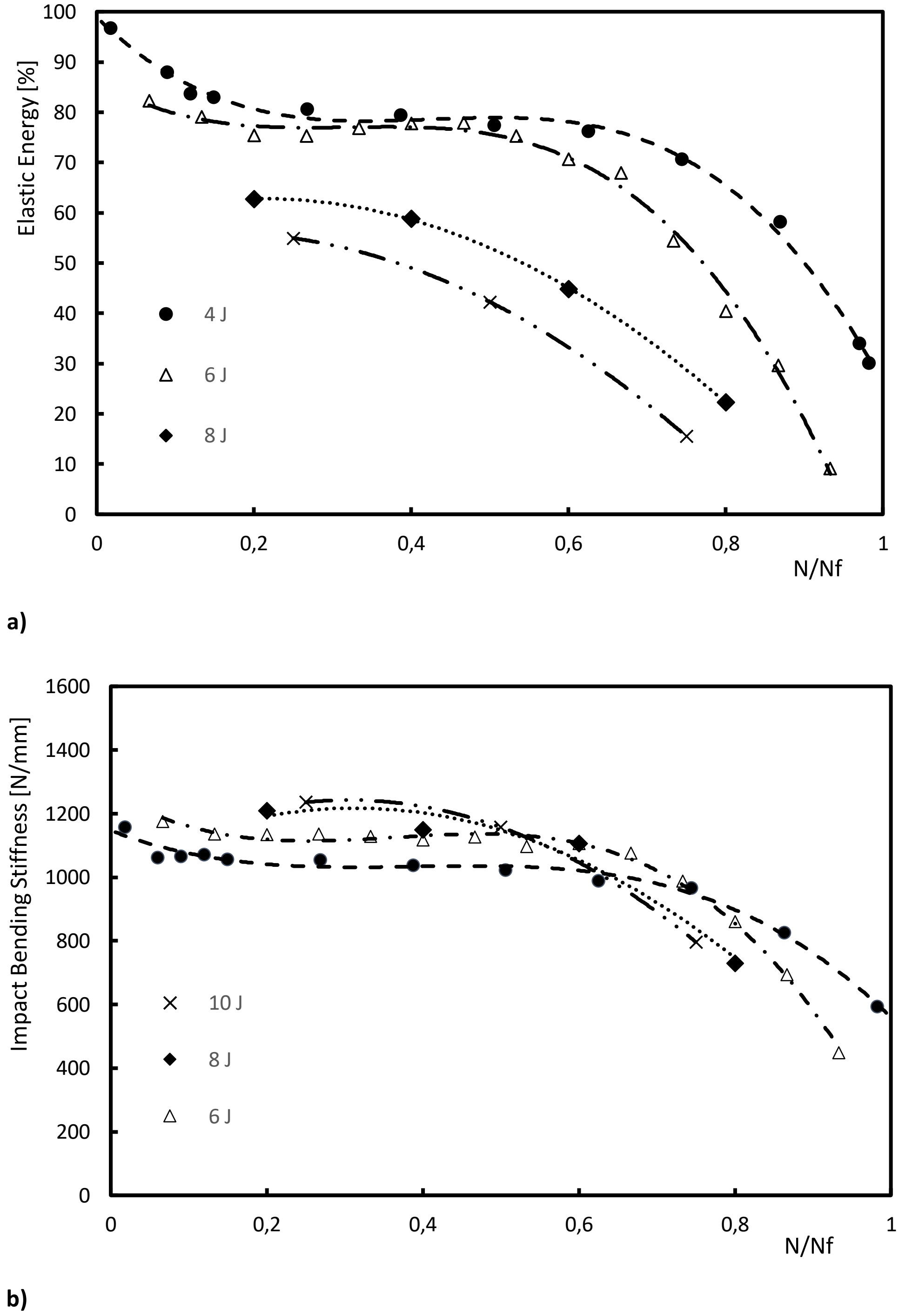


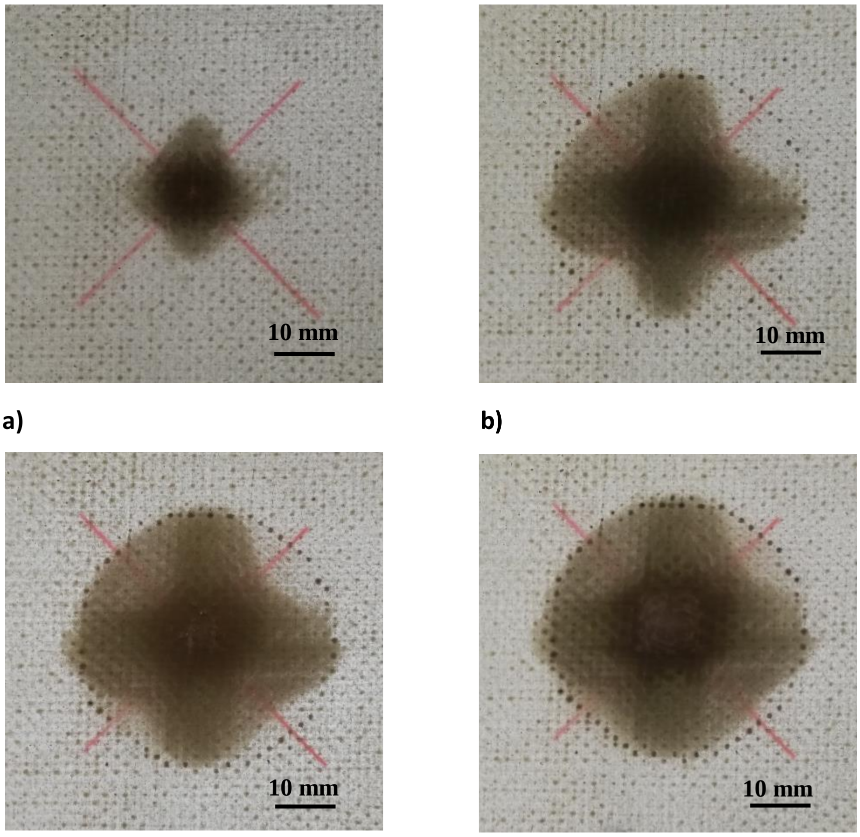
Figure 4.7. Elastic energy (a) and impact bending stiffness (b) versus N/N$_f$.

Figure 4.7 presents the evolution of the damage in terms of elastic energy and impact bending stiffness. According to Figure 4.7 a), the impact energies of 8 J and 10 J can be fitted by a polynomial of order two, which means that, after starting the damage, its progress is very fast. On the other hand, for energies of 4 J and 6 J the data are fitted by polynomial curves of order three. In this case, three stages can be seen in those curves. In the beginning, the elastic energy decreases quickly as consequence of the damage introduced, and matrix cracking is the predominant damage mode. In the second stage, the curve shows a linear evolution, and it's when the fast delamination propagation takes place until saturation. The elastic energy drops suddenly in the third stage, because the fibre breakage decreases the local rigidity at the point of impact.[91]. For the 4 J, the first stage represents about 25%, the second one 35%, and the last one 40% of the total lifetime, while these values are around 20%, 25% and 55%, respectively for 6 J.

Figure 4.7 b) shows the IBS evolution with number of impacts to failure. Similar to Figure 4.7 a), for 8 J and 10 J, the data are fitted by a polynomial of order two, while for 4 J and 6 J they are fitted by a polynomial of order three. One more time, for the first case (energies of 8 J and 10 J), the damage progress is very abrupt, while for the other energies three stages of damage can be identified, which is in agreement with literature [20], [31], [32], [39]. The progression of damage in these three stages is the same that was described for the elastic energy. For the 4 J the first stage represents about 25% of the total life, the second one 35%, and the third one the remaining 40%. In terms of 6 J, these values are about 20%, 30% and 50%, respectively.

The evolution of elastic energy and impact bending stiffness relate to each other and with damage evolution. The percentage of each stage for the curves of 4 J and 6 J is similar for both parameters. This occurs because of the relation between both: with the decreasing values of elastic energy, the energy absorbed increases allowed by the damage mechanisms of the composite, which takes to a decrease of the plate stiffness (IBS).

From the previous analysis, it is possible to observe that the damage evolution is very similar for all impact energies studied. However, for higher energies, the damage progress occurs faster.



a) b) c) d)

Figure 4.8. Typical damage observed for the impact energy of 4 J after: a) 1st impact; b) 45th impact; c) 105th impact; d) penultimate impact.

Figure 4.8 presents, for example, the damage's evolution for 4 J. The average area for the 1st impact is 498.5 mm^2, for the 45th impact is around 1819.6 mm^2, for the 105th is 2035.5 mm^2, and for the penultimate one about 2117.4 mm^2. The last three impacts referred previously represent an increase, relatively to the 1st impact, around 265.0%, 308.3% and 324.8%, respectively. The standard deviation values are around 4.3%, 4.0%, 2.5% and 2.9%, respectively.

Finally, the development of reliable methods for predicting impact fatigue lives is important, although this task is complex in composite laminates as a consequence of the multiple failure modes. For this purpose, experimental tests composed of two blocks, changing from a low energy level to a higher energy level (L–H sequence) or vice versa (H–L sequence), were performed. The first block was defined as one third of the impact fatigue life, obtained with constant energy, and the second one was applied up to failure.

On the other hand, based on a linear cumulative damage rule, the impact fatigue life is estimated assuming that the damage caused by each block should not be affected by the impact load history. According to this rule, the failure during an impact test with variable energies must occur when:

$$\sum_{i=0}^{k} \frac{n_i}{N_i} = 1 \tag{4.2}$$

where n_i is the number of cycles applied at an energy level block corresponding to a lifetime of N_i. Therefore, the damage summation (D) during a variable frequency fatigue test should tend to 1.

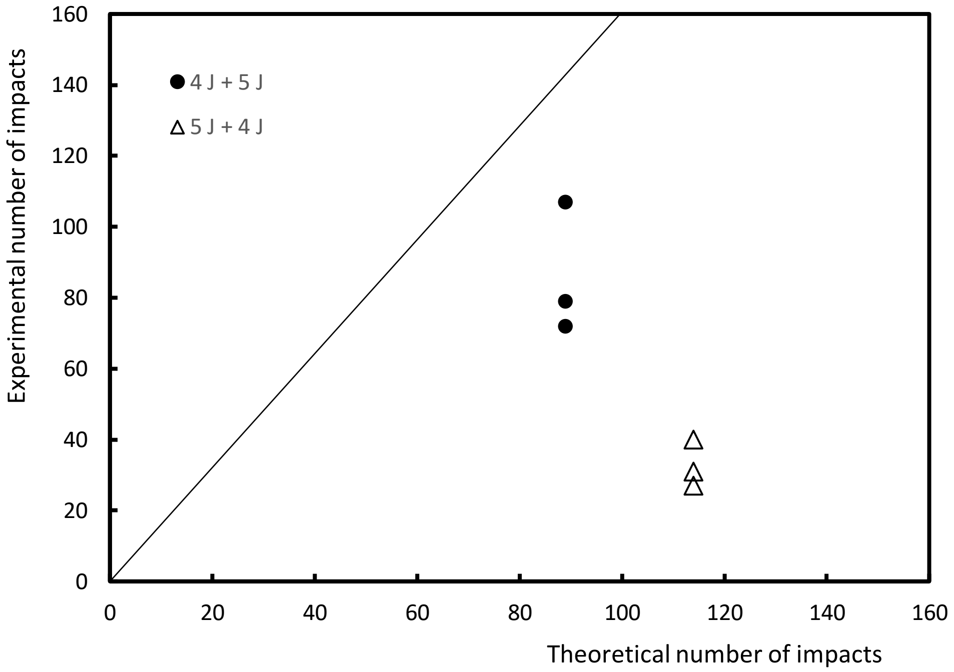


Figure 4.9. Experimental number of impacts versus theoretical number of impacts.

In this context, Figure 4.9 presents the comparison between estimated and experimental results. It is possible to observe that the average ratio between predictions and experimental lives are not close to unit. Therefore, it can be concluded that the linear cumulative damage rule is not applicable to predict the fatigue life in multi-impact tests with variable energy levels for GFRP.

5. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

5.1. Introduction

After finishing the tests and analysing the results according to the objectives imposed initially, it’s now possible to reach to some important conclusions.

It is also possible to think in future work that can be done to support the conclusions and to study multi-impact events on composites in different ways.

5.2. Conclusions

According to the main goal proposed for the present study, the most significant conclusions are:

1. Maximum load and maximum displacement increase with the increasing of the impact energy;
2. For the first impact, elastic energy decreases with the increasing of impact energy, and the impact bending stiffness shows the opposite tendency;
3. The impact energy versus number of impacts to failure can be fitted by a power function, like the S-N curves for fatigue;
4. Maximum load increase with the number of impacts and maximum displacement shows the opposite tendency;
5. The evolution of elastic energy and impact bending stiffness with number of impacts show curves with three stages for low energy levels;
6. Both IBS and elastic energy describe with enough precision the evolution of the damage;
7. The linear cumulative damage rule is not applicable to predict the fatigue life in multi-impact tests with variable energy levels for GFRP.

5.3. Suggestions for Future Work

From the conclusions obtained and all constrains occurred along this study, it is possible to suggest some ideas for future works:

1. To perform multi-impact tests at lower energies, in order to have a more realistic curve of impact energy versus number of impacts to failure;
2. Develop tests with sequences composed by different energy blocks;
3. Develop a similar study for other composite materials;
4. Study the influence of different environmental conditions on the impact fatigue life.

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