



Influencia da Incorporacao de Particulas de Cortica no Comportamento Mecanico de Laminados Polimericos Reforcados com Fibra de Vidro

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Influence of Cork Particle Incorporation on the Mechanical Behaviour of Glass Fibre Reinforced Polymer Laminates

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Abstract

This dissertation investigates the influence of cork particle incorporation on the mechanical behaviour and impact damage response of glass fibre-reinforced polymer laminates, assessing whether cork particles can improve low-velocity impact performance while identifying possible effects on static tensile properties. Composite laminates were manufactured using glass fibre reinforcement and polymer matrices, with cork particles incorporated at different contents. The manufacturing route comprised resin preparation, cork particle dispersion when applicable, manual impregnation and stacking of the glass fibre plies by hand lay-up, consolidation by manual compression between mould plates, and room-temperature curing under compression. The experimental programme included low-velocity impact tests, penetrant-enhanced radiographic inspection and tensile tests on selected configurations. The impact response was analysed through force, displacement and energy histories, while radiographic images were used to evaluate the apparent internal damage area after impact. Complementary laminate configurations were also considered to support the discussion of the influence of matrix system, reinforcement architecture and fibre orientation on the observed behaviour. The results showed that cork particle incorporation affected the impact response of the main laminate configurations. Compared with the cork-free reference, the cork-modified laminates generally reached higher maximum impact forces, increasing by approximately 37.7–48.6%, and presented lower apparent radiographic damage areas, with reductions of approximately 47.1–78.4%. The most favourable response was obtained for the representative 5 wt.% cork configuration, which increased the maximum impact force from 1604.42 N to 2384.36 N and reduced the apparent radiographic damage area from 635.82 mm² to 137.08 mm². However, the response did not improve continuously with increasing cork content, since the highest cork content showed a reduction in impact performance when compared with the intermediate configuration. This behaviour was associated with possible processing-related limitations, mainly increased resin viscosity and reduced flowability, which may have affected fibre impregnation, particle dispersion and laminate homogeneity. The radiographic analysis confirmed that cork particle incorporation modified the damage response under the adopted impact conditions, although the method provided a two-dimensional projection of penetrant-accessible damage rather than a three-dimensional characterisation. The tensile results showed reductions of approximately 58.6% in tensile strength and 59.0% in Young's modulus, while strain at failure increased by approximately 16.5%. These results indicate that, particularly in the unsaturated polyester-based laminate configurations, cork particle incorporation may improve the apparent impact damage response, although with a reduction in static tensile performance. Therefore, the use of cork particles as a dispersed phase in composite laminates requires an appropriate balance between impact damage tolerance, tensile properties, cork content, particle dispersion, matrix system and manufacturing quality. Overall, cork particles showed potential as functional modifiers for glass fibre-reinforced unsaturated polyester laminates subjected to low-velocity impact, while highlighting the need for optimisation of particle content and size, processing conditions and damage characterisation methods.

KEYWORDS: Cork particles; Glass fibre reinforced polymer laminates; Low-velocity impact; Damage assessment; Radiographic inspection; Tensile behaviour.

Resumo

Esta dissertação investiga a influência da incorporação de partículas de cortiça no comportamento mecânico e na resposta ao dano por impacto de laminados poliméricos reforçados com fibra de vidro, avaliando se as partículas de cortiça podem melhorar o desempenho ao impacto de baixa velocidade, identificando simultaneamente os possíveis efeitos da sua incorporação nas propriedades estáticas em tração. Foram fabricados laminados compósitos com reforço de fibra de vidro e matrizes poliméricas, incorporando partículas de cortiça em diferentes teores. A rota de fabrico incluiu a preparação da resina, a dispersão das partículas de cortiça quando aplicável, a impregnação manual e o empilhamento das camadas de fibra de vidro por *hand lay-up*, a consolidação por compressão manual entre placas de molde e a cura à temperatura ambiente sob compressão. O programa experimental incluiu ensaios de impacto de baixa velocidade, inspeção radiográfica com contraste e ensaios de tração em configurações selecionadas. A resposta ao impacto foi analisada através dos históricos de força, deslocamento e energia, enquanto as imagens radiográficas foram utilizadas para avaliar a área aparente de dano interno após o impacto. Foram também consideradas configurações complementares de laminados para apoiar a discussão da influência do sistema de matriz, da arquitetura do reforço e da orientação das fibras no comportamento observado. Os resultados mostraram que a incorporação de partículas de cortiça afetou a resposta ao impacto da configuração principal de laminados. Comparativamente à referência sem cortiça, os laminados modificados com cortiça atingiram, em geral, forças máximas de impacto superiores, com aumentos de aproximadamente 37,7–48,6%, e apresentaram áreas aparentes de dano radiográfico inferiores, com reduções de aproximadamente 47,1–78,4%. A resposta mais favorável foi obtida para a configuração representativa com 5 wt.% de cortiça, que aumentou a força máxima de impacto de 1604,42 N para 2384,36 N e reduziu a área aparente de dano radiográfico de 635,82 mm² para 137,08 mm². No entanto, a resposta não melhorou continuamente com o aumento do teor de cortiça, uma vez que o teor mais elevado apresentou uma redução no desempenho ao impacto quando comparado com a configuração intermédia. Este comportamento foi associado a possíveis limitações relacionadas com o processamento, principalmente associadas ao aumento da viscosidade da resina e a redução da fluidez, que podem ter afetado a impregnação das fibras, a dispersão das partículas e a homogeneidade dos laminados. A análise radiográfica confirmou que a incorporação de partículas de cortiça modificou a resposta ao dano nas condições de impacto adotadas, embora o método tenha fornecido apenas uma projeção bidimensional do dano acessível ao líquido penetrante, não permitindo uma caracterização tridimensional. Os resultados de tração mostraram que a incorporação de partículas de cortiça conduziu a reduções de aproximadamente 58,6% na resistência à tração e 59,0% no módulo de Young, enquanto a extensão na rotura aumentou aproximadamente 16,5%. Estes resultados indicam que, particularmente nas configurações de laminados com matriz de poliéster insaturado, a incorporação de partículas de cortiça pode melhorar a resposta aparente ao dano por impacto, embora com uma redução no desempenho estático à tração. Assim, a utilização de partículas de cortiça como fase dispersa em laminados compósitos requer um equilíbrio adequado entre tolerância ao dano por impacto, propriedades de tração, teor de cortiça, dispersão das partículas, sistema de matriz e qualidade de fabrico.

De forma geral, as partículas de cortiça demonstraram potencial como modificadores funcionais para laminados de poliéster insaturado reforçados com fibra de vidro sujeitos a impacto de baixa velocidade, destacando simultaneamente a necessidade de otimização do teor e tamanho das partículas, das condições de processamento e dos métodos de caracterização de dano.

PALAVRAS-CHAVE: Partículas de cortiça; Laminados reforçados com fibra de vidro; Impacto de baixa velocidade; Avaliação de dano; Inspeção radiográfica; Comportamento à tração.

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Acronyms and Symbols

Acronyms

ASTM	American Society for Testing and Materials
BVID	Barely Visible Impact Damage
CMC	Ceramic Matrix Composite
ENF	End-Notch Flexure
EPP	Expanded Polypropylene
EPS	Expanded Polystyrene
GFRP	Glass Fibre Reinforced Polymer
ISEP	<i>Instituto Superior de Engenharia do Porto</i>
ISO	International Organization for Standardization
LVI	Low-velocity impact
MMC	Metal Matrix Composite
MT	Mat–woven–woven–mat laminate configuration
NR	Non-radial direction
OMC	Organic Matrix Composite
PE	Polyethylene
PEEK	Polyether ether ketone
PMC	Polymer Matrix Composite
PP	Polypropylene
P.Porto	<i>Instituto Politécnico do Porto</i>
R	Radial direction
RE	Epoxy resin matrix
RP	Polyester resin matrix
SBR	Styrene-butadiene rubber
TM	Woven–mat–mat–woven laminate configuration

Symbols

A	Apparent radiographic damage area	mm^2
E	Young's modulus	GPa
F	Force	N
L_0	Initial gauge length	mm
t	Time	s
v	Velocity	m/s
ε	Strain	mm/mm, %
ν	Poisson's ratio	-
σ	Stress	MPa
wt. %	Weight percentage	%

1. Introduction

Composite materials have become increasingly relevant in modern engineering due to their high specific mechanical properties, design flexibility, and ability to combine different constituents within a single material system. Among these materials, glass fibre reinforced polymer composites are widely used in structural and semi-structural applications where low weight, corrosion resistance, and reliable mechanical performance are required. However, despite these advantages, laminated composites remain susceptible to complex damage mechanisms, particularly when subjected to sudden loading conditions such as low-velocity impact (LVI).

This chapter introduces the context and motivation of the present dissertation in Section 1.1, establishing the relevance of the topic and the main problem addressed in this work. The research objectives are then defined in Section 1.2, followed by a description of the methodological approach adopted to achieve them (Section 1.3). Finally, the overall structure of the dissertation is presented in Section 1.4, clarifying the purpose and organisation of each chapter.

1.1. Context and Motivation

The increasing use of composite materials in engineering applications is closely related to the need for lightweight, efficient, and mechanically reliable structures. In sectors such as the automotive, aerospace, marine, construction, and sports industries, laminated polymer composites are often selected because their properties can be tailored through the appropriate combination of matrix system, reinforcement type, fibre orientation, and stacking sequence. This adaptability allows composite structures to achieve favourable stiffness-to-weight and strength-to-weight ratios, making them attractive alternatives to conventional metallic materials in many applications.

Nevertheless, the mechanical performance of laminated composites is strongly influenced by the development of internal damage mechanisms. Unlike isotropic materials, where damage is often more directly associated with visible cracking or plastic deformation, composite laminates may develop several interacting failure modes, including matrix cracking, fibre fracture, fibre–matrix debonding, and interlaminar delamination. Among these mechanisms, delamination is particularly critical because it corresponds to the separation between adjacent plies and may significantly reduce the stiffness, residual strength, and load-bearing capacity of the laminate.

Low-velocity impact events are especially relevant in this context. Although they may occur at relatively low energy levels, such impacts can generate internal damage that is not immediately visible on the surface of the component. This makes impact-induced damage difficult to detect during service and increases the risk of an inaccurate assessment of the structural integrity of the material. For this reason, understanding the response of composite laminates under LVI impact and evaluating the extent of the resulting damage are essential steps for improving damage tolerance and supporting the safe use of these materials in engineering applications.

The interlaminar region plays a central role in the initiation and propagation of delamination. Since this region is generally governed by the properties of the polymer matrix and by the quality of the interface between adjacent reinforcement layers, strategies aimed at modifying the matrix or the interlaminar zone have been widely investigated as a means of improving impact resistance and limiting damage propagation. In this framework, the incorporation of additional phases into the polymer matrix may influence the local stress distribution, energy dissipation mechanisms, and apparent damage development during impact loading.

At the same time, increasing environmental concerns and the need to valorise natural and industrial by-products have encouraged the development of more sustainable material solutions. Cork is a natural cellular material with low density, high recoverability, and relevant energy absorption capacity. These characteristics, together with its renewable origin and environmental advantages, make cork an interesting candidate for use as a functional phase in composite systems, particularly in applications where impact energy dissipation and damage mitigation are relevant.

The incorporation of cork particles into glass fibre reinforced polymer laminates therefore represents a promising approach, however its influence on the mechanical behaviour and impact damage response of these materials requires further investigation. In particular, it is necessary to understand how different cork particle contents affect the impact response, the extent of internal damage, and the balance between impact performance and mechanical properties under static loading. This dissertation is developed within this context, aiming to evaluate the effect of cork particle incorporation on the behaviour of glass fibre reinforced polymer composite laminates subjected to LVI loading.

1.2. Research Objectives

Based on this context, this dissertation aims to investigate the influence of cork particle incorporation on the mechanical behaviour and LVI damage response of glass fibre reinforced polymer composite laminates. The work is particularly focused on understanding how the presence and amount of cork particles affect the impact response, the development of internal damage, and the balance between damage tolerance and mechanical performance.

To achieve this aim, the following specific objectives were established:

- Manufacture of glass fibre-reinforced polymer composite laminates incorporating different cork particle contents and evaluation of their LVI response, with particular focus on unsaturated polyester-based 0/90 woven glass fibre configurations;
- Comparative assessment of complementary laminate configurations in order to analyse the influence of matrix type, fibre orientation, and reinforcement architecture on the impact response and damage development of the composite systems;
- Identification and quantification of impact-induced damage through penetrant-enhanced radiographic inspection and image analysis, supporting a comparative assessment between laminate configurations;
- Characterisation of the tensile behaviour of selected laminate configurations, providing complementary information regarding the influence of cork incorporation on the static mechanical response of the composites;
- Critical assessment of the potential and limitations of cork particles as a functional dispersed phase in glass fibre reinforced polymer laminates subjected to impact loading.

Through these objectives, the dissertation seeks to contribute to a better understanding of the role of cork particles in composite laminates, not only as a sustainable natural material, but also as a possible means of modifying the damage response of fibre-reinforced polymer composites under impact conditions.

1.3. Methodological Approach

The methodological approach adopted in this dissertation was experimental and was defined to evaluate the influence of cork particle incorporation on the impact response, damage development, and selected mechanical properties of glass fibre reinforced polymer composite laminates. The work was carried out through the manufacture of different laminate configurations, followed by mechanical testing, non-destructive damage assessment, and image-based quantification of the damage regions generated by impact loading.

The experimental work was developed in a laboratory context, using composite laminates manufactured specifically for this study. The investigated materials included thermosetting polymer matrices, E-glass fibre reinforcements in different architectures, and cork particles incorporated into the matrix phase. The main experimental group consisted of unsaturated polyester-based 0/90 woven glass fibre laminates with different cork particle contents, allowing the influence of cork incorporation to be analysed while maintaining the matrix system and reinforcement architecture constant. Complementary configurations were also produced to assess additional variables, namely matrix type, fibre orientation, and stacking sequence.

The research procedure was organised in sequential stages. First, the laminates were manufactured by hand lay-up and manually consolidated, with cork particles dispersed in the resin prior to fibre impregnation. The manufactured plates were then cut into test specimens

according to the requirements of the experimental programme. Subsequently, the specimens were subjected to LVI testing under controlled conditions, allowing the force, displacement, velocity, and energy histories to be recorded during the impact event.

After impact testing, the specimens were visually inspected and analysed by penetrant-enhanced radiographic inspection. This technique was selected because LVI may induce internal damage that is not fully visible on the impacted surface. The use of a contrast agent enabled improved detection of the radiographically indicated damage regions, supporting the assessment of internal damage development in the different laminate configurations.

The radiographs obtained after inspection were further analysed using Fiji software. For each specimen, the maximum damage length, maximum damage width, and apparent damage area were measured. The measurement procedure was repeated three times for each radiograph, allowing mean values and standard deviations to be calculated. These data were used to compare the apparent extent of impact-induced damage between the different laminate configurations.

In addition to the impact and radiographic analyses, tensile tests were performed on selected laminates in order to obtain complementary information regarding their static mechanical behaviour. The collected data included impact parameters, radiographic damage measurements, and tensile properties, which together supported the interpretation of the influence of cork particle incorporation on the overall response of the developed composite systems.

Overall, this methodological approach allowed the research objectives to be addressed through the correlation between laminate composition, impact response, apparent internal damage development, and tensile behaviour. In this way, the experimental programme provided the basis for assessing the potential and limitations of cork particle incorporation in glass fibre reinforced polymer composite laminates.

1.4. Dissertation Structure

This dissertation is organised into five chapters, following a progression from the theoretical framing of the research topic to the experimental assessment and interpretation of the obtained results.

After the present introductory chapter, Chapter 2 establishes the theoretical background required to support the study. It begins by addressing the fundamental concepts related to composite materials, including their definition, classification, and main industrial applications, before focusing on the damage mechanisms typically observed in laminated composites, with particular emphasis on delamination and its relevance under low-velocity impact loading. Since the present work investigates the incorporation of cork particles into composite laminates, the chapter also examines the structure, properties, sustainability aspects, and industrial applications of cork. Finally, the mechanical testing methods relevant to the present work are

presented, followed by a critical analysis of the literature, which identifies the main limitations and research opportunities that frame the experimental work.

The experimental basis of the dissertation is developed in Chapter 3, where the transition from the conceptual framework to the practical implementation of the study is established. This chapter defines the material systems, laminate configurations, manufacturing route, and testing procedures adopted to ensure that the influence of cork particle incorporation could be assessed in a controlled and comparative manner. The experimental programme is therefore organised around complementary methods: low-velocity impact testing to evaluate the impact response of the laminates, radiographic inspection and image analysis to assess the apparent internal damage, and tensile testing to provide additional information on their static mechanical behaviour.

Building on the experimental procedures described in Chapter 3, Chapter 4 presents and analyses the results obtained throughout the testing campaign. The impact response, radiographic inspection results, and tensile behaviour are first presented in a structured manner, allowing the main trends observed for each laminate configuration to be identified. These results are then discussed in relation to one another, in order to assess how cork particle incorporation influenced the mechanical response and apparent damage development of the laminates, while also considering the effects of matrix system, fibre orientation, and reinforcement architecture.

The dissertation concludes with Chapter 5, where the main findings are synthesised in light of the objectives initially defined. The limitations of the work are also discussed, allowing the scope of the conclusions to be properly framed and providing a basis for future studies on cork-modified composite laminates subjected to impact loading.

2. State of the Art

This chapter presents a literature review of the main concepts and studies relevant to framing the topic developed in this Master's thesis. Section 2.1 addresses composite materials, focusing on their definition, constitution, classification criteria, and industrial applications, thereby establishing a solid conceptual foundation. Section 2.2 analyses the critical damage mechanisms associated with these materials, with particular emphasis on delamination induced by sudden loading, as well as the mechanisms responsible for its initiation and propagation and the mitigation strategies reported in the literature. The chapter also includes a detailed characterisation of cork in Section 2.3, addressing its structure, properties, environmental advantages, and industrial applications in order to frame its potential as a functional material in composite systems. To support the experimental framework of the present dissertation, Section 2.4 describes the mechanical testing and damage assessment methods relevant to the present work, including impact testing, radiographic inspection, and tensile testing, while Section 2.5 discusses similar studies reported in the literature, providing the basis for positioning the present dissertation in relation to previous work. Finally, Section 2.6 provides a critical analysis of the reviewed literature, synthesising the main conclusions, limitations, and research opportunities that support the experimental work developed in this dissertation.

2.1. Composite Materials: Definition, Classification, and Applications

Composite materials constitute a class of engineering materials of considerable relevance, whose use has grown significantly across various industrial sectors. Understanding their fundamental characteristics, different forms of structural organisation, and the broad range of associated applications is essential to frame their mechanical behaviour and in-service performance.

In this context, this section first presents the definition and constitution of composite materials, based on widely accepted standards and concepts. Subsequently, the main classification criteria are addressed, considering both matrix type and reinforcement type. Finally, the principal industrial applications of composite materials are discussed, highlighting the diversity of contexts in which these materials are employed and establishing the framework for the analysis of the damage mechanisms addressed in the following sections.

2.1.1. Definition and Constitution of Composite Materials

According to ASTM D3878–20b – Standard Terminology for Composite Materials, a composite material consists of two or more insoluble materials combined to produce an engineering material with properties not exhibited by the individual constituents. Although inherently heterogeneous at the microscopic scale, a composite may, in many engineering applications, be considered homogeneous at the macroscopic scale. The constituents retain their individual identities without fully merging, yet act in a coordinated manner to confer superior mechanical, thermal, or structural properties [1].

Similarly, ISO 472:2013 – Plastics—Vocabulary (latest version ISO 472:2013/Amd 1:2018) defines a composite material as a solid product consisting of two or more distinct phases, including a matrix (binding material) and a reinforcement, which may be particulate or fibrous. Additionally, a composite may consist of multiple layers, which may include polymeric films, cellular plastics, metals, wood, or other materials, with or without adhesive interlayers [2].

In accordance with these normative definitions, the term composite material is adopted in this work to designate any material composed of two or more insoluble materials sharing a common interface, whose integration results in global properties superior to those of the individual constituents. Given the multiplicity of possible matrix–reinforcement combinations, it is pertinent to consider different classification criteria, as presented in Section 2.1.2.

2.1.2. Classification of Composite Materials

Composite materials may be classified according to different criteria, reflecting both the nature of their constituents and the structural organisation of the final material. The most frequently adopted classification approaches in the literature are based on the type of matrix, the type of reinforcement, the origin of the constituents, and the structural scale at which the composite is conceived [3]. Figure 1 provides an overview of the primary criteria used for classifying composite materials.

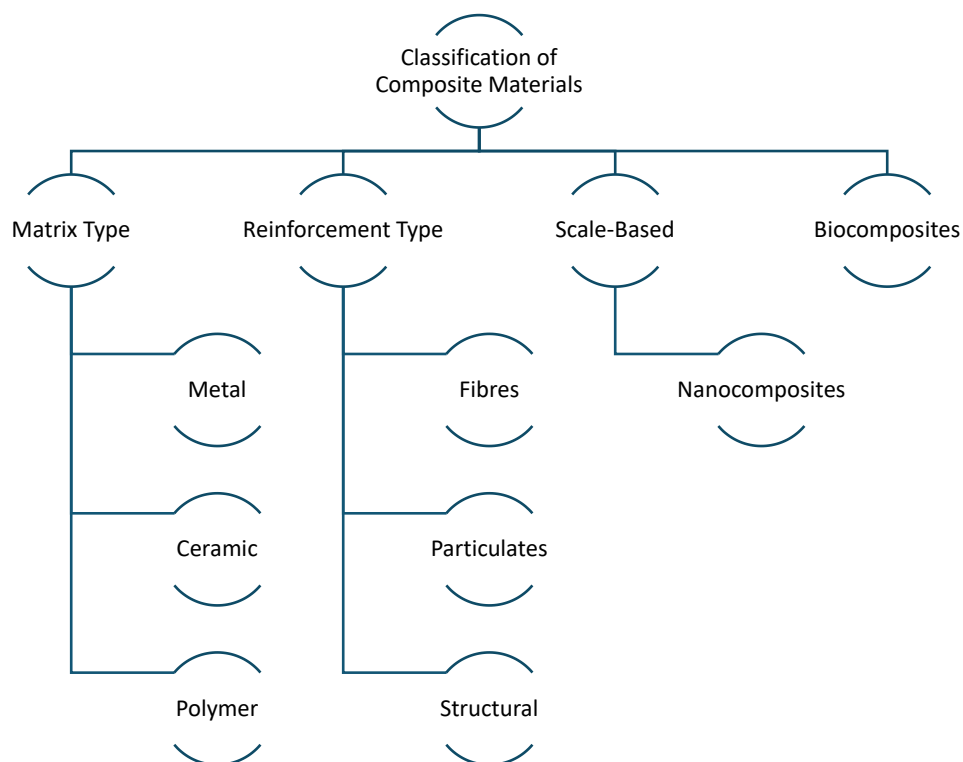


Figure 1 – Classification of composite materials (adapted from [3], [4], [5])

Among these classification systems, the one based on matrix type stands out as one of the most widely adopted. According to this criterion, composites are divided into three main categories: polymer matrix composites (PMCs), metal matrix composites (MMCs); and ceramic matrix composites (CMCs) [3], [5], [6], [7], as shown in Figure 2.

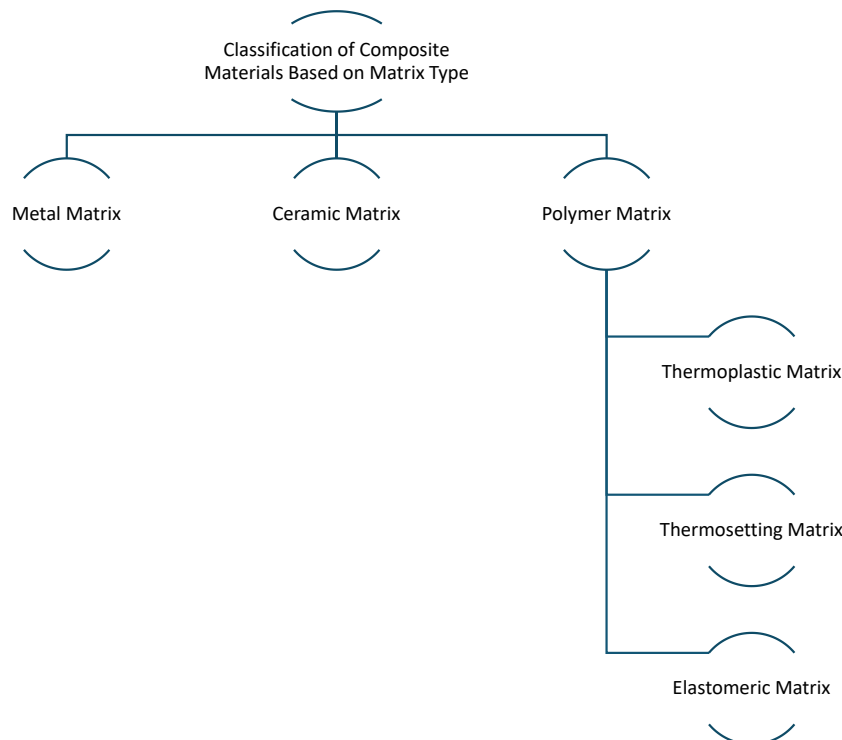


Figure 2 – Classification of composite materials according to matrix type (adapted from [3], [5])

In polymer matrix composites, the continuous phase consists of a polymer that surrounds the reinforcement, ensures stress transfer, and provides shape and structural integrity [6]. In general, polymeric matrices are subdivided into thermosetting, thermoplastic, and elastomeric matrices, each group exhibiting distinct characteristics and applications [3], [6], [7].

Thermosetting matrices, such as epoxy, polyester, and vinyl ester resins, form a highly cross-linked and irreversible three-dimensional structure after curing, exhibiting high stiffness, dimensional stability, and chemical and thermal resistance [6], [7]. In contrast, thermoplastic matrices, such as polyethylene (PE), polypropylene (PP), and polyether ether ketone (PEEK), are characterised by reprocessability, good ductility, and chemical resistance, allowing processes such as injection moulding, extrusion, and thermoforming to be performed with relative ease [6], [7].

Beyond matrix type, composites may also be classified according to the type of reinforcement employed. This classification is based on the geometry, distribution, size, and orientation of the dispersed phase, which may take the form of fibres, particles, or laminated structures [7]. Accordingly, three broad categories are distinguished: fibre-reinforced composites, particulate composites, and structural composites [3], [8], [9], as depicted in Figure 3.

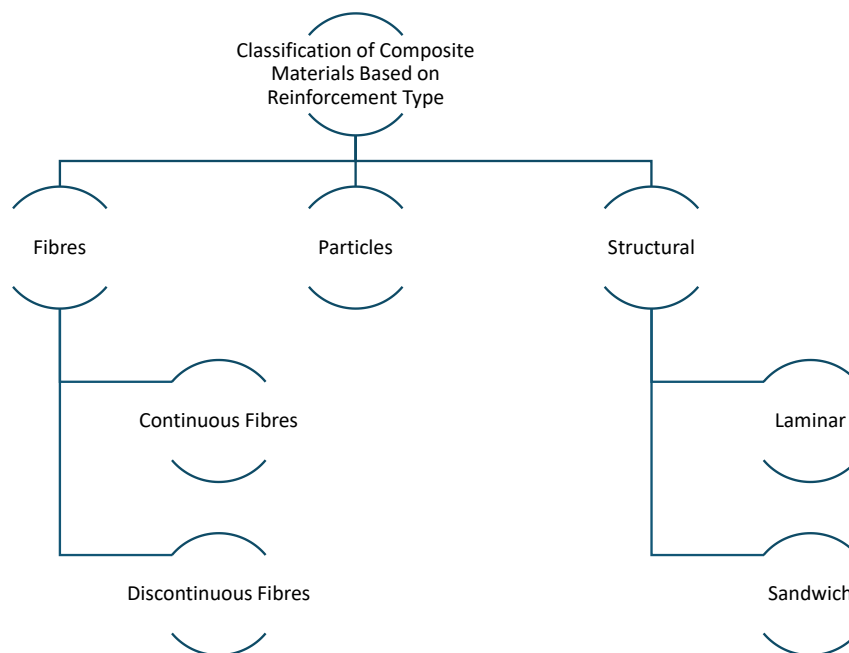


Figure 3 – Classification of composite materials according to reinforcement type (adapted from [3], [5], [7], [9])

In the case of fibre-reinforced composites, the fibres can be classified according to their length, distinguishing between continuous fibres, when they exhibit considerable length, and discontinuous fibres, when they are short. These fibres may be aligned or randomly oriented within the matrix. The high strength-to-weight ratio provided by this type of reinforcement allows superior mechanical properties to be achieved, making it a promising and relevant alternative to metals and alloys [7], [8]. On the other hand, in particle-reinforced composites, the reinforcement consists of particles dispersed within the matrix, which may vary in size and shape. This type of reinforcement mainly contributes to increased stiffness, wear resistance,

and dimensional stability, while also presenting the advantage of being economical and simple to manufacture [4], [7], [8]. Structurally, composites may be classified into laminates and sandwich panels. Laminates are formed by stacked sheets or plies, often fibre-reinforced, while sandwich panels combine high strength exterior with a lightweight core [9].

The different classification approaches for composite materials reflect the diversity of possible combinations between matrix and reinforcement, as well as the variety of structural configurations that these materials can assume. This diversity is directly associated with the wide range of industrial applications of these materials, which are addressed in the following section (Section 2.1.3).

2.1.3. Industrial Applications of Composite Materials

Composite materials currently play a prominent role across multiple industrial sectors and are widely recognised as one of the most versatile and promising classes of materials in modern engineering. The growing interest in these materials stems from the possibility of combining distinct properties within a single system, exploiting the synergy between matrix and reinforcement to meet specific mechanical, thermal, and chemical performance requirements. This adaptability has led to their adoption in diverse fields such as the aerospace, automotive, marine, biomedical, and construction industries [8].

Among the different types of composites, polymer matrix composites stand out as the most widely used in industrial applications due to their low density, ease of processing, and compatibility with different types of reinforcement (fibres or particles). These characteristics make composites particularly attractive for sectors such as the aerospace, automotive, marine, and sports industries, where weight reduction and corrosion resistance are key factors [6]. Furthermore, their high resistance to environmental degradation favours their application in marine structures, while their low weight contributes to the optimisation of structural and functional components in automotive vehicles [6].

More broadly, composite materials are widely used in technical and engineering structures such as sports equipment, aircraft, spacecraft, automobiles, marine vessels, buildings, and bridges. In the aerospace sector, the use of these materials began with glass fibre-reinforced composites and sandwich structures, later evolving to the incorporation of carbon fibre-reinforced composites, initially applied in secondary components such as fairings, doors, and spoilers. With advances in manufacturing technologies and the improved aerodynamic efficiency achieved, these materials have become integral to modern aircraft such as the Boeing 787 and the Airbus A380 [4].

In addition to polymer composites, ceramic matrix composites are used in applications subjected to extreme conditions, such as aircraft braking systems, exhaust nozzles, structural components exposed to large thermal gradients, gas turbines, and high-precision telescope antennas [4], [10].

The automotive industry makes extensive use of composite materials in braking systems, internal structures, hoods, tanks, panels, and impact elements, benefiting from increased stiffness, weight reduction, and improved fatigue resistance. In particular, composites such as C–SiC are used in braking systems subjected to extreme temperatures, while carbon fibre-based materials are applied in trunk lids, structural components, and wireless signal transmission systems [4], [10]. Furthermore, in electric vehicles, nanostructured composites are being considered for energy storage systems, such as supercapacitors and batteries [10].

In the marine sector, composite materials are widely used in high-speed ferries, offshore platforms, racing boats, and fishing vessels, among others, due to their resistance to corrosion and marine degradation [4]. In addition, applications involving carbon fibre-reinforced composites, anti-biofouling coatings incorporating nanoparticles, and sandwich-type hull structures with polymeric cores have been reported for components such as propellers, owing to their corrosion resistance, mechanical stability, and low density [10].

In civil engineering, due to their durability and high mechanical strength, composites are used in applications such as fire-resistant concretes, concrete beams and slabs, bridge systems, earthquake-resistant columns, and deck panels [4]. In the mechanical sector, these materials are applied in components such as gear pairs, pressure vessels, cylinder heads, turbine blades, and hydraulic cylinders [4].

Composite materials also play an increasingly important role in the biomedical sector, where a significant number of composite biomaterials have recently been investigated and evaluated for medical applications due to their advantages over conventional materials [4]. Accordingly, some applications in this field include medical devices such as wound dressings for skin grafts, advanced orthopaedic implants, membranes for separation processes, and haemodialysis [10].

In this context, although traditional composites dominate much of the structural and functional applications described, recent advances in materials engineering have driven the demand for environmentally friendly alternatives while simultaneously maintaining high levels of mechanical and functional performance. In this regard, cork, particularly in the form of agglomerates, has shown remarkable potential in engineering and protective applications due to its energy absorption capacity, thermal and acoustic insulation properties, lightness, and nearly isotropic viscoelastic behaviour [11], [12].

Given the wide range of industrial applications and the high performance associated with composite materials, their use in structural and functional contexts involves exposure to various mechanical, thermal, and environmental loads throughout their service life. These conditions can lead to the development of internal damage mechanisms, often difficult to detect, which affect the mechanical behaviour and structural integrity of the components. In this regard, it is essential to understand the critical damage associated with composite materials, as well as the mechanisms responsible for its initiation and propagation, a topic that will be addressed in Section 2.2.

2.2. Critical Damage in Composite Materials

In general, composite materials exhibit a high strength-to-weight ratio and great versatility for use in various engineering contexts, however, despite these advantages, their application is not without limitations, as these materials can develop critical damage capable of compromising the structural integrity of components. Among the most relevant damage mechanisms is delamination, which corresponds to the separation between adjacent layers of a laminate and can lead to a significant reduction in the material's stiffness and strength [13].

Within this framework, the analysis of damage mechanisms in composite materials assumes particular importance, as it enables an understanding of their structural behaviour when subjected to mechanical loading. Moreover, this knowledge provides the foundation for the development of approaches aimed at damage prevention and mitigation, aspects that are essential for the design and safe use of these materials in practical applications [12].

2.2.1. Types of Critical Damage in Composite Materials

Throughout their service life, composite materials can develop various types of damage that gradually or abruptly affect their structural performance and result from irreversible processes associated with mechanical and thermal loading, the presence of defects introduced during manufacturing, or inherent imperfections in the material's microstructure. The nature of the damage mechanisms and the way they evolve depend on multiple factors, including the composite's geometry, the properties of its constituents, and the service conditions to which it is subjected [14], [15]. Accordingly, the most frequently reported damage mechanisms in the literature include:

- **Initial defects and damage**

One of the primary factors influencing damage behaviour is the presence of **internal voids**, whose evolution can occur under loading. The expansion of these voids tends to locally concentrate stresses, creating regions prone to crack initiation. Moreover, even when their volume fraction is low, these defects can significantly alter the material's overall mechanical response, with their occurrence being strongly dependent on processing conditions such as applied pressure, temperature, and resin viscosity during curing [15], as illustrated in Figure 4(a).

- **Matrix damage**

Among the types of damage that develop predominantly in the matrix are **matrix microcracks**, frequently referred to in the literature as intralaminar cracks, transverse cracks, or ply cracks. These cracks develop within an individual ply and generally propagate parallel to the fibre direction, with their occurrence being associated with tensile loading, cyclic stresses, or thermal variations, and are more common in plies that are unfavourably oriented relative to the principal loading direction. In addition to the progressive degradation of thermomechanical

properties, these microcracks can act as initiation points for larger-scale damage mechanisms, such as delamination [15], [16], as illustrated in Figure 4(b).

- **Interfacial damage**

At the interface between the composite constituents, one of the most frequently identified mechanisms is **interfacial debonding**. This phenomenon occurs when the bond between the fibre and the matrix is no longer able to withstand the locally developed stresses, leading to partial separation between these two phases. Interface degradation compromises the load transfer mechanism within the composite and can create conditions conducive to the formation of additional microcracks, often being identified as an initial stage preceding the activation of more severe failure mechanisms [15], [17], as illustrated in Figure 4(c).

Associated with the fibre–matrix interface behaviour is **interfacial sliding**, which corresponds to the relative movement between the fibre and the matrix along the interface. This mechanism can occur after interfacial debonding or result from the interaction between matrix cracks and the interface, with the presence of residual compressive normal stresses promoting this behaviour, which contributes to stress redistribution and damage progression under thermomechanical loading [15], as illustrated in Figure 4(d).

- **Interlaminar damage**

In composite laminates, structural integrity can be severely compromised when separation occurs between adjacent layers, a phenomenon known as **delamination**, which is often identified in the literature as one of the most critical fracture mechanisms in this type of material. This type of damage is associated with the development of out-of-plane normal and shear stresses, which tend to concentrate in structurally sensitive regions such as free edges, holes, or exposed surfaces. In addition to these regions, delamination may also be initiated by low-velocity impacts or by the interaction and coalescence of previously formed intralaminar cracks, and this mechanism can propagate under subsequent loading, leading to a significant reduction in the laminate's stiffness and strength and substantially increasing the risk of structural failure [15], [18], as illustrated in Figure 4(e).

- **Reinforcement damage**

When the level of mechanical loading applied to a composite exceeds the load-carrying capacity of the fibrous reinforcement, the fracture of individual fibres may occur, known as **fibre fracture** or fibre breakage. This type of damage arises when axial stresses or strains exceed the intrinsic strength of the fibres. In fact, in composites reinforced with continuous fibres, the failure of a single fibre requires load redistribution to neighbouring fibres through the fibre–matrix interface, and this redistribution may lead to the successive failure of adjacent fibres whenever local stress levels remain high [15], [19], as illustrated in Figure 4(f).

In unidirectional composites subjected to compressive loading, **fibre microbuckling** constitutes a dominant failure mechanism. This phenomenon results from the local instability of the fibres and may occur according to two main modes: (i) extensional mode, in which the fibres deform out of phase with each other, and (ii) shear mode, characterised by in-phase deformation; both

modes lead to a significant reduction in the load-carrying capacity of the material [15], as illustrated in Figure 4(g).

In **particulate composites**, a specific damage mechanism is **particle cleavage**, which corresponds to the fracture of rigid reinforcing particles embedded in a ductile matrix. The cracks associated with this process generally develop perpendicular to the direction of the maximum principal stress, contributing to the localised degradation of the composite's mechanical properties [15], as illustrated in Figure 4(h).

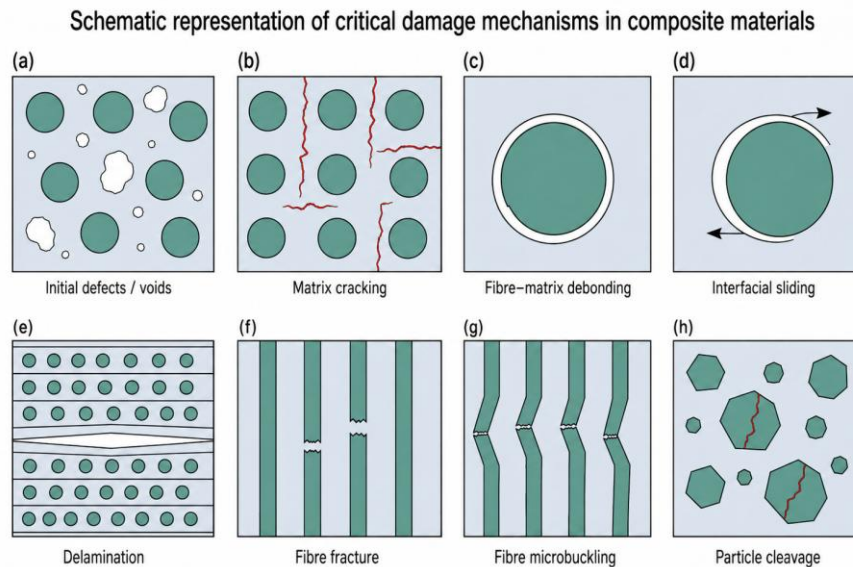


Figure 4 – Schematic representation of the main critical damage mechanisms in composite materials.

In general, each of these mechanisms exhibits characteristic scales and evolves differently as the applied loading increases. The interaction between different mechanisms contributes to an increasingly complex damage scenario throughout the service life of the structure, with the mechanisms effectively activated depending on the properties of the constituent materials, the architecture and orientation of the reinforcement, the characteristics of the interface, and the loading and environmental conditions to which the composite is subjected [15]. Among these mechanisms, delamination is particularly relevant in laminated composites and is therefore discussed in greater detail in Section 2.2.2.

2.2.2. Delamination Mechanisms

In composite materials subjected to low-velocity impact, delamination develops as a result of the combination of out-of-plane normal and shear stresses, primarily concentrated at the interfaces between adjacent plies with different orientations. As reported in the literature, the initiation of this type of damage is associated with the failure of the thin resin layer between plies and is influenced by bending mismatch between neighbouring plies, as well as by impact parameters such as strain rate and impactor geometry [20], [21].

Following initiation, delamination may evolve through interlaminar propagation along the interfaces. End-notch flexure (ENF) tests show that this process involves complex mechanisms associated with the interaction between the crack and the interface microstructure, namely significant deformation of the polymer matrix and fibre–matrix debonding phenomena during crack growth. Additionally, this study indicates that the presence of particles in the interlaminar region can significantly alter the crack path, promoting crack kinking, changes in the propagation trajectory, and, in some cases, temporary crack arrest, leading to a propagation path in which an increased amount of energy is required for the delamination to continue growing [13].

In summary, delamination in composite materials results from a set of interrelated mechanisms involving damage initiation at interlaminar interfaces and its subsequent propagation along these interfaces under complex stress states. These processes lead to the progressive degradation of the structural integrity and mechanical performance of the laminate. In this context, it is essential to understand not only the mechanisms of delamination initiation and evolution, but also the implications associated with its presence in service, which justifies the analysis of the importance of its prevention and control, addressed in Section 2.2.3.

2.2.3. Importance of Delamination Prevention

Delamination represents one of the most critical issues in the design and use of composite material structures, as it directly compromises the effectiveness of the fibre reinforcement. When this damage mechanism develops, the structural behaviour of the component tends to become progressively governed by the properties of the polymer matrix, which are generally inferior to those of the reinforcement, leading to a significant degradation of the material's overall mechanical performance [15].

In this context, the identification, control, and prevention of delamination assume particular importance, especially considering the increasing use of these materials in structural applications where combinations of low density and high load-bearing capacity are required. In fact, the frequency with which delamination is observed in service, coupled with the difficulties associated with its early detection, has motivated a significant number of studies dedicated to the analysis, monitoring, and mitigation of this type of damage [20].

Consequently, the scientific research conducted in this area has generated a substantial body of knowledge, encompassing increasingly advanced analytical, experimental, and numerical approaches. Extensive literature reviews underscore the complex and multifaceted nature of delamination and its influence on the structural behaviour of composites, playing a key role in improving predictive models and guiding the development of design strategies focused on damage tolerance [20].

However, and despite the technological advances achieved in recent years, particularly in the development of non-destructive testing techniques based on ultrasonic methods and piezoelectric sensors, the detection of small-scale delaminations remains challenging,

especially in adhesive joints and structurally complex regions. This limitation emphasises the need to deepen the understanding of the mechanisms responsible for delamination initiation and propagation, as well as the factors influencing its evolution over time [20].

In summary, the significance of delamination as a critical damage mechanism, combined with the challenges associated with its detection and the structural consequences it can cause, highlights the need to address the issue not only from an analytical perspective but also from an intervention standpoint. In this context, the development and application of techniques and strategies aimed at damage mitigation play a central role in improving the performance and durability of composite material structures. Section 2.2.4 thus presents a synthesis of the main approaches reported in the literature for limiting damage initiation and propagation, with particular emphasis on delamination.

2.2.4. Techniques and Strategies for Damage Mitigation

Damage mitigation in composite materials, particularly delamination, has been widely investigated in the literature due to the significant influence of this mechanism on the structural performance and durability of laminates. In general, the proposed strategies aim to reduce the susceptibility to delamination initiation or to limit its propagation after damage onset, acting primarily at the interlaminar region, where this phenomenon most frequently develops [13], [20].

Among the most recurrent approaches are modifications of the interface between layers, including the introduction of interleaved phases or particles dispersed within the matrix, with the objective of altering the interlaminar fracture mechanisms. Studies based on interlaminar fracture tests demonstrate that these modifications may lead to an increase in fracture energy, associated with mechanisms such as crack path deflection, temporary crack arrest, and enlargement of the fracture process zone, thereby contributing to greater resistance to delamination propagation [13].

In summary, the literature shows that the mechanisms associated with delamination initiation and propagation are strongly linked to the behaviour of the interlaminar region and to the energy dissipation processes occurring at this scale. Although many of the available results are derived from quasi-static interlaminar fracture tests, the identified mechanisms provide relevant insights into the behaviour of composite materials under LVI loading. Within this framework, it becomes pertinent to analyse materials with intrinsic properties favourable to energy absorption and the damping of complex in-service loading conditions, particularly dynamic loads that may promote the growth of the delaminated area. Accordingly, Section 2.3 focuses on cork, addressing its structure, properties, and potential application in composite systems, with particular emphasis on the characteristics that justify its interest for impact-related applications.

2.3. Properties and Characteristics of Cork

Cork is a natural material with unique characteristics that have attracted growing interest in the field of materials engineering, particularly in the development of sustainable and functional solutions. Understanding its internal structure, physical, mechanical, and thermal properties, as well as the environmental advantages associated with its use, is essential for evaluating its potential in technical applications and composite systems. In this context, this section begins with a description of the structure and composition of cork, followed by an analysis of its main physical, mechanical, and thermal properties. Subsequently, the environmental advantages associated with its natural origin and its role within sustainability and circular economy strategies are discussed. Finally, the principal industrial applications of cork are presented, highlighting the diversity of contexts in which this material has been employed.

2.3.1. Structure and Composition of Cork

As a natural material, cork is distinguished by an internal organisation and chemical composition that result directly from its biological growth process, decisively influencing its physical and mechanical behaviour. Its anisotropic nature reflects the way the cells are organised within the cork oak tissue, and its structure is commonly analysed according to three main directions: (i) axial, associated with the longitudinal growth of the tree; (ii) radial, related to the increase in trunk thickness; and (iii) tangential, corresponding to the directions perpendicular (orthogonal) to the previous ones. This directional differentiation is fundamental for the correct interpretation of cork properties and its response to mechanical loading [22].

At the microscopic scale, the internal organisation of cork is dominated by a closed cellular architecture, as illustrated in Figure 5, composed of hollow gas-filled cells that are highly compacted and interconnected, forming a continuous network that gives the material a highly characteristic morphology. When observed in cross-section, this structure predominantly reveals cells with a geometry close to hexagonal, regularly arranged and connected base-to-base, resulting in a honeycomb-like configuration. This structural arrangement plays a central role in the mechanical and functional behaviour of cork [22].

In the radial and tangential planes, the cellular morphology presents significant differences compared to the cross-section. In fact, the cells assume an elongated prismatic shape, oriented parallel to each other and organised into rows resulting from the division of a common mother cell. This organisation leads to progressive growth in the radial direction and to a staggered arrangement between adjacent rows, conferring a well-defined structural anisotropy to the material. Consequently, the regularity of this architecture directly influences the response of cork to mechanical loading applied along different directions [22].

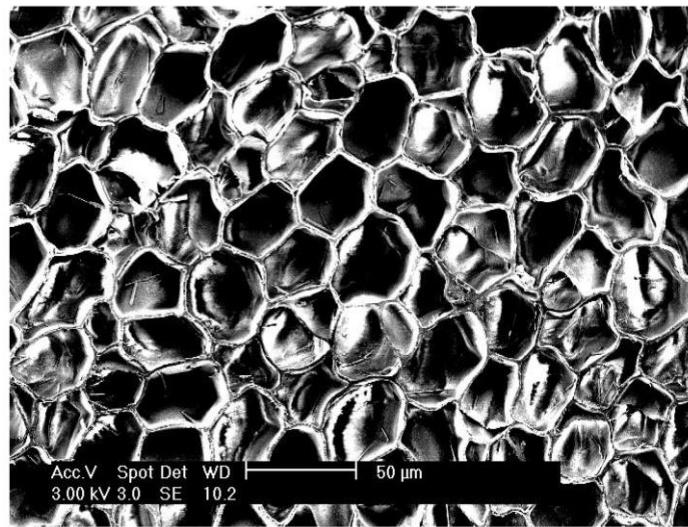


Figure 5 – Microscopic-scale image of the cork structure (retrieved from [23])

The cellular walls of cork exhibit reduced thickness and an undulated morphology, this undulation being particularly evident when observed in the radial plane. The wall thickness typically varies from a few hundred nanometres to approximately one micrometre, reflecting the characteristic structural heterogeneity of this material. In addition, cork is distinguished by the chemical composition of its cellular walls, whose principal constituent is suberin, a complex biopolymer representing approximately 45% of the material's mass, followed by lignin, which corresponds to around 22% of the total composition, while polysaccharides, including cellulose and hemicellulose, account for approximately 18% of the mass. Furthermore, extractive compounds are also present, corresponding to about 15% of the total composition, as well as an ash content generally below 3% [22].

The cellular architecture and chemical composition of cork constitute central elements of its material characterisation. These aspects reflect both its internal organisation and the nature of the cellular wall constituents and are influenced by biological factors associated with the producing species. A detailed analysis of the structure and composition of cork allows a rigorous description of the material, taking into account the variations existing among different types of cork [22].

According to Teixeira, R., the chemical composition of cork varies considerably, with suberin contents ranging between 23.1% and 54.2%, while lignin exhibits variations between 17.1% and 36.4% [24]. This compositional variability reflects biological, environmental, and growth-related differences and results in distinct material behaviours when subjected to mechanical, thermal, and physical loading. Therefore, understanding the properties of cork requires a detailed analysis of how its structure and composition influence its performance, an aspect that will be further developed in Section 2.3.2.

2.3.2. Physical, Mechanical, and Thermal Properties

Cork exhibits a set of distinctive physical and mechanical properties that result directly from its closed cellular structure and the anatomical orientation of the material. Similarly to what occurs in other materials of vegetal origin, such as wood, the analysis of these properties is commonly performed according to the radial (R) and non-radial (NR) directions, the latter corresponding to the tangential and axial directions [25].

Regarding physical properties, the low density of cork results essentially from the high fraction of gas present inside the closed cells. This characteristic, combined with the reduced cell size, limits heat transport within the material, making conduction the predominant heat transfer mechanism. Similarly, sound transmission is reduced, since a significant part of the incident acoustic energy is absorbed and dissipated in the form of heat, a behaviour related to the high porosity and low density of cork [25].

Cork also exhibits specific surface properties, characterised by low surface polarity and high affinity for non-polar liquids. Surface energy studies indicate that its surface possesses an amphoteric character, allowing compatibility with both acidic and basic functional groups, an aspect that is particularly relevant in contexts involving contact with polymeric materials [25].

With regard to mechanical properties, when subjected to compressive loading, the mechanical response of cork is typical of flexible cellular materials, exhibiting a stress–strain curve composed of three well-defined regions. In an initial stage, up to approximately 7% strain, the behaviour is dominated by elastic bending of the cellular walls, followed by a plateau region, approximately constant up to about 70% strain, associated with the progressive buckling of the cell walls. At higher deformation levels, crushing of the cellular walls and structural collapse occur, leading to a significant increase in the stress required to continue deforming the material [25].

The geometry and arrangement of the cells also exert a significant influence on the Poisson's ratio of cork, as the staggered organisation of the cellular bases, combined with the corrugation of the lateral walls, gives rise to distinct behaviours depending on the loading direction. Thus, when loading is applied in the radial direction, a slight expansion in the non-radial direction is observed, resulting in low positive values of Poisson's ratio. In contrast, compression in the non-radial direction leads to contraction in the radial direction, potentially resulting in negative values of Poisson's ratio at high deformation levels, a phenomenon associated with the inversion of the cellular wall corrugation pattern [25].

The mechanical properties of cork also depend on the calibre of the planks, defined by their thickness, which is related to the growth rate of the material. In compression tests, thicker planks generally exhibit lower strength and Young's modulus values, a behaviour attributed to differences in cell dimensions and in the degree of cellular wall corrugation. Conversely, thinner planks contain a greater fraction of late cork cells, characterised by thicker walls and lower corrugation, which is reflected in higher stiffness and mechanical strength values [25].

In general, cork exhibits distinct behaviours under tensile and compressive loading. The Young's modulus in compression is significantly lower than that observed in tension, a phenomenon

associated with the behaviour of the corrugated cellular walls. While compression tends to increase the amplitude of the corrugations, tension promotes their reduction, leading to an increase in the effective stiffness of the material under tensile loading [25]. These properties are summarised in Table 1

Table 1 – Mechanical properties of cork (adapted from [25]).

Properties	Value
Young's modulus in tension – boiled (MPa)	38 ^R
	24 – 26 ^{NR}
Young's modulus in compression (MPa)	8 – 20 ^R
	13 – 15 ^{NR}
Buckling stress – boiled (MPa)	0.75 – 0.80 ^R
	0.60 – 0.70 ^{NR}
Buckling strain (%)	4 ^R
	6 ^{NR}
Tensile failure stress (MPa)	1.0 ^R
	1.1 ^{NR}
Tensile failure strain (%)	5 ^R
	9 ^{NR}
Fracture toughness – boiled (MPa·m ^{1/2})	60 – 130
Poisson's ratio – boiled	0 – 0.097 (V _R /NR)
	0 – 0.064 (V _{NR} /R)
	0.26 – 0.5 (V _{NR} /NR)

^R Measured in the radial direction; ^{NR} Measured in the non-radial direction

Finally, regarding the thermal and dielectric properties of cork, the material exhibits multiple relaxation mechanisms associated with the constituents of the cellular wall, namely suberin and the waxes present in the material. These phenomena are influenced by the presence of adsorbed water and contribute to the behaviour of cork as a dielectric and electrically insulating material, reflecting the diversity of properties resulting from its structure and composition [25].

In addition to the physical, mechanical, and thermal properties discussed, cork also stands out due to characteristics that go beyond its functional performance as an engineering material. Its natural origin, renewable extraction process, and the possibility of valorising industrial waste confer growing interest on cork within the current context of sustainable development. In this framework, it becomes pertinent to analyse the environmental advantages associated with this material, as well as its contribution to sustainability and circular economy strategies, aspects that are addressed in Section 2.3.3.

2.3.3. Sustainability and Environmental Advantages

Cork has been assuming an increasingly important role in the development of sustainable materials, particularly in the context of industrial waste valorisation and the adoption of circular

economy principles. The cork industry generates significant quantities of by-products and waste throughout the different processing stages, which for a long time were considered low-value materials. However, recent studies demonstrate that these residues can be transformed into functional materials with physical and structural properties suitable for engineering applications, simultaneously contributing to the reduction of the environmental impact associated with their management [22].

In this way, the incorporation of cork residues into polymeric matrices has enabled the development of lightweight composite materials, exploiting intrinsic cork characteristics such as low density, elasticity, and closed cellular structure. When compared with composites reinforced with traditional inorganic fillers, these materials present evident environmental advantages, as they promote the use of renewable resources and the reuse of industrial waste [22].

In addition to the environmental contribution associated with waste valorisation, the intrinsic characteristics of cork further reinforce its relevance as a component of functional materials for engineering applications. In this context, the valorisation of cork waste contributes not only to the mitigation of environmental impacts associated with industrial production, but also to the development of material solutions aligned with sustainability and technological innovation strategies, thereby increasing interest in cork as a component of advanced materials [22]. These characteristics have supported the use of cork in a wide range of industrial applications, which are presented in Section 2.3.4.

2.3.4. Industrial Applications

Cork has been increasingly used across a wide variety of industrial sectors, taking advantage of a set of distinctive properties, such as low density, elasticity, impermeability, thermal and acoustic insulation capacity, as well as a high ability to absorb impact and vibration. These characteristics enable its application in both traditional uses and more advanced technological solutions, including composite materials and functional products.

In the construction sector, cork is widely employed as a thermal and acoustic insulation material, as well as in vibration isolation applications. In fact, cork products are used in flooring, wall coverings, false ceilings, expansion joints, and multilayer systems, and are also applied in specific industrial contexts such as cold storage chambers and acoustic insulation in submarines. In some applications, cork is combined with other construction materials, resulting in composite solutions with performance tailored to the demands of the surrounding environment [23].

Cork also finds relevant applications in the automotive, aerospace, and military sectors, where it is used in environments subjected to extreme conditions. Examples include thermal shields applied in space systems, as well as fire-retardant cork agglomerates used in warships and in the internal lining of submarines. These applications demonstrate cork's ability to maintain its

performance under severe conditions, reinforcing its relevance for demanding technical applications [23].

At the same time, one of the most well-known applications of cork occurs in the wine industry, particularly in the production of stoppers. Agglomerated cork, obtained from production residues and lower-quality cork, is transformed into simple or composite stoppers, including specific solutions for sparkling wines, where suitable mechanical and sealing properties are required [23].

In areas related to energy and electronics, cork has been explored in the development of functional materials, benefiting from its cellular structure and electrical insulation properties. Accordingly, cork derivatives have been used in materials for electrodes. More recently, cork has served as a precursor for the production of laser-induced graphene, exhibiting electrical properties comparable to those of reduced graphene oxides. These materials have been applied in the development of flexible supercapacitors and electronic devices, demonstrating high electrochemical stability over multiple charge and discharge cycles [22].

In the environmental field, cork and its derivatives are used in applications associated with pollutant adsorption and oil–water separation, exploiting their affinity with different chemical substances. These applications highlight the potential of cork as a functional material in strategies for environmental impact mitigation and waste treatment [22].

In addition, the incorporation of cork into advanced manufacturing processes, including 3D printing technologies, has enabled the development of materials with properties tailored to specific requirements, such as impact absorption, localised stiffness, and structural lightness. These approaches expand the possibilities for the design and functionalisation of cork-based materials, favouring their integration into innovative industrial solutions [22].

In the mobility sector, cork-based materials have been applied in impact absorption and vibration damping solutions, with particular emphasis on their use in helmets for micromobility and motorcycles. In these contexts, cork has been explored as an alternative to conventional synthetic foams, such as EPS and EPP, due to its ability to withstand multiple impacts and largely recover its original shape after deformation [12], [22]. Similarly, in the footwear industry, cork materials meet the technical requirements of the sector and are widely used in soles, midsoles, insoles, fillers, and coatings. In particular, cork insoles contribute to user comfort by providing high shock absorption, damping, thermal insulation from the ground, and impermeability [22].

In summary, the diversity of industrial applications of cork highlights its potential as a functional and sustainable alternative to traditional materials, including inorganic fillers and reinforcements. The combination of technical performance, raw material availability, and environmental advantages has contributed to the growing valorisation of cork across different areas of engineering and industry [22]. Considering the relevance of mechanical performance in the application of composite materials, the main mechanical testing and damage assessment methods relevant to the present work are presented in Section 2.4.

2.4. Mechanical Testing and Damage Characterisation

Mechanical testing and damage assessment constitute essential tools for characterising the structural behaviour of composite materials and for evaluating their response under different loading conditions. In the context of the present dissertation, particular relevance is given to LVI testing, radiographic inspection, and tensile testing, as these methods enable the assessment of impact response, internal damage development, and static mechanical behaviour. Accordingly, this section presents the general principles of the experimental techniques relevant to the evaluation of the composite laminates investigated in this work.

2.4.1. Impact Testing

Impact testing constitutes a fundamental tool in the mechanical characterisation of composite materials, enabling the evaluation of their behaviour when subjected to suddenly applied loading. Unlike quasi-static tests, impact tests allow the analysis of damage resistance, energy absorption capacity, and the failure mechanisms activated during short-duration events, which are representative of many real service situations, namely accidental impacts, falling objects, or collisions [26].

According to the literature, impact tests on composite materials are commonly classified based on impact velocity, with four main categories being identified: (i) hypervelocity impact; (ii) high-velocity impact; (iii) medium-velocity impact; and (iv) low-velocity impact. In low-velocity impact tests, typically associated with velocities below 10 m/s, the material may suffer significant internal damage while still maintaining apparent structural integrity [26]. Such damage is particularly relevant in laminated composite materials, since it may be difficult to detect visually and can compromise the residual mechanical performance of the structure.

Among the experimental methods most commonly used to perform low-velocity impact tests are drop-weight impact tests and pendulum impact tests, namely Charpy and Izod tests. The drop-weight method [27], illustrated in Figure 6 (a), consists of releasing an impactor from a predetermined height, promoting direct impact on the specimen. This method presents the advantage of not requiring strictly standardised geometries, thereby allowing tests to be carried out on specimens with more complex shapes and approximating real impact conditions. During the test, different scenarios may occur, including impactor arrest, rebound, or complete perforation of the material, depending on the applied impact energy [26].

Pendulum impact tests (Figure 6 (b)), such as Charpy and Izod tests, are widely used in the characterisation of the impact toughness of composite materials. In both cases, the energy absorbed during specimen fracture is determined from the difference between the initial potential energy of the pendulum and the remaining energy after impact. The main difference between these two methods lies in the specimen fixation conditions and the notch position: in the Charpy test, the specimen is supported at its ends and impacted at the central region, whereas in the Izod test the specimen is fixed at the base and impacted at the upper extremity, on the same side as the notch. These tests are particularly useful for comparing different

materials and composite configurations, although they present limitations in representing real impact scenarios in complex structures [26].

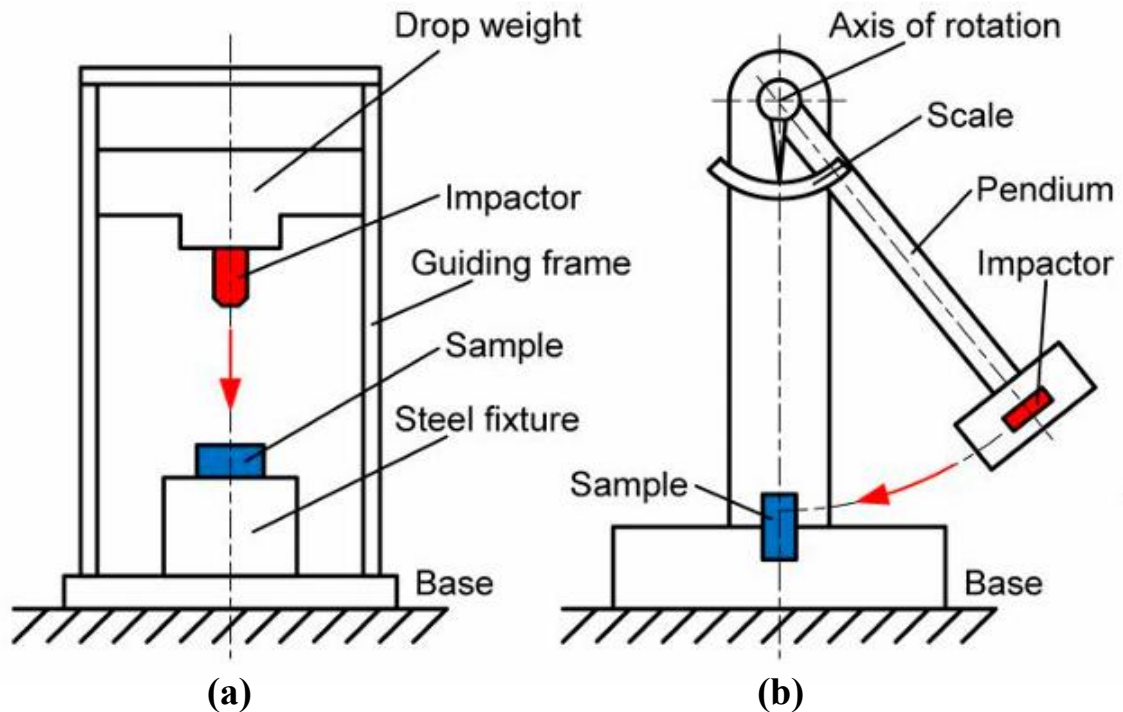


Figure 6 – Schematic representation of impact methods: (a) drop-weight impact test and (b) pendulum impact test (retrieved from [26])

In the context of the mechanical characterisation of composites, impact testing therefore plays a central role, providing essential information regarding damage tolerance and the energy absorption capacity of materials. These characteristics are particularly relevant for structural applications, where low-energy impacts may generate significant internal damage without evident external signs. Consequently, the correct selection of the testing method and the careful interpretation of the obtained results are fundamental aspects in the evaluation of the performance of composite materials under service conditions.

In the present dissertation, the low-velocity impact response of the developed laminates was evaluated using an instrumented drop-weight impact configuration, since this method allows the force, displacement, and energy histories of the impact event to be recorded. However, the mechanical response obtained during impact testing does not fully describe the internal damage state of the laminate. For this reason, impact testing was complemented by radiographic inspection, as discussed in Section 2.4.2.

2.4.2. Radiographic Inspection

Radiographic inspection, commonly referred to as X-radiography, is a non-destructive testing method based on the interaction between penetrating radiation and the material under

examination, being defined in ASTM E1316 (latest version ASTM E1316-26a) as the use of penetrating radiation to detect discontinuities in a material and produce an image after passing through the examined component [28], [29]. In a conventional radiographic arrangement, the component is positioned between an X-ray source and a detector or film, as schematically shown in Figure 7, and the resulting image is formed from the radiation transmitted through the material. Since the degree of attenuation depends on parameters such as material density, thickness, geometry, and absorption characteristics, internal features may be detected when sufficient contrast exists between different regions of the inspected component [28], [30].

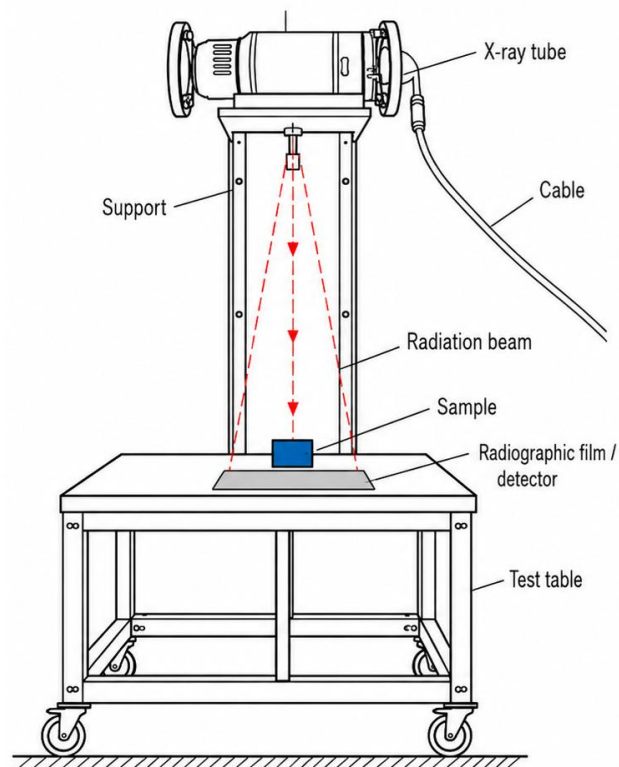


Figure 7 – Schematic representation of the radiographic inspection setup.

In industrial radiography, image quality is strongly influenced by the selected radiation energy, exposure conditions, source-to-detector distance, detector or film characteristics, and the geometry of the inspected part [30]. General radiographic practice standards establish minimum requirements for the control and application of the method to metallic and non-metallic materials [31].

The relevance of radiographic inspection in composite laminates is closely related to the nature of damage generated under low-velocity impact. Fibre-reinforced polymer composites may develop complex internal damage with little or no visible evidence at the surface, often resulting in barely visible impact damage (BVID); this type of damage may involve delamination, matrix cracking, fibre/matrix debonding, fibre fracture, or combinations of these mechanisms [32], [33], [34], [35]. As a result, visual inspection alone is often insufficient to evaluate the severity of impact-induced damage, and non-destructive techniques are required to detect, locate, and compare internal damage without further compromising the structural integrity of the material [34], [35].

Within this context, the suitability of radiographic inspection depends not only on its ability to reveal internal damage, but also on the contrast that can be generated between damaged and undamaged regions. When the attenuation characteristics of the constituents or defects differ sufficiently, radiographs can reveal internal features as variations in grey level; however, conventional radiography may be limited in polymer matrix composites because the contrast between fibres, matrix, cracks, and delaminated regions can be relatively low [28], [35]. Moreover, very thin cracks or delaminations may be difficult to detect if their dimensions are below the spatial resolution of the technique or if their orientation does not produce a significant change in attenuation along the X-ray path [35], [36], [37].

This limitation is particularly important in impact-damaged laminates, where the damage state may include a combination of small-scale matrix cracks and interlaminar separations distributed through the thickness. To overcome the low inherent contrast of certain damage features, radiographic inspection of composite laminates is often enhanced using a radio-opaque penetrant. In penetrant-enhanced X-radiography, a liquid with high X-ray absorption is introduced into surface-connected cracks and interconnected damage networks, including accessible delaminations, thereby increasing the contrast between damaged and undamaged regions [28].

Several studies have used different radio-opaque penetrants, including diiodomethane [28] and zinc iodide solutions [38], [39], [40], to improve the visibility of impact-induced damage in fibre-reinforced composite laminates. More broadly, penetrant-based approaches have also been used to support the assessment of damage size and morphology in impacted composites, allowing damaged regions to be more clearly distinguished from the surrounding material [28], [33], [41].

Once the damaged regions are made visible, radiographic images can be used not only for qualitative damage identification, but also for comparative evaluation between material configurations. In this context, penetrant-enhanced radiography has been applied to assess the extent and morphology of impact damage in composite laminates, including cases ranging from barely visible impact damage to more severe damage states [38], [39], [42]. The method is particularly useful when the objective is to compare the apparent extent of damage produced under similar impact conditions, since parameters such as damage length, damage width, and projected or apparent damage area can be extracted from the radiographs [28], [38]. These measurements provide a quantitative basis for comparing damage resistance between different laminate configurations, although they must be interpreted within the limitations of the technique.

Image processing can further support the quantitative interpretation of radiographic inspection results. In previous studies, radiographs have been imported into image analysis software, calibrated using a known reference distance to estimate damage-related parameters such as damage area [28]. Other works have used digitised radiographic images to measure projected delaminated areas or to compare the accuracy of different non-destructive inspection methods in detecting impact damage [38]. This type of analysis is relevant because it allows the radiographic information to be converted into measurable quantities, reducing the dependence on purely visual interpretation. Nevertheless, the measurement procedure must be applied

consistently, especially when threshold-based segmentation or user-defined damage boundaries are used, since the selected boundary of the damage region can influence the calculated area.

Despite its usefulness, penetrant-enhanced radiographic inspection has important limitations. Since contrast enhancement depends on the infiltration of the radio-opaque liquid, the technique is most effective when the internal damage is interconnected and connected to an external surface through which the penetrant can enter [28], [37], [40]. Damage regions that are closed, isolated, or not accessible to the penetrant may remain partially or completely undetected. In addition, radiographic inspection provides a two-dimensional projection of a three-dimensional damage state, which means that the depth and through-thickness distribution of damage cannot be fully resolved from a single projection image [28], [36].

For this reason, the measured areas should not be interpreted as the complete internal damage state of the laminate, but rather as apparent damage regions that are detectable under the adopted inspection conditions. This distinction is particularly important when radiographic measurements are used for comparative purposes, as the resulting values represent an apparent damage envelope rather than the full three-dimensional damage volume.

In addition to damage assessment after impact, the tensile behaviour of composite laminates is also relevant for evaluating their static mechanical performance, as discussed in Section 2.4.3.

2.4.3. Tensile Testing

Tensile testing is one of the most widely used mechanical tests for characterising the response of materials under uniaxial loading, mainly due to the relative simplicity of the procedure and the reproducibility of the results. In this test, a specimen with defined geometry is subjected to a continuously increasing tensile force, while the applied load and the corresponding elongation or strain are recorded, and the result is commonly represented by a force–elongation or stress–strain curve, from which the mechanical response of the material can be evaluated [43]. For polymer matrix composite materials, ASTM D3039/D3039M defines a standard method for determining in-plane tensile properties of fibre-reinforced composite laminates, using flat rectangular specimens loaded monotonically in tension [44].

During the test, the specimen is fixed between the grips of a testing machine, as shown in Figure 8, so that the tensile load is applied along its longitudinal axis, and as the movable crosshead advances at a controlled rate, the specimen elongates while the applied force is continuously recorded. The deformation may be estimated from machine or transducer displacement, although more accurate strain measurements are obtained using an extensometer, strain gauges, or an equivalent strain measurement system positioned over the gauge section of the specimen. [43], [44]. In composite laminates, proper gripping and alignment are particularly important, since slippage, bending, machining damage, or grip-induced failure can affect the measured response and compromise the validity of the test [44].

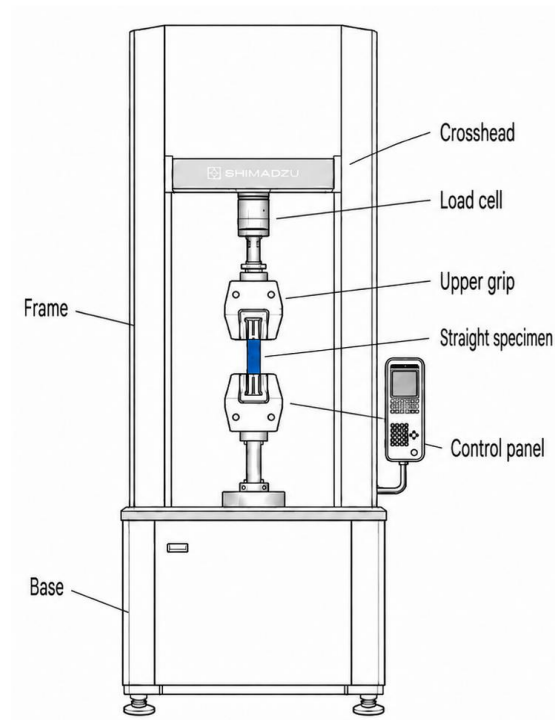


Figure 8 – Schematic representation of the tensile testing setup with the straight specimen clamped between the upper and lower grips.

The tensile stress–strain curve provides important information on the stiffness, strength, and deformation capacity of the material. In the initial region of the curve, the relationship between stress and strain may be approximately linear, corresponding to the elastic response of the material; the slope of this region is associated with the tensile modulus, which represents the stiffness of the material in the loading direction [43]. As loading progresses, the maximum load reached before failure is used to calculate the ultimate tensile strength, while the strain at failure provides information on the deformation capacity of the specimen [44].

In composite materials, additional features may appear in the stress–strain curve, including changes in slope or transition regions associated with damage mechanisms such as matrix cracking or ply delamination [44]. These features are directly related to the heterogeneous nature of fibre-reinforced composites, whose tensile behaviour is governed by the combined contribution of the fibres, matrix, and fibre–matrix interface. In glass fibre reinforced polymer laminates, the fibres are mainly responsible for carrying load and providing stiffness and strength, particularly when they are aligned with the direction of loading, while the polymer matrix binds the fibres together, transfers stresses between them, and contributes to the overall integrity of the laminate [45], [46]. Therefore, the mechanical response of GFRP composites depends on factors such as fibre type, matrix properties, fibre volume fraction, fibre orientation, stacking sequence, and the quality of the fibre–matrix interface [46], [47]. In woven glass fibre laminates, the presence of yarns in orthogonal directions leads to an anisotropic response, and differences between the 0° and 90° directions may arise due to fibre alignment, woven yarn architecture, local fibre volume fraction, fibre misalignment, and strain heterogeneity associated with the warp and weft directions [47], [48].

Although the main focus of this dissertation is the low-velocity impact response and the associated damage development of cork-modified glass fibre reinforced polymers (GFRP) laminates, tensile testing provides complementary information regarding their static mechanical behaviour. In this work, tensile tests were therefore used to evaluate selected 0/90 laminate configurations under uniaxial loading and to obtain parameters such as tensile strength, Young's modulus, and strain at failure. These results support the interpretation of the mechanical performance of the laminates and provide an additional basis for assessing whether the incorporation of cork particles affects the static load-bearing behaviour of the composite system.

2.5. Similar Work

The LVI response of GFRP laminates has been widely investigated in unmodified glass/epoxy and glass/polyester systems, providing a useful baseline for interpreting the behaviour of modified laminates. In these studies, the impact response is commonly evaluated through force–time, force–displacement, and energy–time curves, together with parameters such as peak force, maximum displacement, contact time, absorbed energy, and rebound energy [49], [50], [51], [52], [53]. The evolution of these curves is directly related to damage development, including matrix cracking, delamination, fibre/matrix debonding, fibre fracture, indentation, and, at higher impact energies, penetration or perforation [50], [51], [52], [53]. Studies on glass/polyester and glass/epoxy laminates also show that these responses are strongly affected by laminate thickness, stacking sequence, fibre architecture, impact energy, impactor geometry, and support conditions, meaning that direct comparison between different works must be made carefully [49], [50], [52], [53].

The incorporation of particles or fillers into GFRP and other fibre-reinforced polymer composites has been explored in various studies as a strategy to modify impact damage tolerance. In this context, studies involving particulate fillers are particularly relevant to the present work, since they also aim to modify the polymer matrix rather than changing the fibre reinforcement itself; for instance, the addition of nano-silica to glass/polyester composites has been reported to improve energy absorption and impact strength up to an optimum filler content, while higher contents may reduce performance due to particle agglomeration and poorer dispersion [54].

Similarly, glass/epoxy laminates modified with core–shell polymer microparticles showed delayed damage initiation and improved load-bearing capacity under impact, with the modified laminate presenting an increase of about 60% in ultimate load-bearing capability compared with the unmodified system [55]. These studies indicate that particulate modification can be beneficial when the particles promote crack deflection, matrix toughening, or delayed delamination; however, the same approach may also introduce drawbacks such as increased viscosity, agglomeration, void formation, or reduced stiffness and strength [54], [55], [56].

Among particle- or interlayer-based modification strategies, rubber-modified systems are particularly useful as a comparison with the present work because they involve the introduction

of a more deformable phase into the composite system, with the objective of increasing energy dissipation and limiting impact-induced damage. In rubberised glass-fibre epoxy sandwich composites, the incorporation of scrap tyre rubber particles into the foam core caused only a marginal reduction in peak impact force but led to an approximately 60% reduction in delamination area; however, the same modification reduced the compression strength and modulus of the syntactic foam core by more than 40% at high rubber content [57]. Other studies using rubber or core-shell rubber particles in glass fibre laminates also show improvements in toughness or impact response, albeit these modifications may also introduce processing challenges or reductions in some stiffness- or strength-related properties [56], [57], [58]. Although rubber and cork are different materials, these studies are useful because they illustrate a common issue in particle-modified composites: improvements in damage tolerance may be accompanied by compromises in static mechanical performance.

Additionally, while not introduced as particles, cork has also been investigated in composite structures as a core material, particularly in sandwich-type configurations and multilayer structures subjected to mechanical loading [59], [60], [61]. These works are not directly equivalent to the present study, since cork is generally introduced as a continuous phase rather than as particles dispersed in the matrix; nevertheless, they provide useful evidence that cork-based components can influence energy absorption, deformation behaviour, and damage development. For example, studies on agglomerated or expanded cork sandwich structures have reported differences in perforation threshold, residual indentation behaviour, and damage tolerance when cork cores are compared with conventional polymeric foams [59], [60]. Therefore, these studies are relevant as complementary evidence of the impact-related and structural potential of cork, but they cannot be used as a direct prediction of the behaviour of cork-particle-modified GFRP laminates.

Among the different modification strategies, the studies most directly related to the present dissertation are those in which cork is introduced as a dispersed phase, such as cork powder, particles, or granules, within fibre-reinforced composites. In these systems, previous investigations reported in the literature indicate that cork powder in polymer matrices can improve impact-related indicators, with some works indicating damage areas around 20% lower than control laminates, improved elastic recovery, and increased penetration threshold [62], [63], [64]. Although these studies are relevant because cork is incorporated as a dispersed or cork-based phase within a composite system, they are not directly equivalent to the present work, since they involve different fibre reinforcements, matrix systems, and laminate configurations.

In E-glass/epoxy laminates, the addition of micro-cork particles improved Mode II interlaminar fracture toughness, with maximum increases of approximately 127% for initiation toughness and around 30% for propagation-related fracture parameters when 3 wt.% of cork particles were used [13]. This result is particularly relevant for impact-damaged laminates because delamination is one of the main mechanisms governing damage growth under transverse loading, however, this study concerns interlaminar fracture toughness rather than direct low-velocity impact response, and the material system is E-glass/epoxy rather than E-glass/polyester.

Additionally, among the studies involving particle-modified glass fibre/polymer laminates, the work developed on glass fibre/polyester laminates modified with SBR particles is especially relevant because it considers a material system close to that adopted in the present dissertation [62]. In that work, balanced 0°/90° E-glass fabric laminates were produced with an unsaturated polyester matrix modified with 2.5 wt.% and 5 wt.% of dispersed SBR particles, and tensile tests were performed according to ASTM D3039. The results showed that the incorporation of SBR particles affected the tensile response of the laminates, demonstrating that the addition of a comparatively compliant dispersed phase can influence the static mechanical performance of glass fibre reinforced polyester composites [65].

A similar tendency was reported for epoxy-glass composites modified with rubber recyclate, where static tensile tests showed that all composites containing rubber recyclate presented lower strength parameters than the unmodified reference composite. In that study, the reduction in tensile strength and Young's modulus depended on both the amount and distribution of the rubber recyclate, with randomly distributed recyclate particles in the matrix producing more pronounced reductions than sandwich-type arrangements. The authors attributed this behaviour to the disturbance of fibre–matrix bonding and to the reduction of material homogeneity caused by the introduced particles [66].

Post-impact damage assessment has also been used in similar studies to complement the interpretation of impact curves. Techniques such as visual inspection, optical microscopy, X-ray computed tomography, thermography, radiography, digital image correlation, and image processing have been applied to identify and quantify impact-induced damage [50], [59], [67], [68]. These approaches are particularly important because the damage produced by LVI may extend internally even when the surface indentation is limited. Therefore, studies that combine impact testing with damage assessment provide a more reliable basis for comparing modified and unmodified laminates, especially when the objective is to relate changes in force, displacement, and absorbed energy to the apparent damage area or damage morphology.

2.6. Critical Analysis of the Literature Review

The literature review shows that laminated composite materials are widely used in structural applications due to their favourable specific mechanical properties and the possibility of tailoring their response through the selection of matrix type, reinforcement architecture, fibre orientation, and stacking sequence. However, these materials remain susceptible to complex damage mechanisms, particularly under LVI loading. Among these mechanisms, delamination is especially relevant because it may develop internally, remain difficult to detect by visual inspection, and significantly compromise the residual mechanical performance of the laminate.

The reviewed studies also show that LVI testing provides essential information on the impact response of composite laminates, including parameters such as peak force, displacement and energy evolution. Nevertheless, these parameters do not fully describe the internal damage state of the material. For this reason, the interpretation of impact response curves must be complemented by post-impact damage assessment techniques, especially when the objective

is to compare laminate configurations or evaluate the influence of material modifications on damage development.

Regarding damage mitigation strategies, the literature indicates that the incorporation of particles, fillers, or interlayer materials can modify the response of fibre-reinforced composites by promoting mechanisms such as matrix toughening, crack deflection, delayed delamination growth, and increased energy dissipation. However, the effect of particulate modification is not necessarily linear or universally beneficial. Depending on the type and amount of modifier, as well as its dispersion, compatibility with the matrix, and influence on processing, particle incorporation may also lead to agglomeration, void formation, increased viscosity, poorer impregnation, or reductions in stiffness and strength. Therefore, particle-modified laminates must be assessed considering both damage tolerance and possible compromises in mechanical performance.

Within this context, cork is a particularly relevant material because of its cellular structure, low density and energy absorption capacity. Previous studies involving cork-based composite systems suggest that cork can contribute to impact-related performance and damage tolerance. However, much of the available literature considers cork as a core material, an interlayer, or a dispersed phase in material systems that are not directly equivalent to glass fibre/polyester laminates. Similarly, studies involving other particulate or rubber-based modifications provide useful comparative insight, but they do not directly establish the behaviour of cork-particle-modified GFRP/polyester laminates under LVI loading.

Therefore, the main gap identified in the literature concerns the limited availability of studies addressing cork particles dispersed within glass fibre-reinforced polyester laminates, particularly under low-velocity impact loading and with complementary post-impact damage assessment. This gap justifies the experimental framework of the present dissertation, which focuses on assessing how cork particle incorporation affects the impact response and apparent damage development of GFRP/polyester laminates, while also considering complementary static mechanical characterisation.

3. Methods and Applications

This chapter presents the experimental methodology adopted to investigate the influence of cork particle incorporation on the mechanical behaviour and impact damage response of glass fibre reinforced polymer composite laminates. The chapter describes the constituent materials, laminate manufacturing procedures, specimen preparation methods, and experimental techniques employed throughout the study, establishing the methodological framework supporting the mechanical and damage characterisation of the developed composite systems.

Initially, the constituent materials used in laminate fabrication are presented, including the polymer matrices, glass fibre reinforcements, and cork particles incorporated into the composite structure. Subsequently, the manufacturing procedures and specimen preparation methods are described, with particular emphasis on laminate configuration, reinforcement architecture, and cork particle incorporation strategies. Finally, the experimental methodologies adopted for the mechanical characterisation of the laminates are detailed, focusing on LVI testing, radiographic damage assessment, and complementary tensile characterisation procedures used to evaluate the influence of cork incorporation on the mechanical response and damage evolution of the composite laminates.

3.1. Materials

This section presents the constituent materials used in the manufacture of the composite laminates investigated throughout this work, including the polymer matrices, glass fibre reinforcements, and cork particles incorporated into the composite system. The characteristics of the selected material systems and reinforcement architectures are described in the following sections.

3.1.1. Matrix

The composite laminates developed in this work were manufactured using two different thermosetting polymer matrices: an unsaturated polyester resin and an epoxy resin. For brevity, the unsaturated polyester resin is hereafter referred to as “polyester resin” throughout this dissertation. This resin was adopted as the primary matrix system due to its widespread use in structural composite applications, favourable processing characteristics, and

compatibility with glass fibre reinforcements. The polyester resin used in this work was an orthophthalic unsaturated polyester resin. In contrast, epoxy resin was employed in selected complementary laminates in order to evaluate the influence of matrix type on the mechanical response and impact behaviour of the composite systems.

In both cases, the polymer matrix acted as the continuous phase of the laminate, promoting fibre impregnation, ensuring stress transfer between reinforcement layers, and providing structural integrity to the composite material. Furthermore, the matrix played a central role in the incorporation and dispersion of cork particles within the laminates, directly influencing the interfacial interactions between the constituent phases and the resulting damage evolution mechanisms under impact loading conditions.

Since batch-specific manufacturer datasheets were not available for the resin systems used in this work, the values presented in Table 2 were adopted as typical reference properties [69].

Table 2 – Main physical, mechanical, and processing properties of the thermosetting polymer matrices [69].

Properties	Polyester	Epoxy
Density at 20 °C [g/cm ³]	1.10	1.30
Tensile strength [MPa]	55	62
Young's modulus [GPa]	3.6	3.2

Besides the polymer matrix, the reinforcement system plays a central role in defining the mechanical and structural behaviour of the composite laminates. Accordingly, the glass fibre reinforcements adopted throughout this work are presented in Section 3.1.2.

3.1.2. Fibre Reinforcement

The reinforcement systems used throughout this work consisted of woven fabrics and mat layers based on E-glass fibres. These materials were selected due to their high specific strength, favourable stiffness-to-weight ratio, relatively low cost, and extensive use in structural composite applications subjected to impact and mechanical loading conditions.

The developed laminates incorporated woven fabrics with different fibre orientations, while selected complementary configurations also included mat reinforcement layers integrated into hybrid stacking arrangements. This combination of reinforcement architectures enabled the evaluation of the influence of fibre orientation and stacking sequence on the structural response and damage behaviour of the composite systems.

Besides providing the primary load-carrying capability of the laminates, the reinforcement phase strongly influenced the stiffness, deformation behaviour, and impact resistance of the developed composite structures. The main characteristics of the reinforcement materials adopted throughout this work are summarised in Table 3 [69].

Table 3 – Main physical and mechanical properties of the E-glass fibre reinforcement systems adopted [69].

Properties	Woven Fabric	Mat
Density [g/cm ³]	2.54	2.54
Tensile strength [MPa]	3500	3500
Young's modulus [GPa]	72	72
Areal density [g/m ²]	300	300

In addition to the fibrous reinforcement architecture, the developed composites also incorporated cork particles as a dispersed particulate phase within the polymer matrix, whose characteristics and intended role within the composite structure are presented in Section 3.1.3.

3.1.3. Particulate Phase

Cork particles were incorporated into the polymer matrix as a dispersed particulate phase in order to evaluate their influence on the impact response and damage behaviour of the composite laminates. The cork particles used in this work presented a nominal particle size range of 0.2–0.5 mm and a bulk density of 100–140 kg/m³, according to the supplier information. Cork was selected due to its low density, cellular structure, and energy absorption capability, characteristics that make it particularly relevant for applications involving dynamic loading conditions.

Different cork particle contents were incorporated into the laminates according to the composite configuration under investigation, allowing the evaluation of their influence on the stress redistribution mechanisms, energy absorption capability, and damage propagation behaviour of the composite systems under dynamic loading conditions. Prior to laminate manufacture, the cork particles were dispersed within the polymer matrix, promoting modifications in the interlaminar regions of the laminates and influencing the interactions between the constituent phases.

The combination of the selected polymer matrices, fibrous reinforcement systems, and cork particles enabled the development of composite laminates with different reinforcement architectures and material configurations, whose manufacturing procedures and laminate configurations are described in Section 3.2.

3.2. Laminate Manufacturing and Specimen Preparation

This section describes the manufacturing procedures adopted for the production of the composite laminates and the preparation of the test specimens used throughout the experimental programme. The laminate fabrication process, cork particle incorporation procedure, curing conditions, and specimen preparation methods are described in the following

sections. In addition, the different laminate configurations considered in this work and the identification system adopted for the specimens are described.

3.2.1. Manufacturing Procedure

The composite laminates investigated in this work were manufactured using a hand lay-up moulding process combined with manual compression. Initially, two flat plywood plates were prepared and covered with cellophane® sheets in order to prevent adhesion between the composite laminate and the mould surfaces during curing.

Prior to laminate fabrication, the polymer matrices were prepared through the incorporation of the corresponding curing agents and additives according to the requirements of each resin system. For the polyester-based laminates, the resin mixture included polyester resin, catalyst, and cobalt accelerator in order to initiate and accelerate the curing reaction. The catalyst was added at 2 wt.% relative to the resin mass, while the cobalt accelerator was added at 0.2 wt.% relative to the resin mass. In the case of the epoxy-based laminates, the matrix system consisted of epoxy resin and the corresponding hardener, mixed according to the curing requirements of the resin system.

Cork particles were incorporated into the resin mixture according to the laminate configuration under investigation. The cork content was defined as a mass percentage relative to the resin mass. After the addition of the cork particles, the mixture was manually stirred in order to promote particle dispersion within the polymer matrix prior to laminate impregnation.

The incorporation of cork particles increased the viscosity of the mixture and progressively reduced the flowability of the resin system as the cork particle concentration increased, making resin distribution and fibre impregnation more difficult for laminates with higher cork contents.

Following resin preparation, the glass fibre reinforcement layers were sequentially positioned and manually impregnated using the corresponding resin mixture. This procedure was carried out progressively to promote adequate resin distribution throughout the laminate thickness and minimise the formation of voids and dry regions within the composite structure.

After stacking, the laminates were consolidated between the plywood plates through manual compression. Pressure was applied during the fabrication and curing stages in order to improve fibre impregnation, reduce excessive resin accumulation, and promote laminate consolidation. Following consolidation, the laminates were left to cure under ambient laboratory conditions prior to specimen cutting and preparation.

The main stages of the laminate manufacturing process adopted throughout this work are illustrated in Figure 9.

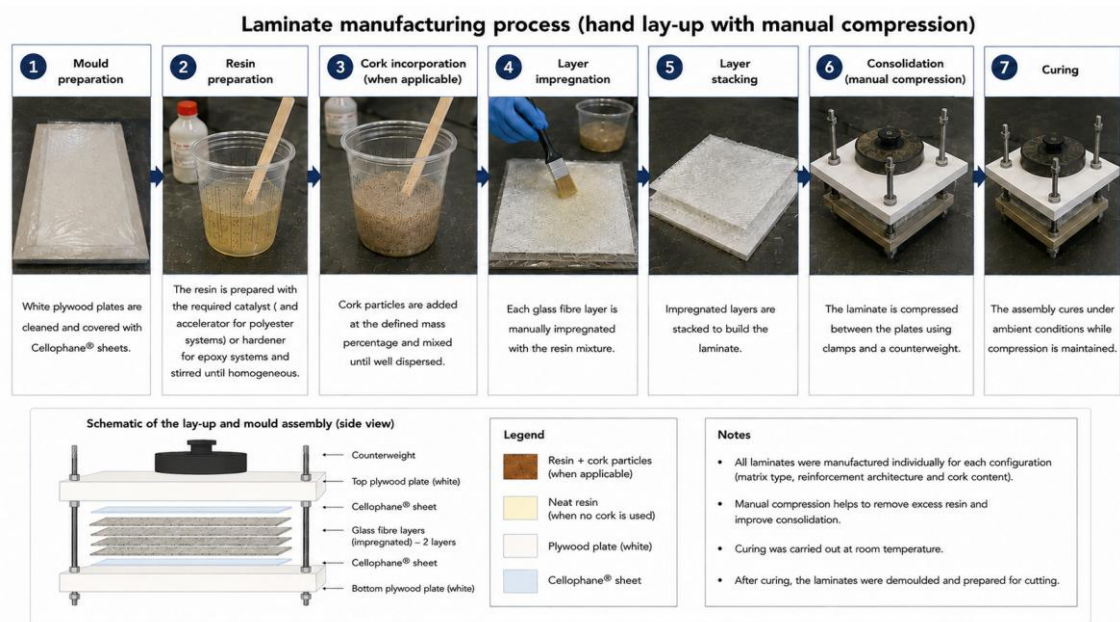


Figure 9 – Representative stages of the hand lay-up manufacturing procedure adopted for laminate fabrication.

Following the laminate manufacturing procedure, different composite configurations were developed to support the experimental investigation carried out in this work. The laminate configurations considered throughout the experimental programme are presented in Section 3.2.2.

3.2.2. Laminate Configurations

The experimental programme comprised two categories of composite laminates: a main group and a complementary group. The main laminates were designed to evaluate the influence of cork particle incorporation on the impact behaviour of glass fibre reinforced polyester composites, while the complementary laminates were manufactured to investigate the influence of additional parameters, including matrix type, fibre orientation, and reinforcement architecture.

Different laminate configurations were therefore considered in order to support the comparative analysis of the mechanical response and damage behaviour of the composites under impact loading conditions.

3.2.2.1. Laminate Identification System

Before presenting the different laminate configurations, an identification system was established to ensure the consistent identification of the test specimens throughout the

experimental campaign and, subsequently, to facilitate the organisation, interpretation, and comparison of the results obtained for the different composite systems.

The adopted nomenclature combines information regarding the reinforcement configuration, cork particle content, and matrix system incorporated into each laminate. The general structure of the adopted nomenclature is schematically illustrated below.

$$0_{90}/45/MT/TM \text{ } _X \text{ } RP/RE$$

Where:

- First term: reinforcement configuration;
- Second term: cork particle content [%];
- Final term: matrix system.

The individual elements used in the laminate designation system and their corresponding meanings are summarised in Table 4.

Table 4 – Definition of the code elements used in the laminate identification system.

Code	Description
0 ₉₀	Laminates reinforced with woven 0/90 glass fibre fabric
45	Laminates reinforced with woven ±45 glass fibre fabric
MT	Hybrid laminate with mat–woven–woven–mat (manta–tecido–tecido–manta) stacking sequence
TM	Hybrid laminate with woven–mat–mat–woven (tecido–manta–manta–tecido) stacking sequence
X	Cork particle content [%] relative to the resin mass
RP	Polyester-based laminates (“Resina Poliéster”)
RE	Epoxy-based laminates (“Resina Epoxy”)

The laminate designations adopted in this work for the different composite configurations are summarised in Table 5.

Table 5 – Identification and designation of the laminate configurations developed in this work.

Laminate ID	Description
0_90_ORP	Polyester-based 0/90 woven glass fibre laminate without cork particles
0_90_2RP	Polyester-based 0/90 woven glass fibre laminate with 2.5% cork particles
0_90_5RP	Polyester-based 0/90 woven glass fibre laminate with 5% cork particles
0_90_6RP ¹	Polyester-based 0/90 woven glass fibre laminate with 5% cork particles
0_90_7RP	Polyester-based 0/90 woven glass fibre laminate with 7.5% cork particles
0_90_0RE	Epoxy-based 0/90 woven glass fibre laminate without cork particles
0_90_5RE	Epoxy-based 0/90 woven glass fibre laminate with 5% cork particles
45_3RP ²	Polyester-based ± 45 woven glass fibre laminate with 2.5% cork particles
MT_3RP	Polyester-based mat–woven–woven–mat laminate with 3% cork particles
TM_5RP	Polyester-based woven–mat–mat–woven laminate with 5% cork particles

¹ Additional test specimen corresponding to the 5% cork particle laminate configuration; ²The laminate designation was maintained for consistency with the experimental identification system, although the actual cork particle content corresponded to 2.5%.

The laminate designation system established in this section was adopted consistently throughout the experimental campaign, providing a structured approach for the identification, organisation, and comparative analysis of the different composite configurations investigated in this work. With the adopted nomenclature defined, the laminate systems manufactured for the experimental programme are presented in the following sections, distinguishing between the main laminates and the complementary configurations developed to evaluate the influence of additional material and reinforcement parameters.

3.2.2.2. Main Laminates

The main experimental group consisted of glass fibre reinforced polyester laminates manufactured using four layers of woven 0/90 glass fibre fabric. In this group, the reinforcement architecture and matrix system were kept constant, while the cork particle concentration was varied in order to evaluate its influence on the impact behaviour and damage response of the laminates.

Four cork particle concentrations were considered: 0%, 2.5%, 5%, and 7.5% (mass percentage relative to the resin mass). This experimental group was therefore intended to isolate the influence of cork particle incorporation on the mechanical behaviour of the laminates without introducing additional variations associated with matrix type or reinforcement architecture. In addition to the impact testing campaign, selected laminate configurations belonging to the main group were also used for tensile characterisation. In this case, tensile tests were conducted only for the reference laminate without cork particles and for the laminate containing 5% cork incorporation, in order to evaluate the influence of cork particle addition on the tensile response of the composites.

The laminate configurations belonging to the main experimental group are summarised in Table 6.

Table 6 – Main laminate configurations and corresponding cork particle contents.

Laminate ID	Cork Content [%]
0_90_ORP	0
0_90_2RP	2.5
0_90_5RP	5
0_90_6RP	5
0_90_7RP	7.5

The corresponding reinforcement architecture and manufactured laminate are presented in Figure 10(a)–Figure 10(e), respectively. As the cork content increased, the visual appearance of the laminate surface became progressively dominated by the presence of cork particles dispersed within the polymer matrix. For clarity, Figure 10 presents laminate 0_90_6RP as the representative manufactured laminate for the 5 wt.% cork configuration, while the complete visual record of the main laminate group, including both 5 wt.% cork laminates (0_90_5RP and 0_90_6RP), is provided in Appendix A.

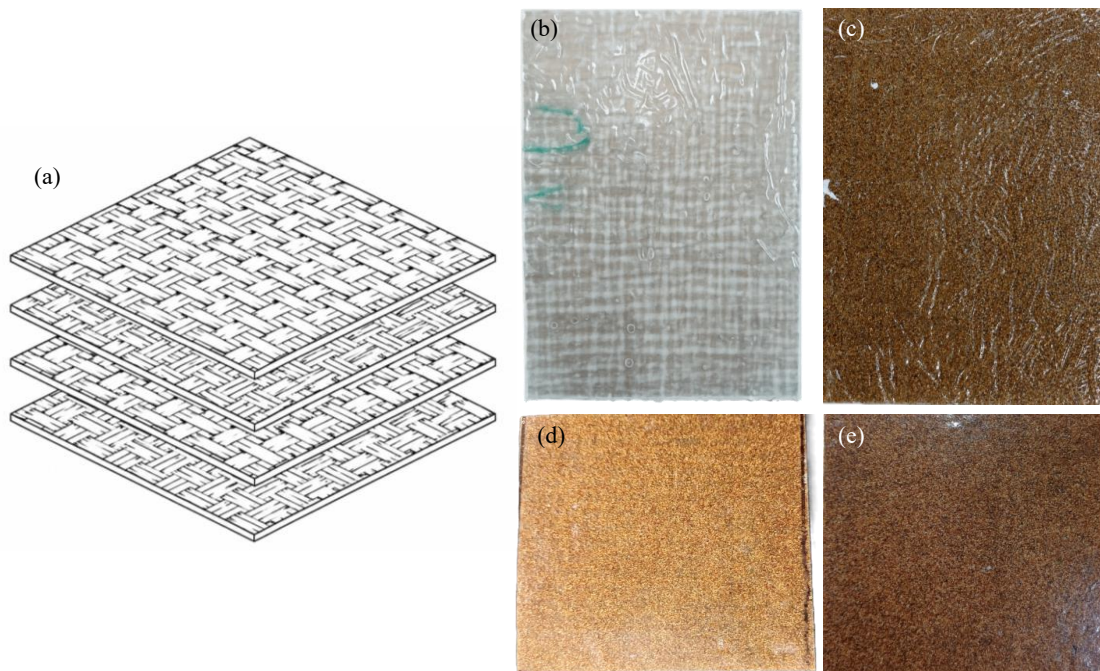


Figure 10 – (a) Schematic representation of the four-layer 0/90 woven glass fibre reinforcement architecture; photographs of the manufactured laminates: (b) 0_90_ORP; (c) 0_90_2RP; (d) 0_90_6RP; (e) 0_90_7RP.

In addition to the main laminates, a complementary experimental group was manufactured in order to investigate the influence of matrix type, fibre orientation, and reinforcement stacking sequence on the mechanical behaviour of the composites, as presented in Section 3.2.2.3.

3.2.2.3. Complementary Laminates

To evaluate the influence of the polymer matrix, laminates manufactured with polyester resin were compared with equivalent epoxy-based laminates containing identical reinforcement architectures and cork particle contents. In this case, epoxy-based laminates were produced for cork particle contents of 0% and 5% (mass percentage relative to the resin mass). The reinforcement architecture adopted for these laminates is illustrated in Figure 11(a), while photographs of the manufactured epoxy laminates without cork particles and with 5% cork incorporation are presented in Figure 11(b) and Figure 11(c), respectively.

Furthermore, additional laminate configurations were also considered in order to investigate the influence of fibre orientation and hybrid reinforcement arrangements on the impact response and damage behaviour of the composites. The complementary group therefore included laminates reinforced with woven $\pm 45^\circ$ glass fibre fabrics manufactured with a cork particle content of 2.5%, with the corresponding reinforcement architecture and manufactured laminate illustrated in Figure 11(d) and Figure 11(e), as well as hybrid laminates combining woven fabric and mat layers arranged according to different stacking sequences.

A mat–woven–woven–mat configuration containing 3% cork particles was manufactured, with its stacking sequence and laminate surface presented in Figure 11(f) and Figure 11(g). Additionally, a woven–mat–mat–woven configuration incorporating 5% cork particles was produced, as illustrated in Figure 11(h) and Figure 11(i), respectively.

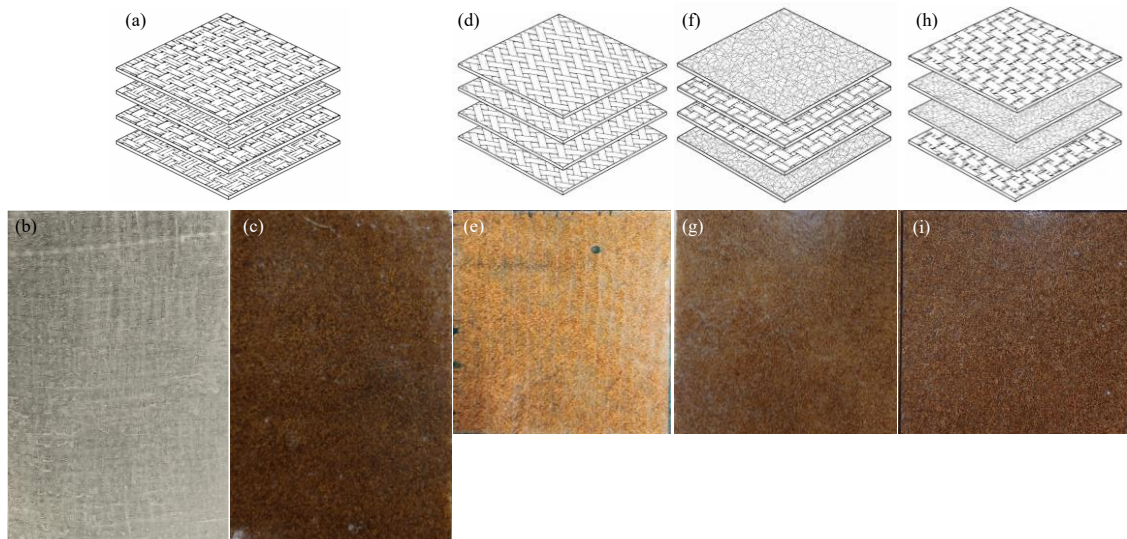


Figure 11 –Schematic representation of the reinforcement architectures and corresponding manufactured complementary laminate configurations: 0_90_0RE and 0_90_5RE (a–c), 45_3RP (d–e), MT_3RP (f–g), and TM_5RP (h–i).

The laminate configurations belonging to the complementary experimental group are summarised in

Table 7.

Table 7 – Complementary laminate configurations and corresponding variables under analysis.

Laminate ID	Variable under analysis
0_90_0RE	Matrix Type
0_90_5RE	Matrix Type
45_3RP	Fibre orientation
MT_3RP	Stacking sequence
TM_5RP	Stacking sequence

Following the manufacture of the laminate plates and definition of the different laminate configurations, the corresponding test specimens were prepared according to the requirements of the experimental procedures adopted in this work. The specimen preparation process included laminate cutting, dimensional adjustment, and specimen identification prior to testing. The procedures adopted for specimen preparation are described in the following section (Section 3.2.3).

3.2.3. Specimen Preparation

Following the laminate manufacturing process, the composite plates were cut into individual test specimens according to the dimensional requirements of the experimental procedures adopted in this work. The cutting process was performed using a water-jet-assisted cutting system in order to minimise excessive material damage and edge defects during specimen preparation. A representative example of the specimen cutting process is presented in Figure 12.



Figure 12 – Cutting process adopted for the preparation of the composite test specimens.

After cutting, the specimens were visually inspected and identified according to the laminate designation system previously defined. Specimens with nominal dimensions of 150 mm × 100 mm and 100 mm × 100 mm were prepared depending on the laminate configuration, material availability, and the need to maximise the number of specimens obtained from the manufactured laminate plates.

The nominal dimensions adopted for each laminate configuration are summarised in Table 8.

Table 8 – Nominal dimensions adopted for the different laminate configurations.

Laminate ID	Dimensions [mm ²]
0_90_0RP	150 × 100
0_90_2RP	150 × 100
0_90_5RP	100 × 100
0_90_6RP	100 × 100
0_90_7RP	100 × 100
0_90_0RE	150 × 100
0_90_5RE	150 × 100
45_3RP	100 × 100
MT_3RP	100 × 100
TM_5RP	100 × 100

Following specimen preparation and dimensional verification, the composite laminates were subjected to the experimental testing procedures adopted in this work. The testing methodologies, experimental configurations, and equipment used for the mechanical characterisation of the laminates are presented in Section 3.3.

3.3. Experimental Methods

This section presents the experimental procedures adopted for the mechanical characterisation and damage evaluation of the manufactured composite laminates. The experimental programme included LVI testing, radiographic inspection, and tensile testing, allowing the assessment of the mechanical response and damage mechanisms with the different laminate configurations investigated throughout this work.

The methodologies, experimental conditions, and testing procedures adopted throughout the study are described in the following sections.

3.3.1. Low-Velocity Impact Testing

Impact tests were conducted to evaluate the impact response of the composite laminates and their ability to absorb energy under impact loading conditions. These tests are particularly relevant for fibre-reinforced composites, since impact events may induce damage mechanisms such as matrix cracking, fibre fracture, and interlaminar delamination. The experimental procedure followed the ASTM D7136/D7136M–20 standard for measuring the damage resistance of composite materials subjected to low-velocity impact loading.

The low-velocity impact tests were performed using a Rosand instrumented falling-weight impact machine, shown in Figure 13(a). The experimental setup consisted of a guided falling-weight tower equipped with an instrumented impactor and a rigid support fixture, designed to maintain the specimens under controlled boundary conditions during testing, as illustrated in Figure 13 (b).

The composite specimens were positioned over a rectangular support fixture and mechanically clamped using a dedicated fixation system in order to minimise undesired specimen movement during impact, details of the adopted fixture configuration and specimen positioning are presented in Figure 13(c). Since part of the experimental campaign was conducted using specimens with reduced dimensions, an additional support adaptor was developed and integrated into the fixture system. This adaptor was used to ensure adequate specimen positioning and fixation, improve compatibility with the testing setup, and keep the boundary conditions as comparable as possible to those adopted for the standard-sized specimens, as shown in Figure 13(d).

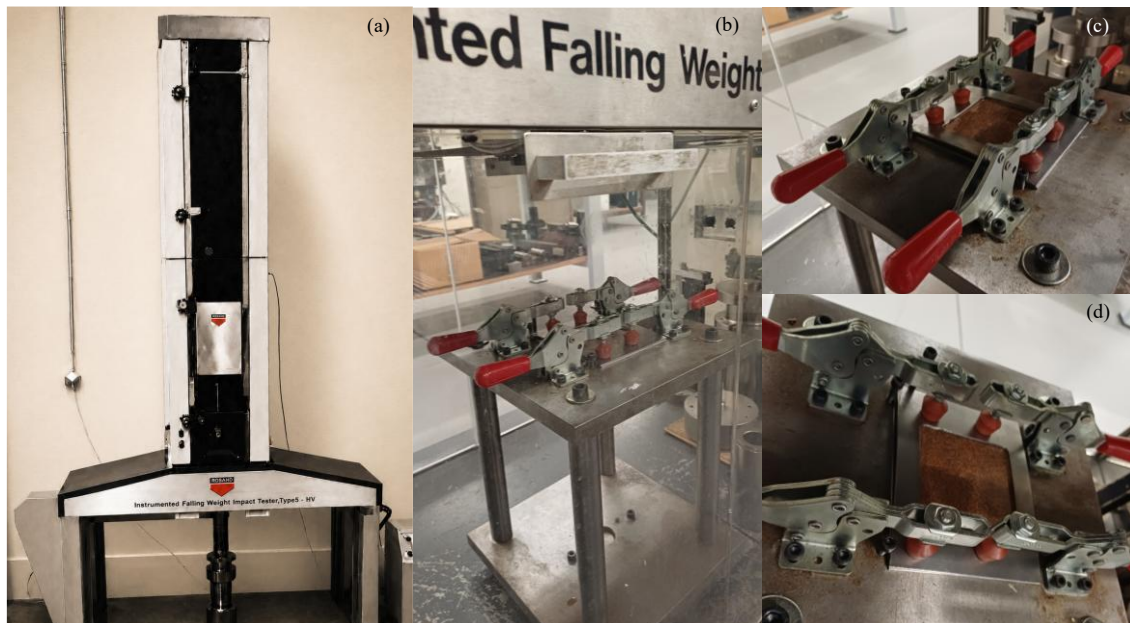


Figure 13 – Experimental setup adopted for the low-velocity impact tests: (a) Rosand instrumented falling-weight impact machine; (b) impact region of the testing system; (c) support fixture and specimen positioning; (d) clamping system and support adaptor for reduced-size specimens.

The impact tests were conducted under controlled experimental conditions using a nominal impact energy of 10 J and an impactor mass of 4.23 kg, corresponding to an impactor velocity of approximately 2.17 m/s immediately prior to impact. A single impact test was performed for each laminate configuration investigated in this work; however, for the 5 wt.% cork polyester laminate configuration, an additional specimen was tested in order to support the comparative assessment of the experimental response. All tests were performed at room temperature (18 °C), and the main experimental conditions adopted throughout the impact testing campaign are summarised in Table 9.

Table 9 – Impact testing conditions adopted for the experimental programme.

Parameter	Value
Testing standard	ASTM D7136/D7136M–20
Impact energy	10 J
Impactor velocity	~2.17 m/s
Impactor mass	~4.23 kg
Specimen dimensions	150 × 100 mm / 100 × 100 mm
Boundary conditions	Fully clamped
Testing temperature	18 °C

The impact machine was equipped with an integrated data acquisition system responsible for continuously recording the force, displacement, velocity, and energy signals throughout the impact event. The experimental data obtained during testing were subsequently processed using the software associated with the testing equipment.

After impact testing, the specimens were visually inspected in order to identify the presence of surface damage, indentation, cracking, and other visible impact-induced features. Additional internal damage evaluation was subsequently performed through radiographic inspection, as described in Section 3.3.2.

3.3.2. Radiographic Analysis

Radiographic inspection was performed after the low-velocity impact tests in order to evaluate the presence and distribution of internal damage mechanisms induced within the composite laminates. This non-destructive inspection technique allows the identification of damage features such as delamination, matrix cracking, and internal fracture zones that may not be visible through external visual inspection.

In order to enhance the visibility of internal defects during the imaging procedure, a diiodomethane-based liquid contrast agent, presented in Figure 14(a), was applied to the impacted specimens prior to X-ray exposure. Due to its high density and penetration capability, the contrast agent infiltrates cracks, delaminated regions, and other internal damage zones, thereby improving the distinction between damaged and undamaged areas in the resulting radiographic images.

Following the application of the contrast agent, the specimens were positioned directly over industrial radiographic films for X-ray exposure. MX125 D4 radiographic films, shown in Figure 14(b), were employed throughout the inspection campaign due to their high image quality and suitability for detecting fine internal defects in composite laminates. The films were maintained

in direct contact with the specimens in order to maximise image sharpness and improve defect detection sensitivity.



Figure 14 – Materials used during the radiographic inspection procedure: (a) diiodomethane contrast agent; (b) MX125 D4 industrial radiographic films.

The radiographic inspections were conducted using an industrial X-ray system equipped with a portable X-ray source positioned above the inspection table, with the experimental radiographic setup adopted throughout the inspection campaign, including the X-ray source, specimen positioning, and film arrangement, presented in Figure 15.



Figure 15 – Experimental radiographic inspection setup adopted throughout the inspection campaign: (a) general view of the X-ray inspection system; (b) portable X-ray source used during radiographic exposure; (c) positioning of the impacted specimen over the radiographic film prior to X-ray exposure.

Prior to the start of the radiographic inspection campaign, several preliminary exposure tests were carried out in order to calibrate the X-ray system and establish suitable imaging conditions for the composite laminates investigated in this work. Different combinations of voltage,

current intensity, and exposure time were evaluated to determine the exposure conditions capable of providing adequate image contrast and defect visibility for the laminate thicknesses analysed. Based on the preliminary trials, the exposure conditions corresponding to Test 4 were selected for the inspection procedure, with the corresponding preliminary exposure parameters evaluated during the calibration stage summarised in Table 10.

Table 10 – Preliminary radiographic exposure parameters evaluated during optimisation of the inspection procedure.

Test	Voltage [kV]	Current [mA]	Exposure time [s]	Observations
1	65	1.0	7	Insufficient image contrast
2	75	1.0	12	Insufficient image contrast
3	95	1.5	20	Improved image definition
4	110	2.0	25	Optimal image definition (selected)

Following parameter optimisation, the impacted specimens were positioned between the X-ray source and the radiographic film under the selected controlled exposure conditions, as illustrated in Figure 15(c) and Figure 16. In order to ensure proper specimen identification and facilitate the subsequent analysis of the radiographic images, lead characters corresponding to the laminate identification codes were positioned together with the specimens during exposure.



Figure 16 – Setup adopted for the radiographic inspection and specimen positioning prior to X-ray exposure.

Post-exposure, the radiographic films were processed in a darkroom environment. The chemical procedure involved successive immersion of the films in developing and fixing solutions, followed by washing and drying stages, with the chemical baths maintained at a controlled temperature of 28 °C throughout the operation, in order to obtain the final radiographs suitable for defect evaluation. The film processing workflow and the radiographs obtained during the inspection procedure are illustrated in Figure 17.



Figure 17 – Darkroom radiographic film processing equipment and processing workflow.

The radiographic images obtained throughout the inspection campaign were subsequently analysed using Fiji software, an ImageJ-based image processing platform, in order to quantify the apparent damage regions generated by low-velocity impact. For each specimen, the image was first duplicated to preserve the original file, after which the scale was calibrated and the maximum length and width of the radiographically indicated damage region were then measured.

In addition to these linear measurements, the central damage region associated with the impact event was manually delineated, allowing the apparent damaged area to be determined. This procedure was repeated three times for each specimen, and the corresponding mean values and standard deviations were calculated for the damage length, width, and area.

It should be noted that the measured damage areas correspond to the regions detected by penetrant-enhanced radiography and should therefore be interpreted as apparent damage envelopes rather than as a complete representation of the through-thickness damage state. The effectiveness of this method depends on the ability of the contrast agent to infiltrate the damaged regions and on the connection of these regions to the external surface. Furthermore, since radiography provides a two-dimensional projection of the damage, it does not allow the depth or complete through-thickness distribution of damage mechanisms to be directly determined. For this reason, the quantified damage areas were used primarily for comparative purposes between laminate configurations.

Following the radiographic inspection and image analysis procedures, tensile tests were also performed on selected laminate configurations in order to complement the impact and damage assessment with a static mechanical characterisation. The tensile testing methodology is described in Section 3.3.3.

3.3.3. Tensile Testing

In order to evaluate the tensile behaviour of the manufactured composite laminates, uniaxial tensile tests were performed under controlled laboratory conditions using a SHIMADZU Autograph AG-X universal testing machine equipped with a 10 kN load cell, following the procedures established in ASTM D3039. The tests were conducted at a crosshead displacement rate of 2 mm/min. The objective was to determine the principal mechanical properties of the laminates, namely tensile strength, Young's modulus, and strain at failure, allowing the evaluation of the influence of cork particle incorporation on the tensile response of the composite systems.

Prior to testing, all specimens were weighed using a precision balance with an accuracy of ± 0.01 g. The initial gauge length (L_0) was defined as 150 mm for all specimens, which were carefully positioned and aligned within the machine grips to ensure uniform load application throughout the test. Particular attention was given to the gripping pressure in order to prevent premature failure near the clamping regions, which could compromise the validity of the experimental results.

During the tensile tests, the force and displacement data were continuously recorded throughout the loading process until specimen failure. Following each experiment, the testing machine generated data files containing the force and displacement coordinates associated with the loading history of each specimen, which were subsequently processed to obtain the corresponding stress–strain curves and determine the mechanical properties of the laminates. In order to improve the accuracy of the stiffness evaluation, linear regression analysis was applied to the initial linear elastic region of the stress–strain curves, allowing the determination of the Young's modulus for each specimen.

The experimental procedures and characterisation methodologies presented throughout this chapter provided the framework required for the evaluation of the mechanical response and damage behaviour of the developed composite laminates. The results obtained from the experimental campaign, together with their corresponding analysis and discussion, are presented in Section 4.

4. Results and Discussion

This chapter presents and discusses the experimental results obtained for the composite laminates developed throughout this work, with emphasis on the influence of cork particle incorporation on their impact response, damage development, and mechanical performance. The experimental observations obtained from LVI testing, radiographic inspection, and tensile characterisation are analysed in order to identify the effects of cork content, matrix system, and reinforcement architecture on the structural behaviour of the laminates.

The results are organised according to the experimental methodology adopted, allowing a comparative evaluation of the different laminate configurations and supporting the interpretation of the associated damage mechanisms under mechanical loading conditions.

4.1. Presentation of Results

This section presents the experimental results obtained for the composite laminates developed throughout this work, organised according to the corresponding mechanical characterisation procedures. The results are presented in order to enable a comparative evaluation of the influence of cork particle incorporation, matrix system, and reinforcement configuration on the response of the different laminate configurations.

Particular emphasis is given to the LVI behaviour of the laminates and to the associated damage development observed throughout the experimental campaign. Radiographic inspection results are also presented to support the evaluation of internal damage features and damage distribution within the impacted laminates.

4.1.1. Low-Velocity Impact Results

The results obtained from the LVI tests conducted throughout the experimental campaign are presented in this section, including the principal impact parameters measured for both the main and complementary laminate configurations. The results obtained for the main laminate group are first presented in Section 4.1.1.1.

4.1.1.1. Main Laminates

Table 11 summarises the principal impact parameters obtained for the main laminate group subjected to low-velocity impact testing, including the maximum force, displacement, absorbed energy, and impact velocity recorded during the experiments.

Table 11 – Summary of the principal impact parameters measured for the main laminate configurations subjected to LVI testing.

Laminate ID	Values at Peak			Values at Failure		Impact Velocity [m/s]
	Force [N]	Displacement [m]	Energy [J]	Displacement [m]	Energy [J]	
0_90_ORP	1604.42	0.010931	7.42508	0.009618	8.96672	2.16991
0_90_2RP	2234.62	0.009839	9.38761	0.007371	9.04399	2.17334
0_90_5RP	2337.49	0.009698	9.46358	0.007297	9.09955	2.16991
0_90_6RP	2384.36	0.010193	9.60945	0.007625	9.27304	2.18022
0_90_7RP	2209.28	0.009755	9.42191	0.007532	9.18304	2.16991

Overall, the laminates containing cork particles exhibited higher maximum impact force values when compared with the cork-free configuration. Among the tested laminates, the 0_90_6RP configuration presented the highest peak force under the adopted impact conditions.

Before presenting the impact response curves, it should be noted that, for clarity purposes, only a single representative curve is presented for the 5 wt.% cork laminate configuration in the force–time, energy–time, and force–displacement plots shown throughout this section. The selected curve corresponds to laminate 0_90_6RP, while the complete set of impact response curves, including the first test performed for the 5 wt.% laminate (0_90_5RP), is provided in Appendix B.

The force–time histories presented in Figure 18 revealed a clear difference between the response of the cork-free laminate and those containing cork particles, particularly in terms of the maximum force reached during the impact event.

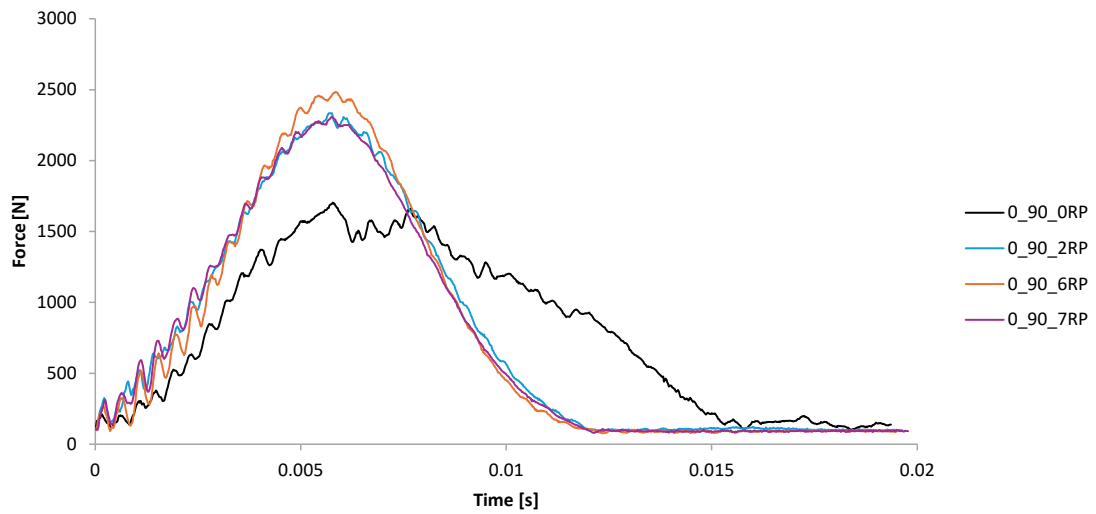


Figure 18 – Force–time histories obtained for the main laminate configurations subjected to low-velocity impact loading conditions.

The energy–time responses presented in Figure 19 indicate differences in the energy absorption behaviour of the laminate configurations, especially between the cork-free laminate and the cork-reinforced configurations.

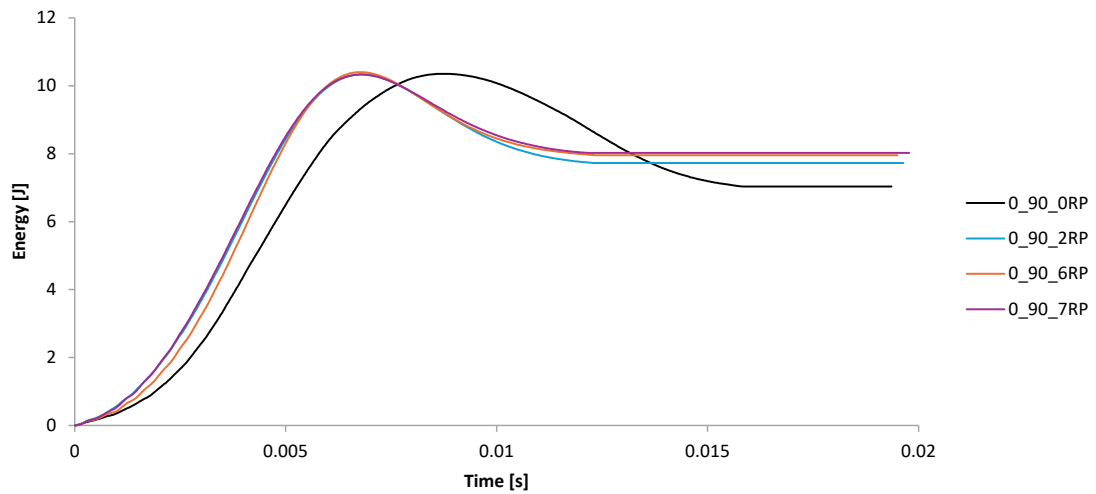


Figure 19 – Energy–time histories obtained for the main laminate configurations subjected to low-velocity impact loading conditions.

The force–displacement responses obtained during the impact events are presented in Figure 20. The complete responses are shown in Figure 20(a), while Figure 20(b) highlights the behaviour up to the maximum impact force.

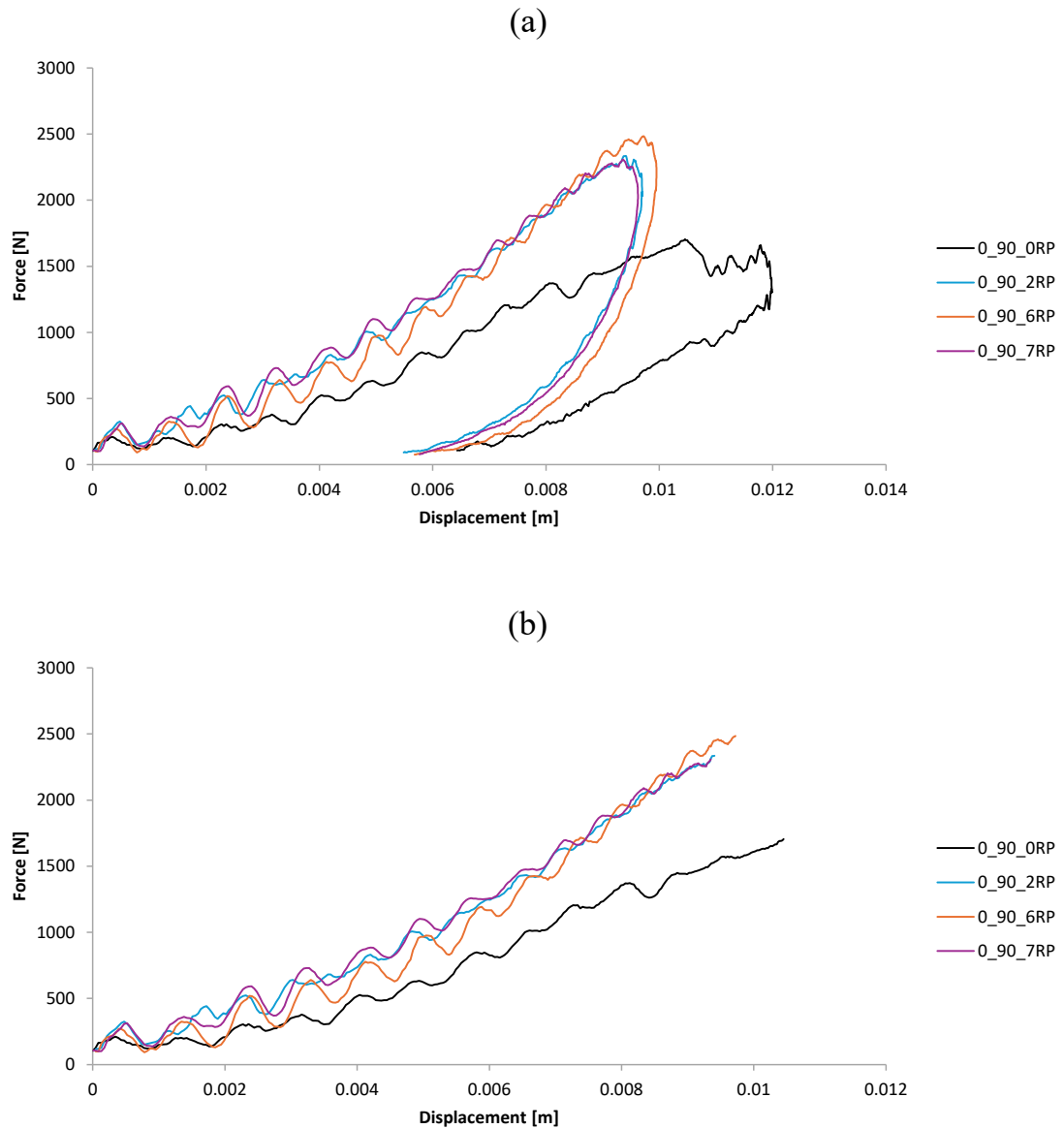


Figure 20 – Force–displacement response obtained for the main laminate configurations under low-velocity impact conditions: (a) complete force–displacement response; (b) force–displacement response up to the maximum impact force.

Representative examples of the surface damage observed after low-velocity impact testing for the main laminate configurations are shown in Figure 21. Laminate 0_90_6RP is presented as the representative specimen for the 5 wt.% cork configuration, while the complete set of post-impact surface images, including both 0_90_5RP and 0_90_6RP, is provided in Appendix A.

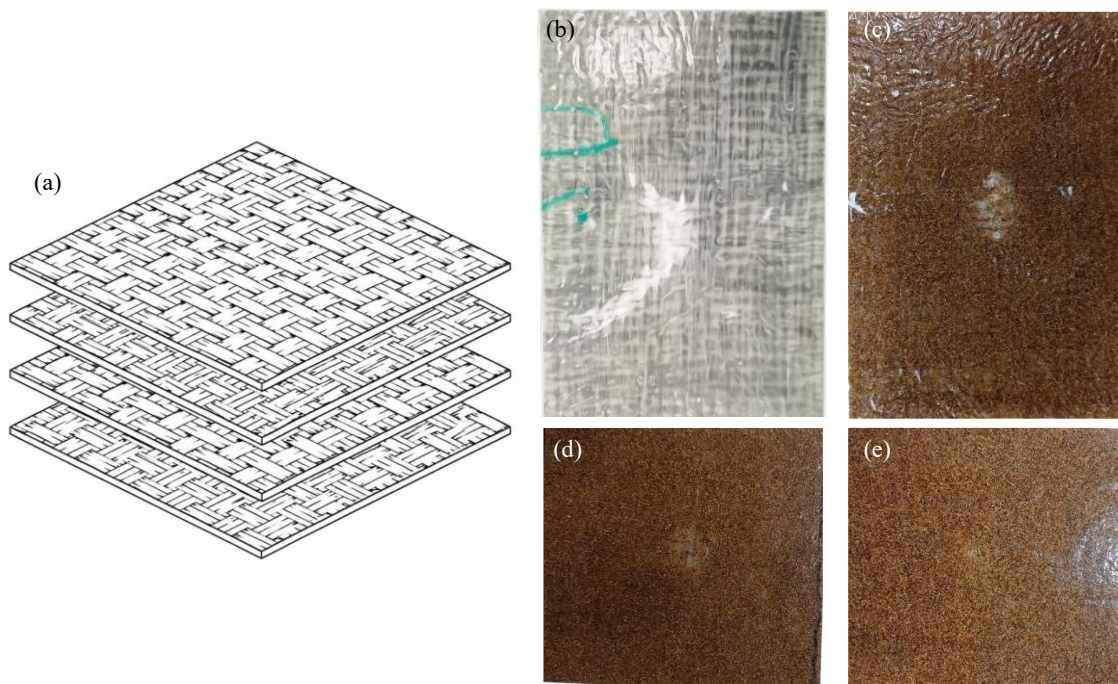


Figure 21 – (a) Schematic representation of the four-layer 0/90 woven glass fibre reinforcement architecture; surface damage observed after low-velocity impact testing: (b) 0_90_ORP; (c) 0_90_2RP; (d) 0_90_6RP; (e) 0_90_7RP.

Overall, the impact response curves and the corresponding surface damage observations revealed clear differences between the cork-free laminate and the cork-reinforced configurations under the adopted impact conditions. A similar analysis was subsequently conducted for the complementary laminate configurations, whose results are presented in Section 4.1.1.2.

4.1.1.2. Complementary Laminates

Table 12 summarises the principal impact parameters obtained for the complementary laminate configurations subjected to low-velocity impact testing, including the maximum force, displacement, absorbed energy, and impact velocity recorded during the experiments.

Table 12 – Summary of the principal impact parameters measured for the complementary laminate configurations subjected to LVI testing.

Laminate ID	Values at Peak			Values at Failure		Impact Velocity [m/s]
	Force [N]	Displacement [m]	Energy [J]	Displacement [m]	Energy [J]	
45_3RP	2482.71	0.00985734	9.75706	0.00733813	9.13274	2.17334
0_90_0RE	2094.7	0.0142429	8.97918	0.011929	9.52988	2.17334
0_90_5RE	1991.83	0.00940743	8.58731	0.00843804	9.82113	2.17334
MT_3RP	2386.36	0.00967572	9.02365	0.00754179	9.32286	2.16991
TM_5RP	2377.25	0.0085769	8.69866	0.00712265	9.34538	2.16991

The impact response of the complementary laminates is organised into three comparative groups in order to distinguish the effects of matrix system, fibre orientation, and stacking arrangement. This organisation enables each variable introduced in the complementary configurations to be examined separately, while maintaining a clear connection with the main laminate configurations previously presented.

Before presenting the impact response curves, it should be noted that, as in the previous section, only a single representative curve is shown for the 5 wt.% cork polyester laminate configuration in the main text. The complete set of impact response curves for the matrix system comparison, including laminate 0_90_5RP, is provided in Appendix C, while the corresponding curves for the 5 wt.% cork stacking arrangement comparison are presented in Appendix D.

The first comparison addresses the effect of the matrix system by considering the 0/90 laminates manufactured with polyester and epoxy matrices. The corresponding force–time histories are presented in Figure 22. For laminate 0_90_0RE, a local data acquisition anomaly was identified in the recorded response; therefore, the affected data points were removed prior to plotting, and only the valid experimental data are presented.

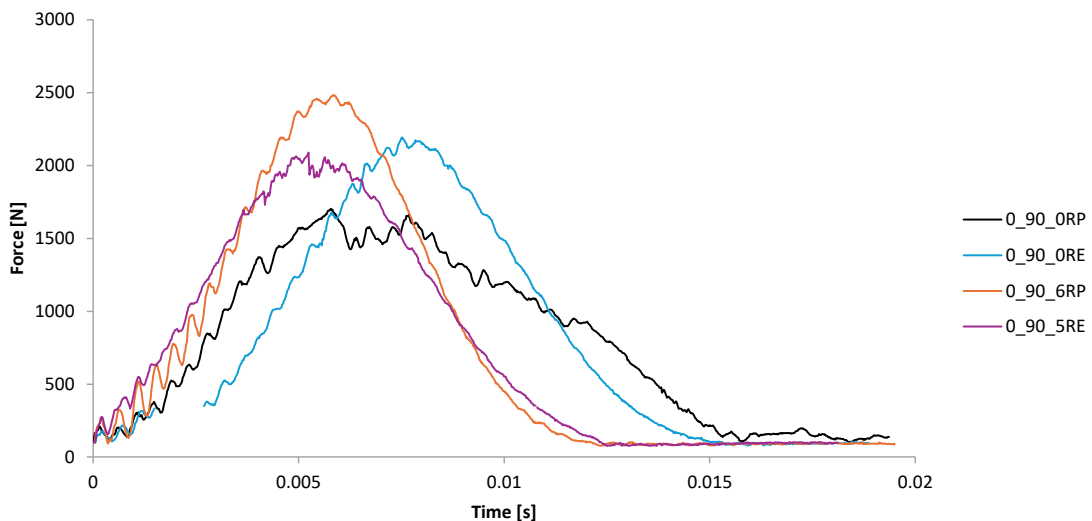


Figure 22 – Force–time histories obtained for the 0/90 laminate configurations manufactured with different matrix systems subjected to low-velocity impact loading conditions.

The force–time histories presented in Figure 22 show noticeable differences between the polyester- and epoxy-based 0/90 laminates, particularly in terms of maximum force, contact duration, and the time at which the peak force was reached.

The energy–time responses presented in Figure 23 show noticeable differences in the energy absorption behaviour of the compared 0/90 laminates. The cork-modified configurations exhibited a faster increase in energy and reached their maximum values earlier in the impact event, while the cork-free laminates presented a more gradual evolution.

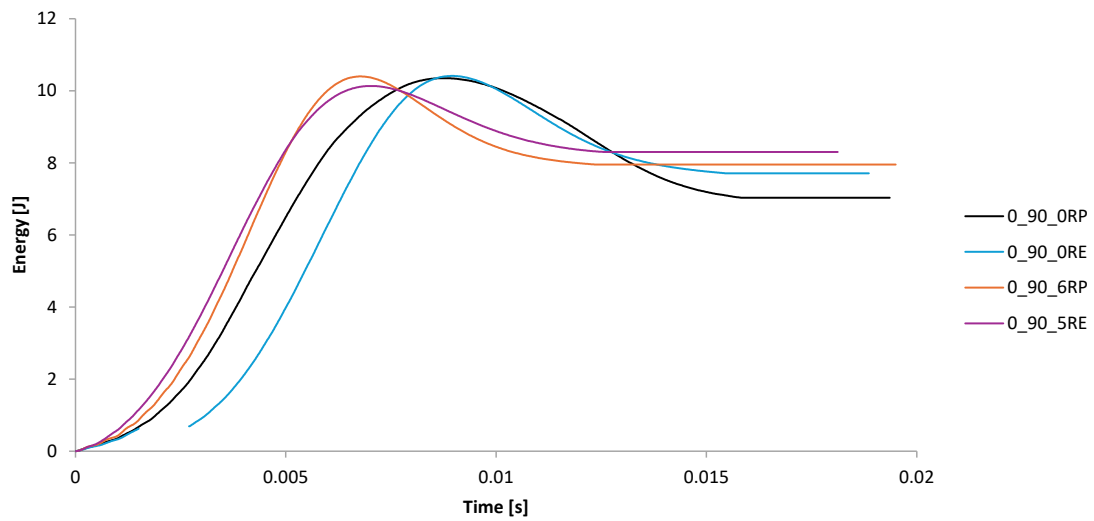


Figure 23 – Energy–time histories obtained for the 0/90 laminate configurations manufactured with different matrix systems subjected to low-velocity impact loading conditions.

Figure 24 presents the force–displacement behaviour of the 0/90 laminate configurations manufactured with different matrix systems, including the complete response in Figure 24(a) and the response up to the maximum impact force in Figure 24(b). The curves reveal differences in deformation behaviour between the compared laminates, with the epoxy-based cork-free configuration exhibiting the highest displacement before reaching peak force, while the cork-modified configurations reached higher force values at lower displacement levels under the adopted impact conditions.

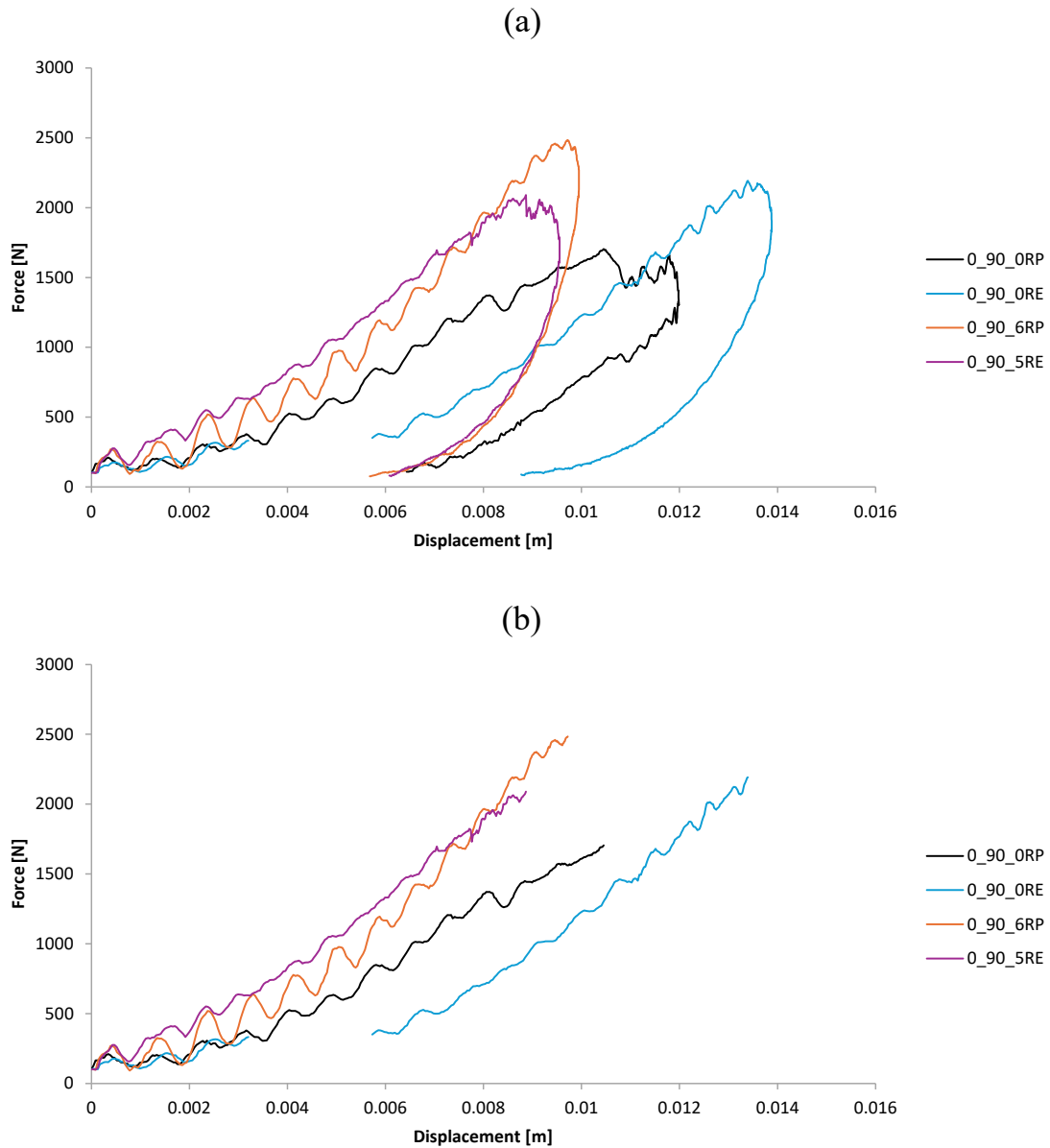


Figure 24 – Force–displacement response obtained for the complementary laminate configurations under low-velocity impact conditions: (a) complete force–displacement response; (b) force–displacement response up to the maximum impact force.

After assessing the influence of the matrix system, the effect of reinforcement architecture was evaluated by comparing laminate configurations with different fibre orientations and stacking arrangements. The first comparison considers the complementary laminates with lower cork particle contents, including the 0/90 woven configuration, the ± 45 woven configuration, and the mat-containing hybrid configuration.

The force–time histories presented in Figure 25 show similar overall impact response trends among the compared configurations, with differences mainly observed in the maximum force values reached during the impact event.

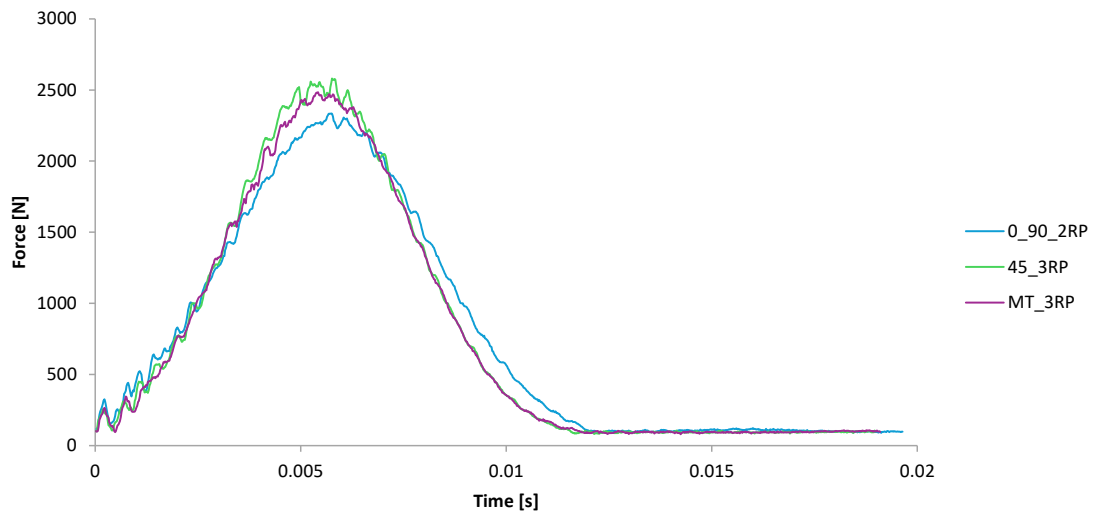


Figure 25 – Force–time histories obtained for the complementary reinforcement configurations with lower cork particle contents.

The energy–time responses presented in Figure 26 indicate comparable energy absorption behaviour for the complementary configurations with lower cork particle contents, with only slight differences in the final absorbed energy values.

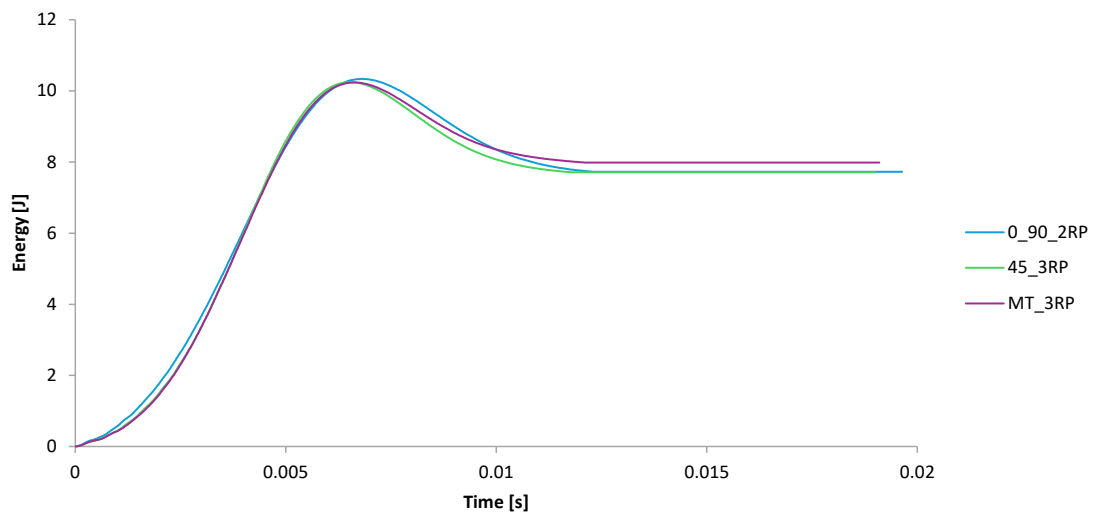


Figure 26 – Energy–time histories obtained for the complementary reinforcement configurations with lower cork particle contents.

The force–displacement responses presented in Figure 27 allow the comparison of the deformation behaviour associated with the different reinforcement architectures, with the complete responses shown in Figure 27(a) and the behaviour up to the maximum impact force highlighted in Figure 27(b).

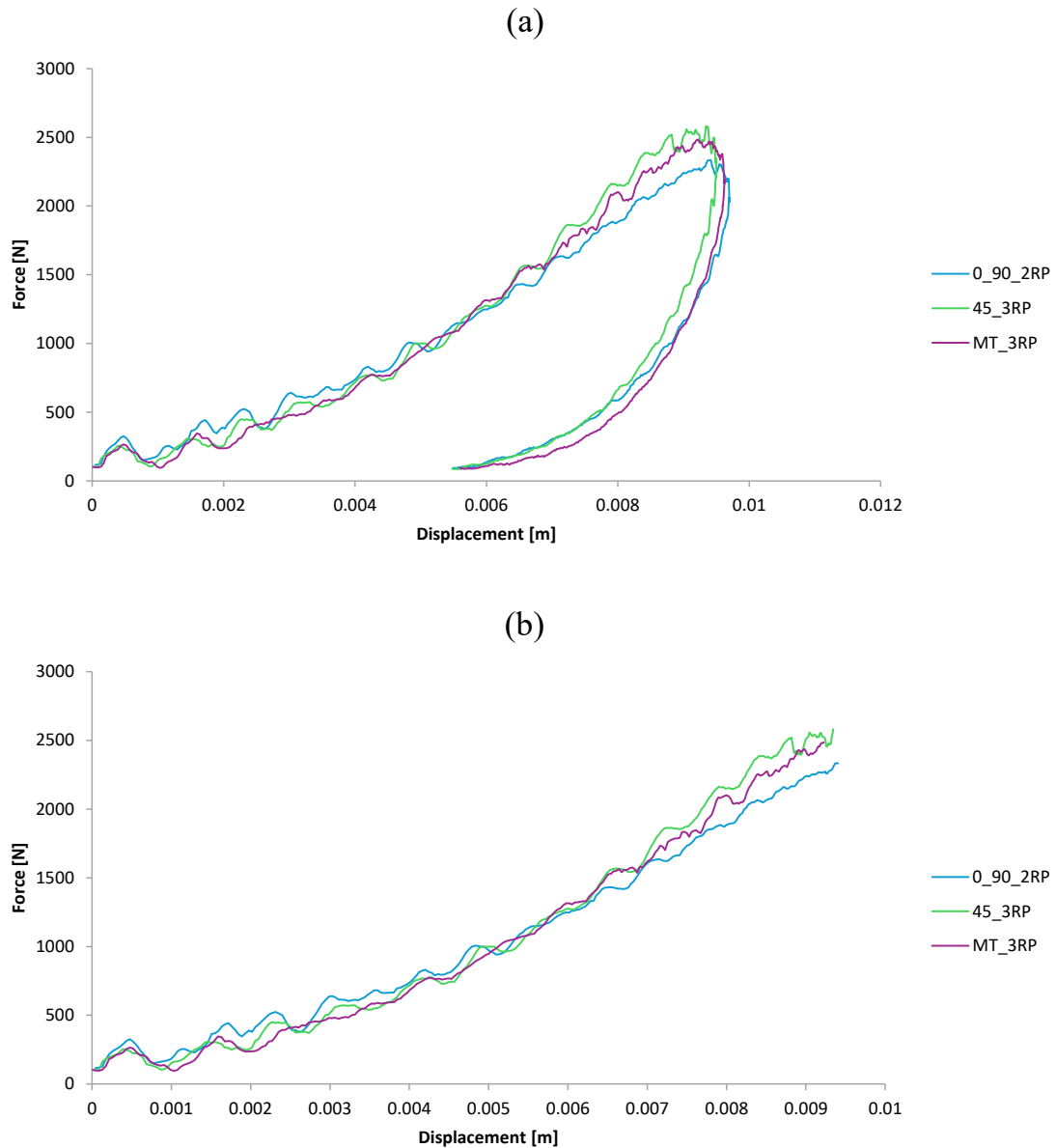


Figure 27 – Force–displacement response obtained for the complementary reinforcement configurations with lower cork particle contents: (a) complete force–displacement response; (b) force–displacement response up to the maximum impact force.

Following the comparison of the complementary configurations with lower cork particle contents, the reinforcement architecture effect was further assessed for the laminates containing 5 wt.% cork particles. This comparison considers the 0/90 woven configuration and the woven–mat–mat–woven hybrid configuration, allowing the influence of stacking arrangement to be presented for the same cork particle content.

The force–time histories presented in Figure 28 show differences in the impact response of the 5 wt.% cork configurations. Although both laminates reached similar maximum force values, the woven–mat–mat–woven hybrid configuration exhibited a shorter contact duration and reached the maximum force slightly earlier during the impact event.

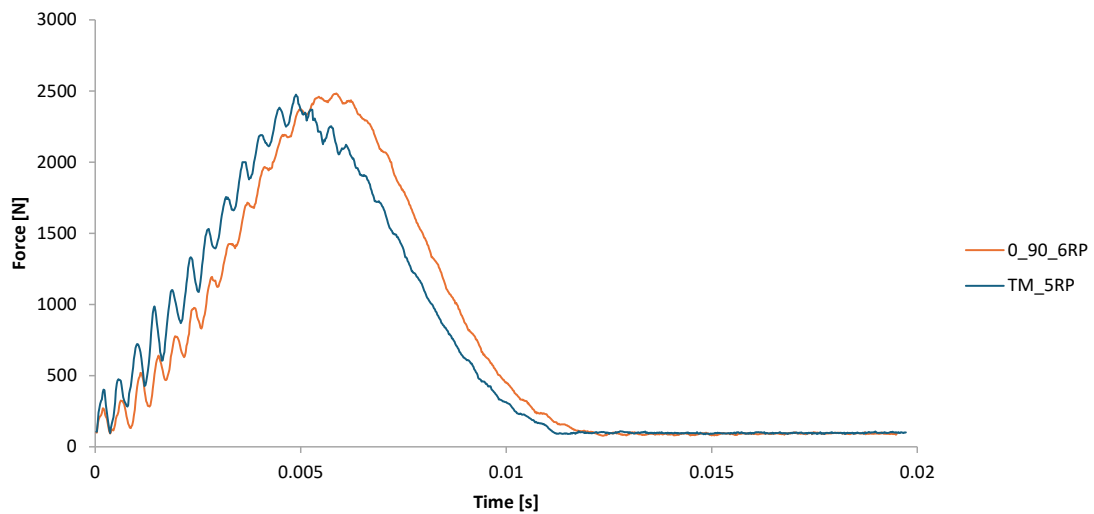


Figure 28 – Force–time histories obtained for the complementary reinforcement configurations containing 5 wt.% cork particles.

The energy–time responses presented in Figure 29 indicate similar overall energy absorption behaviour for the two 5 wt.% cork configurations, however, slight differences can be observed in the evolution of the absorbed energy, with the TM_5RP laminate reaching its maximum energy value earlier than the 0_90_6RP.

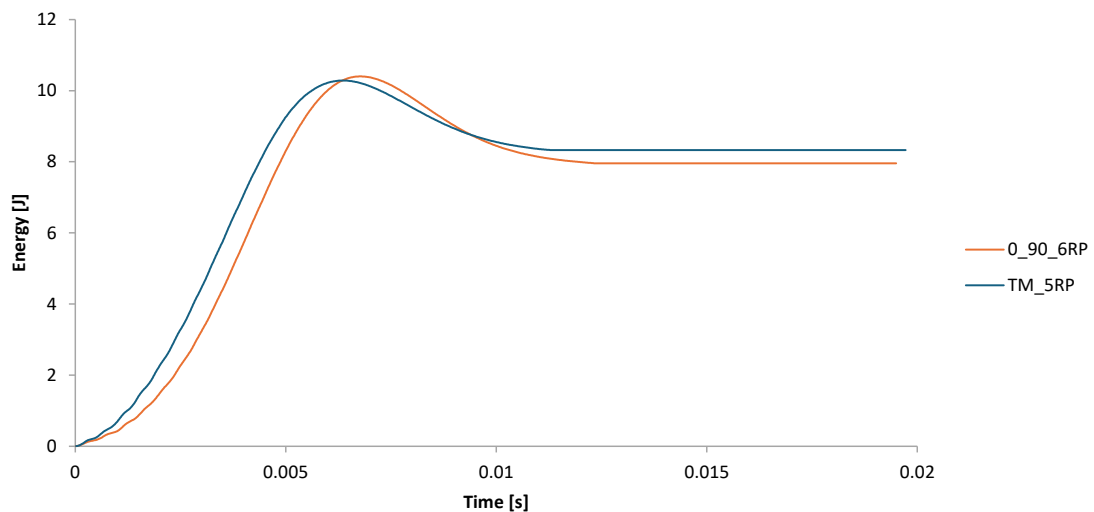


Figure 29 – Energy–time histories obtained for the complementary reinforcement configurations containing 5 wt.% cork particles.

The force–displacement responses presented in Figure 30 allow the deformation behaviour of the two 5 wt.% cork configurations to be compared. The complete responses are shown in Figure 30(a), while Figure 30(b) highlights the behaviour up to the maximum impact force.

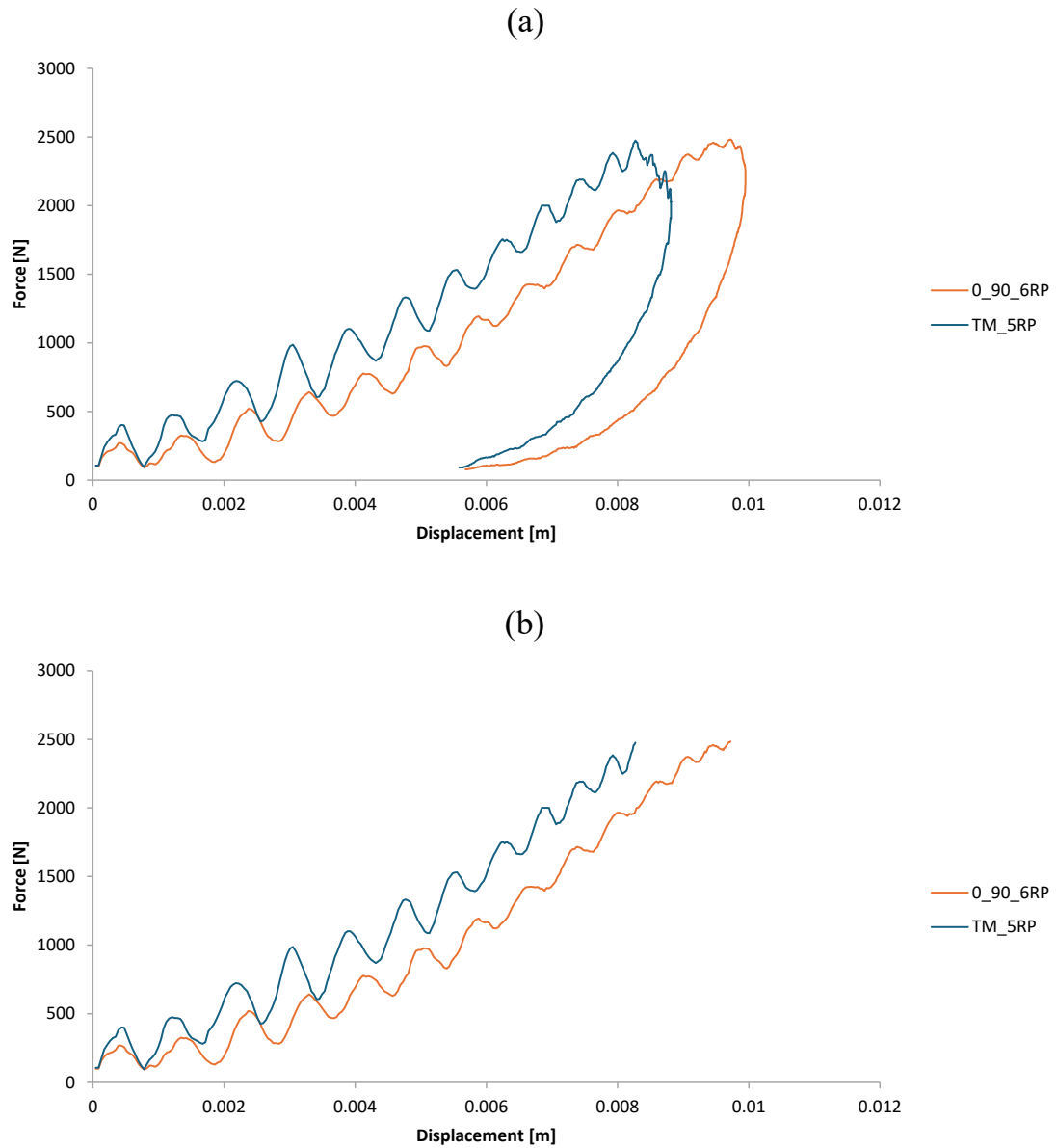


Figure 30 – Force–displacement response obtained for the complementary reinforcement configurations containing 5 wt.% cork particles: (a) complete force–displacement response; (b) force–displacement response up to the maximum impact force.

Representative examples of the surface damage observed after low-velocity impact testing for the complementary laminate configurations are shown in Figure 31.

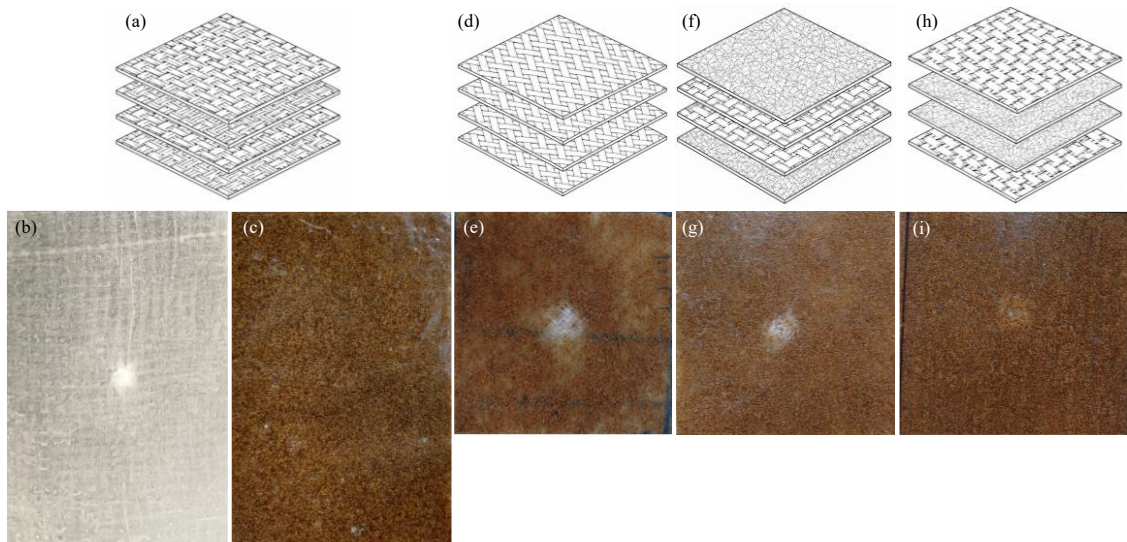


Figure 31 – Schematic representation of the reinforcement architectures and corresponding post-impact surface appearance of the complementary laminate configurations: (a–c) 0_90_0RE and 0_90_5RE, (d–e) 45_3RP, (f–g) MT_3RP, and (h–i) TM_5RP.

Overall, the impact response curves and the corresponding surface damage observations revealed differences between the complementary laminate configurations under the adopted impact conditions. The results presented in this section provide a basis for comparing the influence of matrix system, fibre orientation, and stacking arrangement on the impact behaviour of the developed laminates. For completeness, an additional comparative set of plots including all laminate configurations considered in the stacking sequence analysis is provided in Appendix E.

Following the analysis of the impact response and visible surface damage, radiographic inspection was carried out to further assess the internal damage developed within the impacted specimens. The radiographic analysis results are presented in Section 4.1.2

4.1.2. Radiographic Analysis

Radiographic inspection was performed following the LVI testing in order to evaluate the internal damage developed within the composite laminates. The obtained radiographs provide complementary information regarding the distribution and extent of the damage generated during impact loading and support the assessment of the damage mechanisms associated with the different laminate configurations.

4.1.2.1. Main Laminates

The radiographic inspection results obtained for the main laminate group are presented in Figure 32. The acquired radiographs allow a direct comparison of the damage patterns developed under the adopted impact conditions.

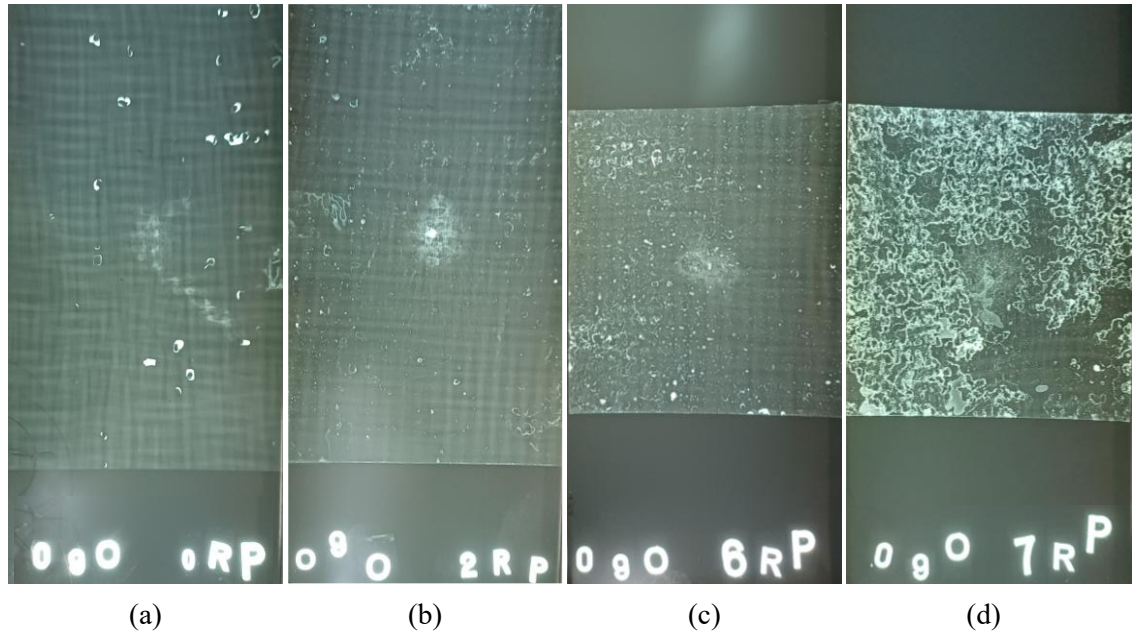


Figure 32 – Radiographic images of the main laminate configurations following low-velocity impact testing: (a) 0_90_0RP; (b) 0_90_2RP; (c) 0_90_6RP; and (d) 0_90_7RP.

For consistency with the impact response results presented in Section 4.1.1, only the radiographic inspection results corresponding to laminate 0_90_6RP are included for the 5 wt.% cork configuration. The radiographs obtained for the complete set of laminates, including 0_90_5RP, are provided in Appendix F.

To facilitate the correlation between the visible surface damage and the corresponding internal damage features identified by radiographic inspection, photographs of the impacted specimens and their respective radiographs are presented in Figure 33.

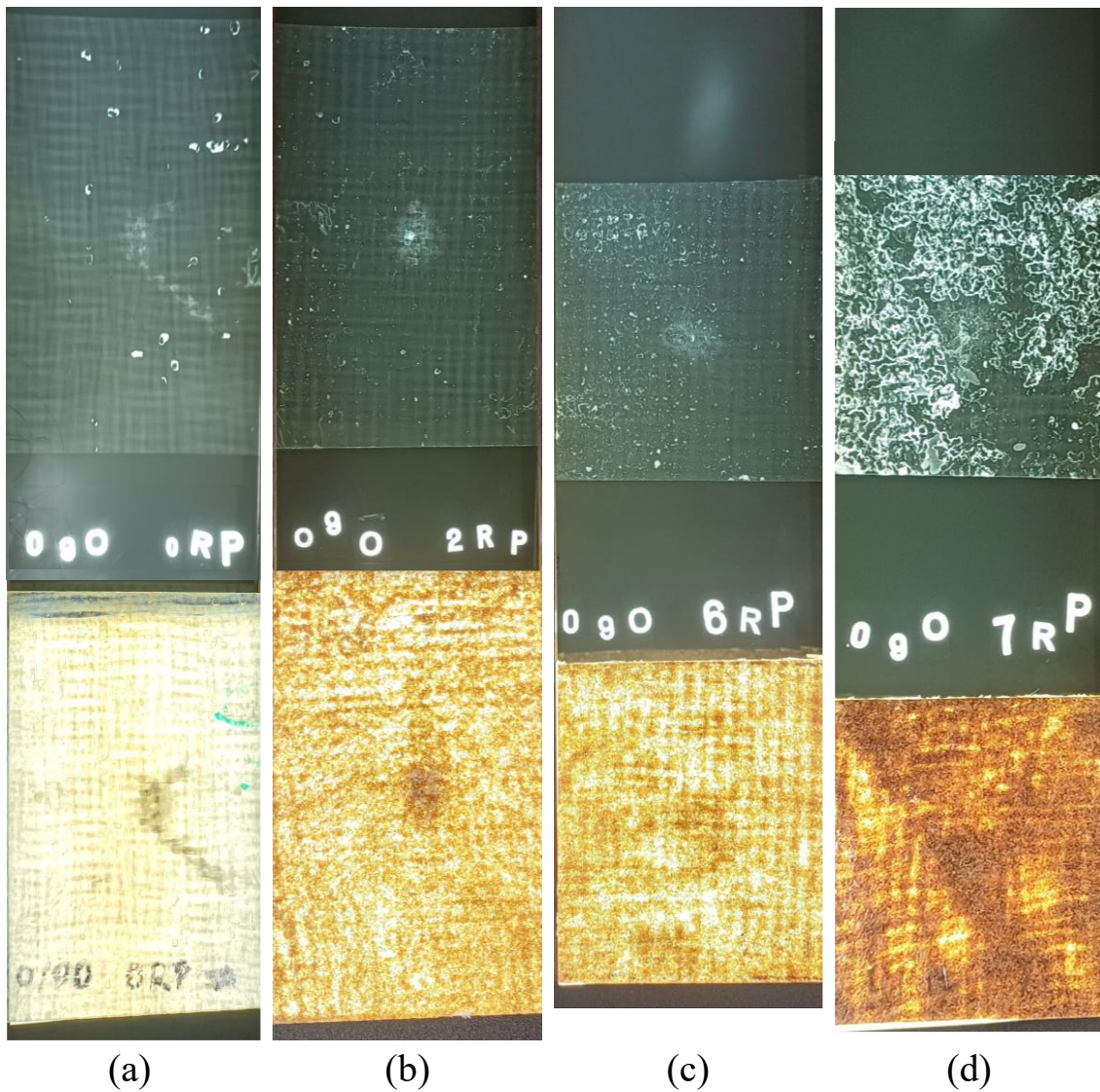


Figure 33 – Comparison between the radiographic inspection results and the corresponding photographs of the impacted specimens for the main laminate configurations: (a) 0_90_0RP; (b) 0_90_2RP; (c) 0_90_6RP; and (d) 0_90_7RP.

The damage regions observed in the penetrant-enhanced radiographs were quantified for the main laminate configurations according to the image-processing procedure described in Section 3.3.2. Table 13 summarises the mean values and corresponding standard deviations obtained for the measured damage length and width, as well as for the apparent damage area identified from the radiographic images.

Table 13 – Dimensions of the radiographically indicated damage regions for the main laminate configurations.

Laminate ID	Length [mm]	Width [mm]	Area [mm ²]
0_90_ORP	46.53 ± 0.24	36.93 ± 0.62	635.82 ± 12.60
0_90_2RP	23.50 ± 0.35	19.44 ± 0.68	336.28 ± 6.01
0_90_5RP	15.29 ± 0.12	12.75 ± 0.12	153.78 ± 3.75
0_90_6RP	10.89 ± 0.53	18.87 ± 0.11	137.08 ± 1.31
0_90_7RP	20.71 ± 0.45	20.92 ± 0.15	308.80 ± 2.41

The individual measurement values supporting the statistical summary presented in Table 13 are provided in Appendix G.

To facilitate the visual interpretation of the apparent damage area assessment, Figure 34 presents the penetrant-enhanced radiographic images with the delineated apparent damage regions. For consistency with the radiographic results presented above, only laminate 0_90_6RP is shown for the 5 wt.% cork configuration, while the corresponding delineated image for laminate 0_90_5RP is provided in Appendix F.

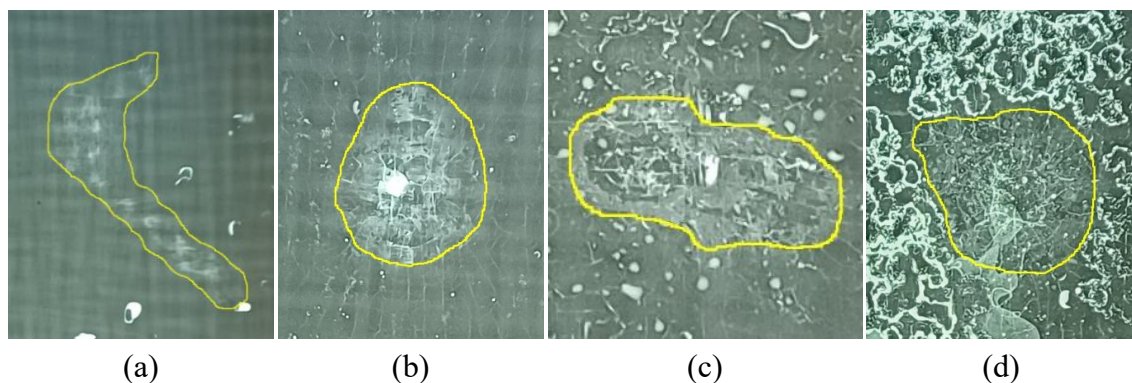


Figure 34 – Apparent damage regions delineated on the penetrant-enhanced radiographic images of the main laminate configurations: (a) 0_90_ORP; (b) 0_90_2RP; (c) 0_90_6RP; and (d) 0_90_7RP.

Similar radiographic inspection procedures were conducted for the complementary laminate configurations, whose results are presented in Section 4.1.2.2.

4.1.2.2. Complementary Laminates

The radiographic inspection results obtained for the complementary laminate configurations are presented in Figure 35. The acquired radiographs allow the comparison of the damage patterns developed in laminates with different matrix systems, fibre orientations, and reinforcement architectures subjected to the same impact conditions.

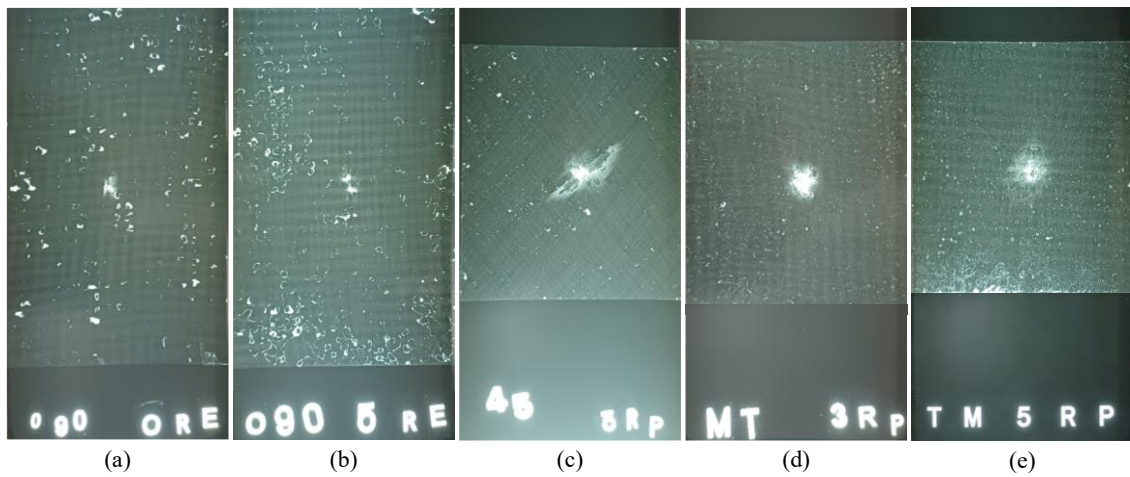


Figure 35 – Radiographic images of the complementary laminate configurations following low-velocity impact testing: (a) 0_90_0RE; (b) 0_90_5RE; (c) 45_3RP; (d) MT_3RP; and (e) TM_5RP.

To facilitate the correlation between the visible surface damage and the corresponding internal damage features identified by radiographic inspection, photographs of the impacted specimens and their respective radiographs are presented in Figure 36.

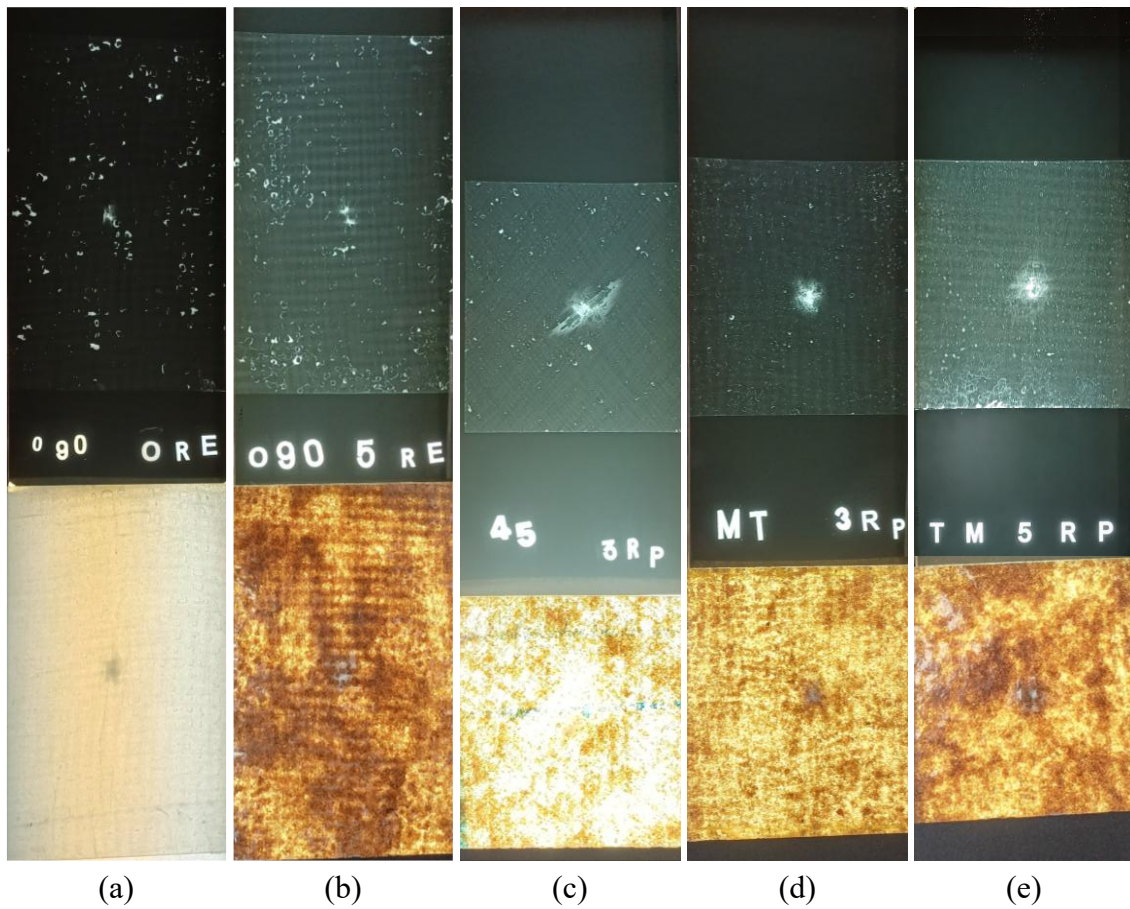


Figure 36 – Comparison between the radiographic inspection results and the corresponding photographs of the impacted specimens for the complementary laminate configurations: (a) 0_90_0RE; (b) 0_90_5RE; (c) 45_3RP; (d) MT_3RP; and (e) TM_5RP.

The damage regions observed in the penetrant-enhanced radiographs were also quantified for the complementary laminate configurations according to the image-processing procedure described in Section 3.3.2. Table 14 summarises the mean values and corresponding standard deviations obtained for the measured damage length and width, as well as for the apparent damage area identified from the radiographic images.

Table 14 – Dimensions of the radiographically indicated damage regions for the complementary laminate configurations.

Laminate ID	Length [mm]	Width [mm]	Area [mm ²]
0_90_0RE	13.05 ± 0.32	6.82 ± 0.44	69.82 ± 1.30
0_90_5RE	14.45 ± 0.16	9.82 ± 0.29	120.53 ± 2.94
45_3RP	23.56 ± 0.57	30.23 ± 0.26	410.52 ± 9.33
MT_3RP	15.32 ± 0.28	13.90 ± 0.20	164.09 ± 3.74
TM_5RP	20.82 ± 0.54	16.89 ± 0.45	263.24 ± 3.23

The individual measurement values supporting the statistical summary presented in Table 14 are provided in Appendix H.

Figure 37 presents the radiographic images with the apparent damage regions delineated, illustrating the regions considered for the quantitative assessment of the complementary laminate configurations.

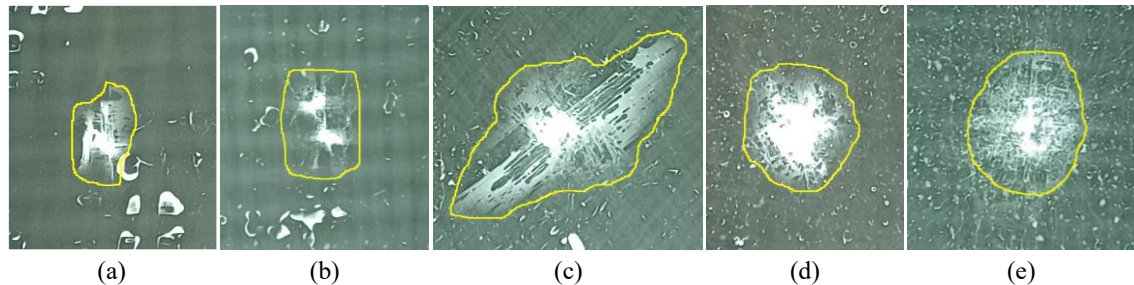


Figure 37 – Apparent damage regions delineated on the penetrant-enhanced radiographic images of the complementary laminate configurations: (a) 0_90_0RE; (b) 0_90_5RE; (c) 45_3RP; (d) MT_3RP; and (e) TM_5RP.

Following the impact and radiographic assessments, the results obtained from the tensile characterisation of the developed laminate configurations are presented in the following section (Section 4.1.3).

4.1.3. Tensile Results

The tensile tests were performed to evaluate the influence of cork particle incorporation on the tensile behaviour of the developed composite laminates. The obtained results provide complementary information regarding the mechanical performance of the materials under

static loading conditions and support the assessment of the effect of the particulate incorporation on the structural response of the laminates.

The principal tensile properties obtained for the tested laminate configurations are summarised in Table 15 as mean values, including tensile strength, Young's modulus, and strain at failure, determined from the experimental stress–strain responses. The corresponding standard deviations are also reported to provide an indication of the dispersion of the experimental results.

Table 15 – Principal tensile properties obtained for the tested laminate configurations.

Cork content [wt.%]	Tensile strength [MPa]	Young's modulus [GPa]	Strain [%]
0	252.95 ± 47.73	7.51 ± 0.78	4.25 ± 0.92
5	104.60 ± 5.80	3.08 ± 0.15	4.95 ± 0.07

The complete individual tensile results, together with the width and thickness measurements of the two specimens tested for each cork content, are provided in Appendix I.

Accordingly, the stress–strain responses obtained during tensile testing are presented in Figure 38. These curves provide a qualitative comparison of the deformation behaviour of the cork-free and cork-modified laminates and illustrate the differences observed in stiffness and maximum stress between the tested configurations.

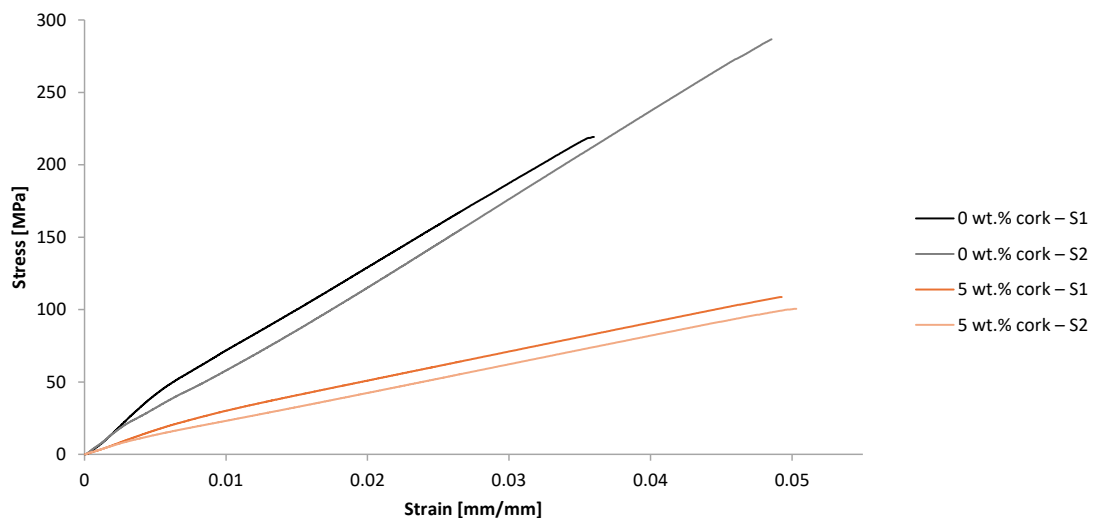


Figure 38 – Stress–strain curves obtained for the tested laminate configurations. S1 and S2 refer to the two tensile specimens tested for each selected laminate configuration.

The stress–strain responses presented in Figure 38 showed an approximately linear region up to failure for both laminate configurations. Differences in the slope of the curves and in the maximum stress attained were observed between the cork-free and cork-modified laminates.

The tensile results presented in this section complete the experimental results obtained for the tested laminate configurations under static loading conditions. The detailed discussion of the tensile results, together with the impact response, visual inspection, and radiographic damage assessment presented in the previous sections, is provided in Section 4.2.

4.2. Results Discussion

This section discusses the experimental results presented in Section 4.1, with the aim of interpreting the influence of cork particle incorporation, matrix system, fibre orientation, and reinforcement architecture on the mechanical response and apparent damage development of the composite laminates. The discussion first focuses on the main laminate configurations, for which the effect of cork particle content can be more directly assessed, and then considers the complementary configurations in order to analyse the influence of additional material and structural variables. Finally, the tensile results and the comparison with similar studies reported in the literature are considered to provide an overall assessment of the performance and limitations of the developed cork-modified laminates.

4.2.1. Effect of Cork Particle Content on the Impact Response of the Main Laminates

The discussion of the impact response begins with the main laminate configurations, namely 0_90_ORP, 0_90_2RP, 0_90_6RP, and 0_90_7RP. These laminates constitute the most suitable group for evaluating the specific influence of cork particle content, since the matrix system and reinforcement architecture were kept constant. Therefore, the main variable under analysis in this section is the amount of cork particles incorporated into the polymer matrix.

For the 5 wt.% cork configuration, the discussion in the main text is based on the representative laminate 0_90_6RP, in agreement with the impact response curves presented in Section 4.1.1. The first test performed for the same cork content, identified as 0_90_5RP, is considered as complementary information and is provided in Appendix J. This approach allows the discussion to remain consistent with the representative results presented in the main text, while preserving the complete experimental dataset for reference.

The effect of cork particle content was first assessed through the principal impact parameters reported in Table 11 and the corresponding force–time, energy–time, and force–displacement responses shown in Figure 18 - Figure 20. Among these parameters, the maximum impact force provides the clearest initial indication of the influence of cork incorporation, considering that the reference laminate, 0_90_ORP, exhibited the lowest peak force, reaching 1604.42 N, whereas all cork-containing configurations presented higher maximum force values.

For the laminate containing 2.5 wt.% cork particles, 0_90_2RP, the maximum force increased by approximately 39.3% relative to the reference laminate. The representative 5 wt.% cork configuration, 0_90_6RP, reached the highest maximum force among the main laminates, with a peak value of 2384.36 N, representing an increase of approximately 48.6% compared with the reference laminate. In the case of the 7.5 wt.% cork laminate, 0_90_7RP, the maximum force remained substantially higher than that of the cork-free laminate, although this value was lower than those obtained for the 2.5 wt.% and 5 wt.% configurations, corresponding to an increase of approximately 37.7% relative to the reference laminate.

This trend is further highlighted in Figure 39, where the maximum impact force is represented as a function of cork particle content. The graph shows that the increase in peak force did not follow a linear progression with cork content. Instead, the response improved up to the representative 5 wt.% configuration, while the further increase to 7.5 wt.% did not result in an additional increase in maximum force.

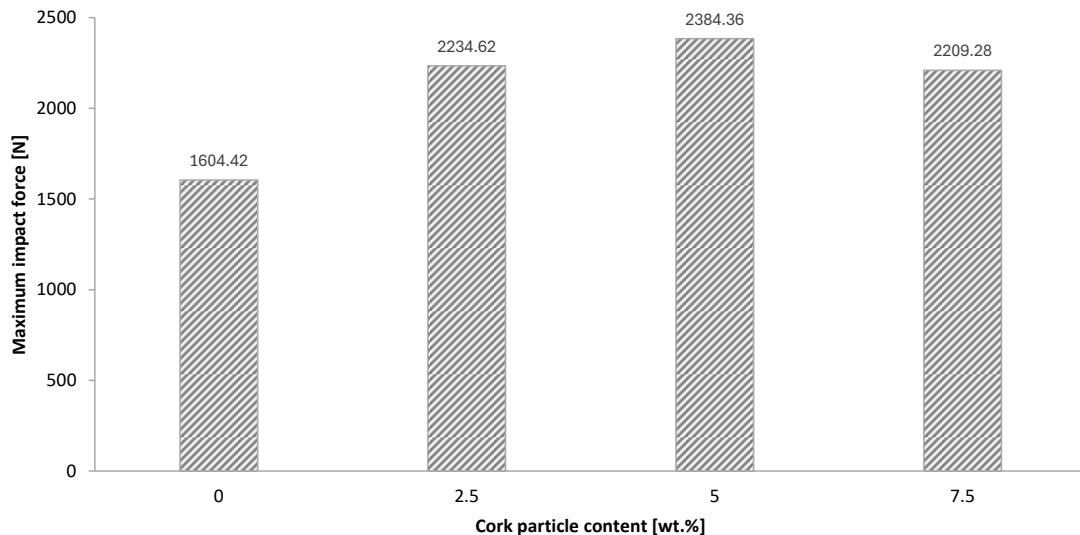


Figure 39 – Maximum impact force as a function of cork particle content for the representative main laminate configurations.

The reduction observed for the 7.5 wt.% configuration may be associated with the processing difficulties introduced by higher cork particle contents. As described in Section 3.2.1, increasing the cork concentration increased the viscosity of the resin mixture, making resin distribution and fibre impregnation more difficult. Under these conditions, local heterogeneities, particle agglomeration, or void formation may have occurred more easily, potentially limiting the beneficial effect observed for the intermediate cork contents. Similar limitations have been reported in particle-modified composite systems, where excessive filler contents may reduce performance due to poorer dispersion, agglomeration, increased viscosity, void formation, or reductions in stiffness and strength [54]. Therefore, the lower peak force obtained for the 7.5 wt.% laminate should not necessarily be interpreted as a loss of the effect of cork particles, but rather as an indication that higher cork contents may introduce processing-related limitations.

Beyond the peak force values, the shape of the force–time curves also provides relevant information regarding the behaviour of the laminates during loading. As shown in Figure 18, the cork-containing laminates reached higher force levels than the reference laminate but also exhibited differences in the evolution of force throughout the impact event. These differences are visible in the initial force increase, the maximum force region, and the post-peak response, indicating that cork incorporation affected not only the peak load-bearing capacity but also the way in which the laminates responded during impact loading.

This behaviour suggests that the incorporation of cork particles modified the global impact response of the laminates. However, the force–time curves alone do not allow the observed differences to be assigned to a specific damage mechanism, since the recorded response may

be influenced by several simultaneous phenomena, including laminate bending, local indentation, matrix cracking, delamination initiation, fibre-related damage, and rebound behaviour.

The energy–time responses shown in Figure 19 provide complementary information on the evolution of the energy response during impact. Since all laminates were tested under the same nominal impact energy, the final energy values were relatively close; nevertheless, small differences in the energy evolution can be observed between the cork-free and cork-containing laminates, indicating that the incorporation of cork particles influenced the way in which energy was transferred and dissipated during the event. In particular, the cork-containing laminates exhibited a faster initial increase in energy and reached the maximum energy level earlier than the cork-free reference laminate, whereas the cork-free laminate showed a more prolonged energy increase before reaching its maximum value. These differences may be related to variations in deformation, local damage development, and rebound behaviour. However, the energy response alone is not sufficient to determine which laminate presented better damage tolerance, since similar energy levels may correspond to different internal damage states.

Additionally, the force–displacement responses presented in Figure 20 further support the interpretation of the impact behaviour. To complement this analysis, Figure 40 presents the maximum displacement reached during the impact event as a function of cork particle content for the representative main laminate configurations.

In this analysis, the maximum displacement corresponds to the largest displacement reached during the impact event and should be distinguished from the displacement recorded at peak force reported in Table 11.

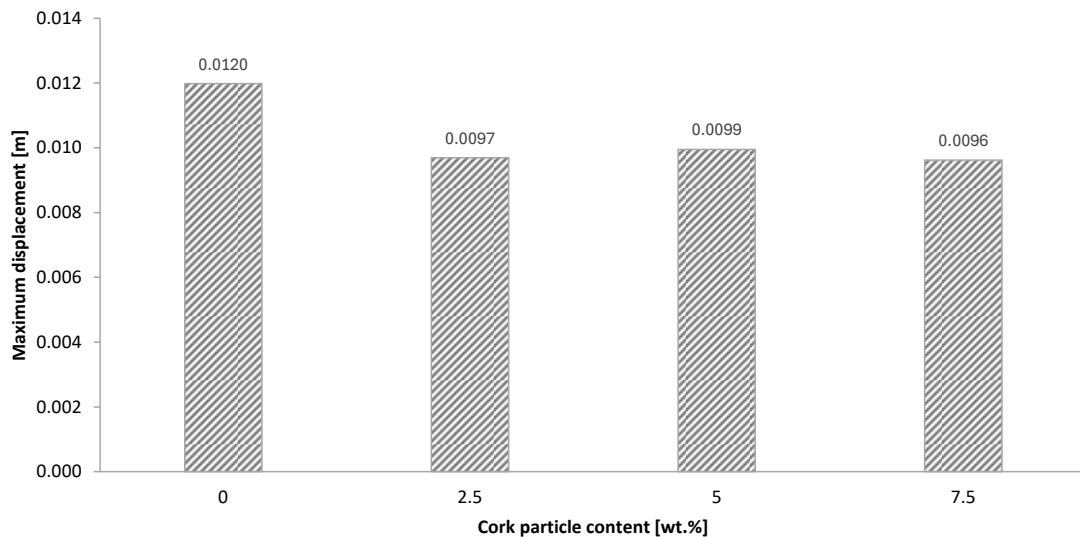


Figure 40 – Maximum displacement as a function of cork particle content for the representative main laminate configurations.

Although the cork-free laminate presented the highest maximum displacement, approximately 20% higher than that obtained for the representative 5 wt.% cork laminate, 0_90_6RP, the displacement recorded at maximum force was not markedly different from those obtained for

the cork-containing laminates. This indicates that the main difference between the configurations was not the displacement required to reach peak force, but rather the force level sustained within a comparable displacement range. Therefore, the cork-modified laminates exhibited higher peak forces without requiring substantially greater deformation up to the maximum force region, suggesting a higher apparent resistance during the initial impact response. However, this behaviour should be interpreted as part of the global impact response rather than as a direct measurement of laminate stiffness, since the curves are influenced by bending, local indentation, damage initiation, and boundary conditions during the test.

The visual inspection of the impacted specimens, shown in Figure 21, provided a qualitative first assessment of the surface damage developed in the main laminate configurations. In the cork-free laminate, 0_90_ORP, the impact region was more clearly visible, with a larger altered region observed on the specimen surface. The appearance of this region suggests that several damage mechanisms may have contributed to the visible response, including local indentation, matrix cracking, fibre/matrix debonding, delamination, and fibre breakage. However, these mechanisms cannot be individually confirmed from visual inspection alone, since different damage modes may produce similar surface features.

For the cork-containing laminates, the visible damage appeared more localised around the impact region. In the 0_90_2RP configuration, the surface features observed near the impact zone may be associated with localised fibre exposure or possible fibre breakage, together with matrix cracking and local indentation. In the representative 5 wt.% laminate, 0_90_6RP, the impacted region was also visible, although the affected surface area appeared less extensive, which may indicate a more localised damage response, but the contribution of mechanisms such as matrix cracking, fibre/matrix debonding, and delamination cannot be distinguished solely by visual observation. In the 0_90_7RP laminate, the visible damage was less clearly distinguishable from the surrounding surface, which may be partly related to the darker and more heterogeneous surface appearance caused by the higher cork particle content.

Overall, the visual inspection suggests that the incorporation of cork particles modified the surface damage appearance of the laminates after impact. The cork-free laminate showed a more extensive visible alteration, while the cork-containing laminates generally exhibited more localised surface damage features.

Nevertheless, these observations remain qualitative and are strongly influenced by surface finish, lighting conditions, cork particle distribution, and laminate transparency; moreover, low-velocity impact damage in laminated composites may develop internally without being fully visible on the external surfaces. For this reason, visual inspection alone is insufficient to assess the actual extent and distribution of damage. Therefore, the relationship between cork particle content, impact response, and apparent internal damage is analysed in Section 4.2.2 based on the radiographic inspection results.

4.2.2. Relationship between Cork Content, Impact Response, and Apparent Internal Damage

In accordance with the representative approach adopted in Section 4.1.2, the 5 wt.% cork condition is discussed in the main text using laminate O_90_6RP, while the corresponding radiographic results obtained for O_90_5RP are presented in Appendix K as complementary information. The comparison is therefore focused on the representative main laminate configurations: O_90_ORP, O_90_2RP, O_90_6RP, and O_90_7RP.

As shown in Table 13 and in the radiographic images presented in Figure 32 - Figure 34, the cork-free laminate, O_90_ORP, exhibited the largest radiographically indicated damage region among the representative main configurations. This laminate presented a mean apparent damage area of 635.82 mm², with mean damage length and width values of 46.53 mm and 36.93 mm, respectively. These values indicate that, under the adopted impact conditions, the reference laminate developed a more extensive radiographically detected apparent damage region than the cork-modified configurations.

For the 2.5 wt.% cork laminate, O_90_2RP, the mean apparent damaged area decreased to 336.28 mm², corresponding to a reduction of approximately 47.1% relative to the reference laminate. Most notably, the representative 5 wt.% cork laminate, O_90_6RP, presented the lowest apparent damage area among the configurations considered in the main discussion, with a mean value of 137.08 mm², corresponding to a reduction of approximately 78.4% when compared with the cork-free laminate. In contrast, the 7.5 wt.% cork laminate, O_90_7RP, showed an increase in apparent damage area relative to the 5 wt.% configuration, reaching a mean value of 308.80 mm², although this value remained approximately 51.4% lower than that of the reference laminate.

This trend is illustrated in Figure 41, where the mean apparent damage area is represented as a function of cork particle content for the representative main laminate configurations. In this and in the subsequent radiographic damage plots, the error bars correspond to the standard deviation calculated from repeated image-based measurements of each delineated damage region, and therefore reflect measurement variability.

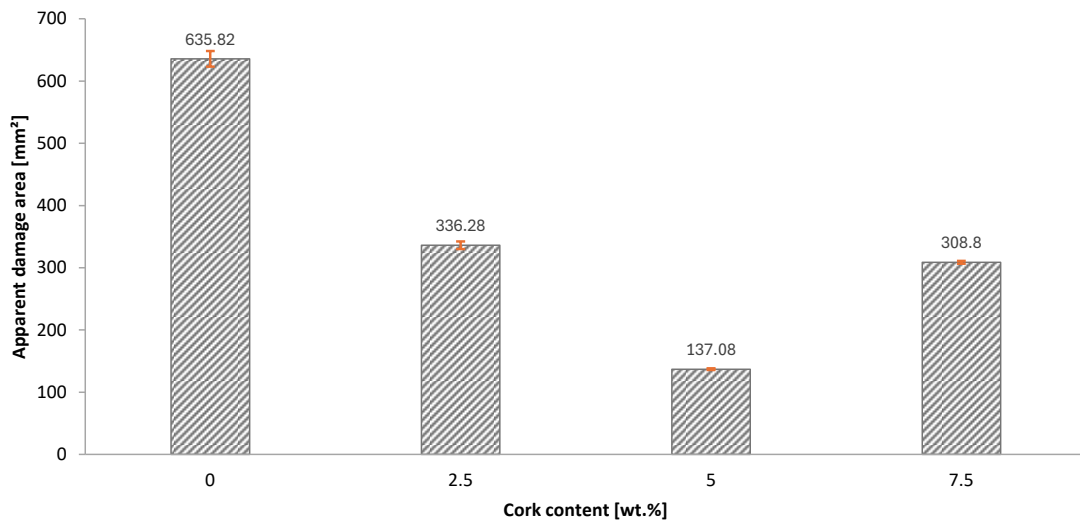


Figure 41 – Apparent damage area measured from penetrant-enhanced radiographic images as a function of cork particle content for the representative main laminate configurations.

The results show that the reduction in apparent internal damage did not follow a simple linear relationship with cork content. The most pronounced reduction was observed for the representative 5 wt.% cork configuration, whereas increasing the cork content to 7.5 wt.% did not lead to a further decrease in the apparent damage area. This behaviour is consistent with the trend previously observed for the impact response, where the 5 wt.% laminate also exhibited the highest maximum impact force, while the 7.5 wt.% configuration showed a slight decrease in peak force relative to the intermediate cork contents.

This simultaneous increase in maximum impact force and reduction in radiographically detected apparent damage area suggests that the cork-containing laminates were able to sustain higher contact forces while limiting the radiographically detected damage extent. Therefore, the results may indicate a more favourable balance between load-bearing capacity and the development of apparent damage during impact; however, this relationship should be interpreted with caution.

Although the representative 5 wt.% laminate combined the highest peak force with the lowest apparent damage area, this does not mean that the higher peak force directly caused the reduction in damage area. The final damage condition is likely governed by several interacting mechanisms and specimen-specific factors, including laminate deformation, local indentation, matrix cracking, fibre/matrix interaction, delamination growth, and the quality of cork particle dispersion within the matrix. It should also be recalled that the measured area may not represent the complete internal damage state, since it only includes damage that was accessible to the radiopaque penetrant, namely damage that was sufficiently interconnected and connected to an external opening to allow liquid infiltration.

At the same time, the mean damage length and width values provide complementary information on the geometry of the apparent damage regions. The reference laminate exhibited both the highest damage length and width, indicating a wider and more extended damage envelope, while the cork-containing laminates generally showed smaller apparent

damage dimensions. However, the reductions in length and width were not proportional for all configurations, for example, the 0_90_6RP laminate presented the lowest damage length, but its damage width was not reduced to the same extent.

This indicates that the decrease in apparent damage area did not occur through a uniform geometric contraction of the damaged region. Instead, the measured damage geometry may have been affected by local specimen features, such as cork particle dispersion, possible agglomeration, local heterogeneities, or voids formed during processing. Therefore, the length and width values should be considered complementary indicators of apparent damage morphology, while the apparent damage area remains the most robust parameter for comparing the radiographically indicated damage extent between configurations.

The relationship between the mechanical impact response and the apparent damage area is particularly relevant. The laminates containing cork particles reached higher maximum impact forces than the cork-free laminate and, at the same time, presented lower apparent damage areas. This suggests that cork incorporation altered not only the load-bearing response during impact, but also the extent of damage detected after the event. The representative 5 wt.% cork laminate showed the most favourable combination among the main configurations, combining the highest peak force with the lowest apparent damage area.

To further examine this relationship, Figure 42 compares the maximum impact force with the apparent damage area for the representative main laminate configurations. This representation allows the mechanical response during impact to be considered together with the radiographically detected damage extent, highlighting the comparatively favourable position of the representative 5 wt.% cork laminate.

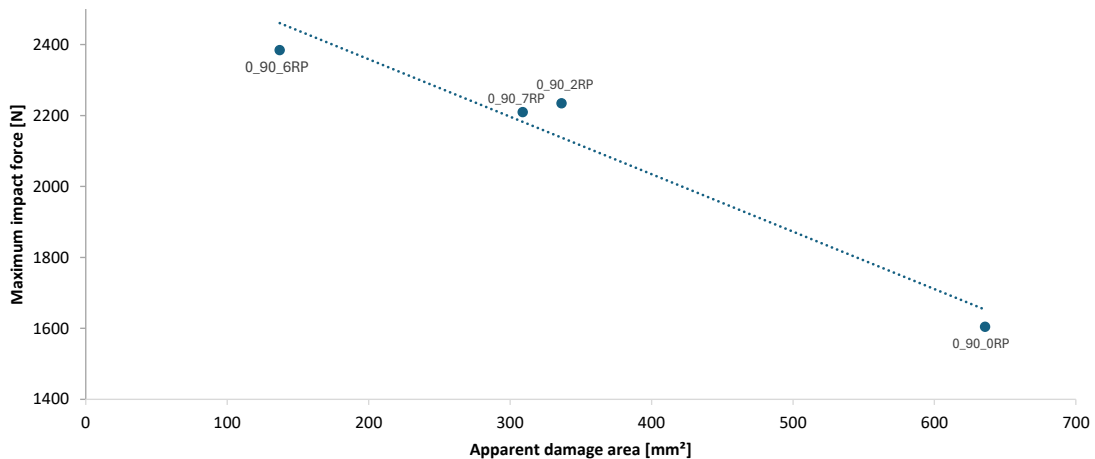


Figure 42 – Relationship between maximum impact force and apparent damage area for the representative main laminate configurations.

As shown in Figure 42, the cork-free laminate is positioned in the region associated with lower maximum force and higher apparent damage area, whereas the cork-modified configurations tend to present higher maximum force values and lower apparent damage areas. This tendency indicates that the incorporation of cork particles may have contributed to improving the apparent damage resistance of the laminates under the adopted impact conditions.

Nevertheless, this relationship should be interpreted qualitatively, since the number of tested configurations is limited and the results do not allow a statistical correlation to be established.

The increase in radiographically detected apparent damage area observed for the 7.5 wt.% configuration reinforces the idea that, under the conditions analysed, higher cork contents are not necessarily more beneficial. As previously discussed, higher particle contents may introduce processing-related limitations, potentially reducing the effectiveness of cork incorporation and contributing to the less favourable response observed for the 7.5 wt.% laminate when compared with the representative 5 wt.% configuration. In addition, since the radiographic measurements are based on a two-dimensional projection of penetrant-accessible damage, they do not provide a complete description of the three-dimensional damage state through the laminate thickness.

Despite these limitations, the radiographic results provide a valuable comparative basis for assessing the influence of cork particle content on impact-induced damage. Overall, the results indicate that cork incorporation reduced the radiographically detected apparent damage area relative to the cork-free laminate, with the most favourable response observed for the representative 5 wt.% configuration. Therefore, cork particle content influenced not only the mechanical response recorded during impact, but also the apparent extent and distribution of damage detected after impact loading.

The following section (Section 4.2.3) extends this analysis to the complementary laminates, focusing on the influence of matrix system and reinforcement architecture.

4.2.3. Effect of Matrix System and Reinforcement Architecture on the Impact and Damage Response

After analysing the influence of cork particle content on the main laminate configurations, the complementary laminates were considered in order to assess how other material and structural parameters may also affect the impact and damage response. These configurations were not intended to replace the analysis of cork content, but rather to provide additional insight into the role of matrix system, fibre orientation, and reinforcement architecture. Therefore, the results discussed in this section should be interpreted as indicative trends, since the complementary configurations do not isolate all variables perfectly.

The first comparison concerns the influence of the matrix system. For this purpose, the polyester-based 0/90 laminates were compared with equivalent epoxy-based configurations, considering both the cork-free laminates, 0_90_ORP and 0_90_0RE, and the 5 wt.% cork-containing laminates, represented by 0_90_6RP and 0_90_5RE. Figure 43 compares the maximum impact force and the mean apparent damage area obtained for these selected configurations. The error bars in the apparent damage area plot correspond to the standard deviation calculated from repeated image measurements of each radiographic damage region, following the same approach adopted in the previous section. The complete set of results for the matrix-system comparison is provided in Appendix L.

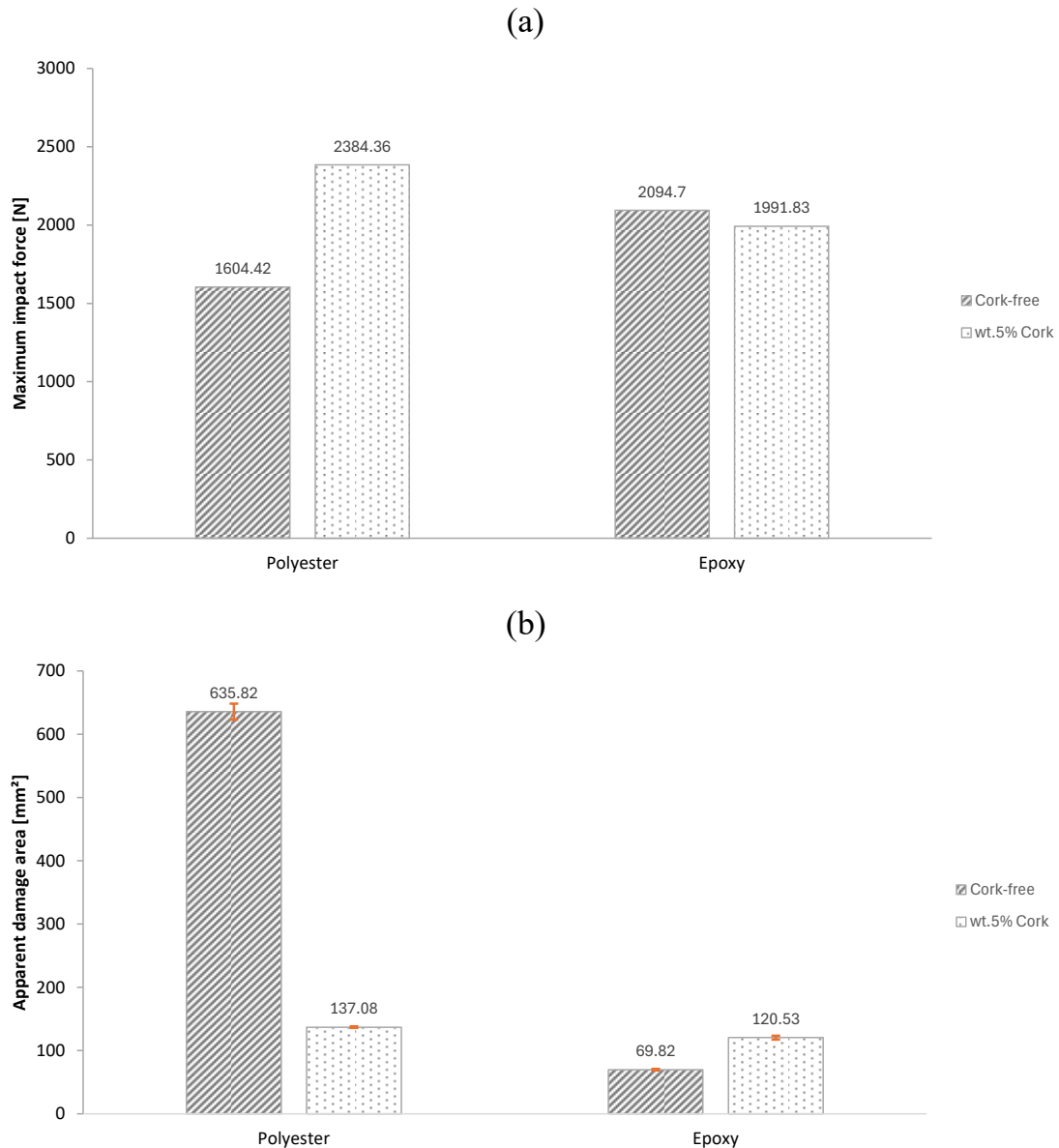


Figure 43 – Effect of matrix system on selected 0°/90° laminate configurations: (a) maximum impact force; (b) mean apparent damage area measured from penetrant-enhanced radiographic images.

For the cork-free laminates, the epoxy-based configuration, 0_90_ORE, reached a higher maximum impact force than the polyester-based reference laminate, 0_90_ORP. The peak force increased from 1604.42 N for 0_90_ORP to 2094.70 N for 0_90_ORE. In parallel, the apparent damage area was considerably lower for the epoxy-based laminate, decreasing from 635.82 mm² to 69.82 mm². This indicates that, under the adopted impact conditions, changing the matrix system strongly affected both the load-bearing response and the radiographically detected damage extent of the cork-free 0/90 laminates.

For the laminates containing 5 wt.% cork particles, the comparison between 0_90_6RP and 0_90_5RE showed a different tendency. The polyester-based laminate, 0_90_6RP, reached a higher maximum impact force, with a value of 2384.36 N, compared with 1991.83 N for the

epoxy-based laminate, 0_90_5RE; however, the apparent damage areas were relatively close, with 137.08 mm² for 0_90_6RP and 120.53 mm² for 0_90_5RE.

This result suggests that cork particle incorporation did not produce the same effect in the epoxy-based system as in the polyester-based laminates. While the epoxy matrix appeared to be more effective in limiting the radiographically detected apparent damage in the cork-free condition, the addition of cork particles did not further reduce the apparent damage area and was accompanied by a lower peak force. Therefore, the effect of cork incorporation appears to depend on the matrix system and on the interaction between the particles and the surrounding polymer phase.

The displacement and energy values also indicate that the matrix system affected the deformation behaviour during impact, although the influence of cork incorporation on displacement was still apparent. In both matrix systems, the cork-free laminates reached higher displacements at peak force and maximum displacement values than the corresponding 5 wt.% cork-containing configurations. This suggests that, within the selected 0/90 comparisons, cork incorporation was associated with lower displacement values up to the maximum force region. Nevertheless, the relationship between displacement and apparent damage area was not the same as that observed for the main polyester laminates.

For the cork-free configurations, the epoxy-based laminate reached a higher displacement at peak force than the polyester-based reference laminate, while still presenting a substantially lower apparent damage area. This indicates that the displacement response cannot be interpreted independently of the matrix system, since the matrix influences fibre/matrix load transfer, crack initiation, and the way in which damage propagates through the laminate.

In contrast, for the 5 wt.% cork configurations, the epoxy-based laminate reached peak force at a lower displacement than 0_90_6RP and showed a slightly lower apparent damage area. Therefore, the results suggest that the matrix system modified the balance between deformation, load-bearing response, and radiographically detected damage. The energy values remained within a comparable range for the configurations analysed, indicating that similar global energy levels may correspond to different force–displacement responses and different apparent damage states.

Following the matrix-system comparison, the analysis was extended to selected polyester-based configurations in order to examine how fibre orientation and reinforcement architecture affected the impact response and radiographically detected apparent damage. Figure 44 compares the maximum impact force and apparent damage area for selected polyester-based laminates with different reinforcement arrangements and comparable cork particle contents where possible. Therefore, the figure should be interpreted as a comparative overview of selected configurations rather than as a direct trend with cork particle content.

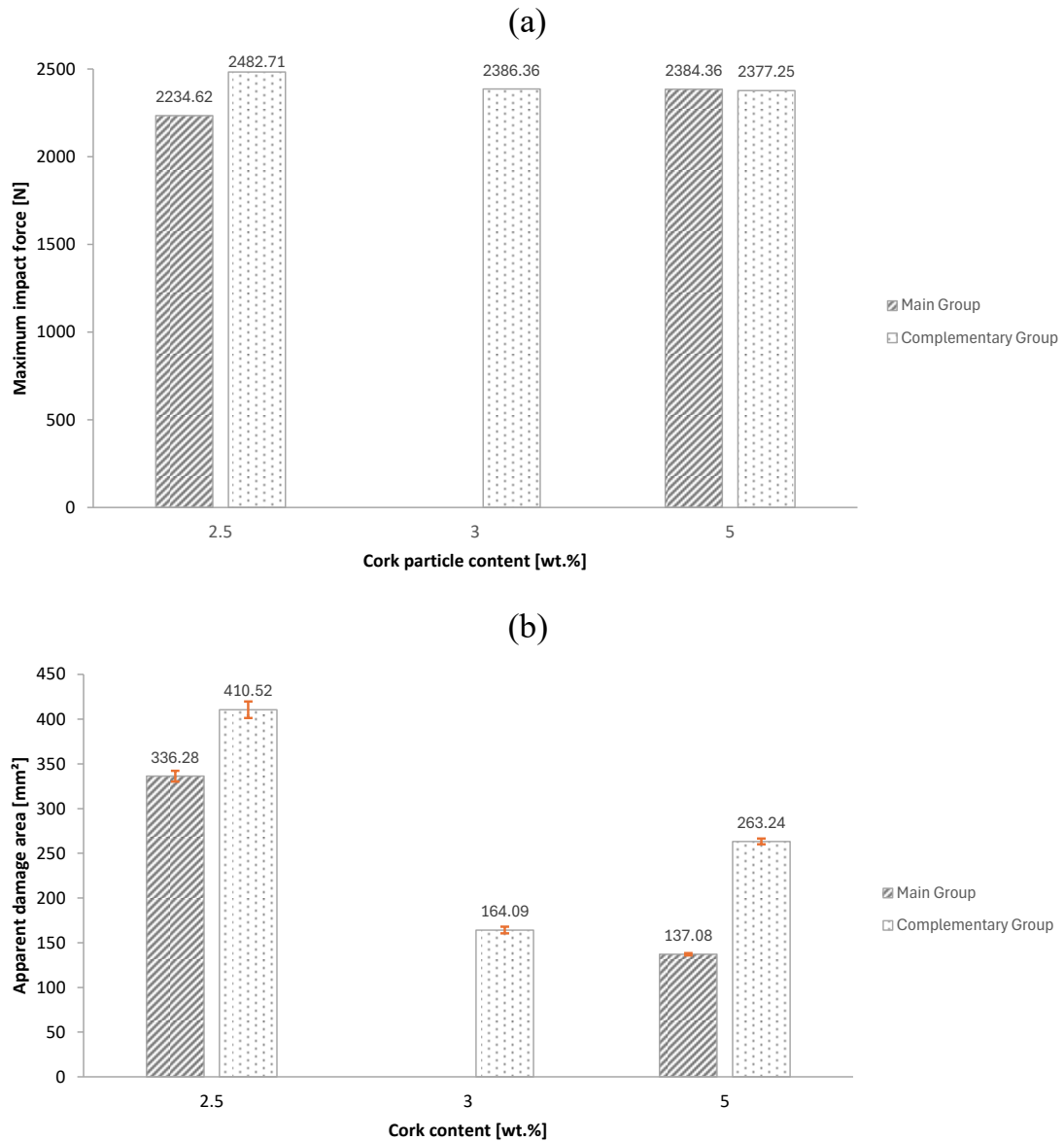


Figure 44 – Effect of fibre orientation and reinforcement architecture on the impact and apparent damage response of selected polyester-based laminate configurations: (a) maximum impact force; (b) mean apparent damage area measured from penetrant-enhanced radiographic images.

The influence of fibre orientation can be assessed by comparing 0_90_2RP with 45_3RP, both corresponding to polyester-based woven glass fibre laminates with comparable cork particle content. The $\pm 45^\circ$ laminate, 45_3RP, reached a higher maximum impact force, with 2482.71 N compared with 2234.62 N for 0_90_2RP. However, the apparent damage area also increased, from 336.28 mm² for 0_90_2RP to 410.52 mm² for 45_3RP. This indicates that the higher load-bearing response observed for the $\pm 45^\circ$ configuration was not accompanied by a reduction in radiographically detected damage. The change in fibre orientation may have altered the deformation mode of the laminate and the path followed by damage during propagation, influencing the final apparent damage distribution.

The effect of reinforcement architecture can be further analysed by comparing the 0/90 woven laminates with the mat-containing hybrid configurations. For the lower cork content configurations, MT_3RP, in which mat layers were placed on the outer surfaces of the laminate, reached a higher maximum impact force than 0_90_2RP, with values of 2386.36 N and 2234.62 N, respectively. At the same time, the apparent damage area decreased substantially, from 336.28 mm² for 0_90_2RP to 164.09 mm² for MT_3RP. This suggests that, in this configuration, the incorporation of the mat layer may have contributed to a different stress distribution and a more confined radiographically detected damage region. Nevertheless, this comparison should be interpreted with caution, since the cork particle contents are not exactly identical.

For the 5 wt.% cork configurations, 0_90_6RP and TM_5RP presented very similar maximum impact force values, 2384.36 N and 2377.25 N, respectively. However, in TM_5RP, where woven fabric layers formed the outer surfaces and mat layers were positioned in the central region of the laminate, the apparent damage area was higher, reaching 263.24 mm² compared with 137.08 mm² for 0_90_6RP. This indicates that similar maximum force values may correspond to different damage states, reinforcing the importance of combining impact response curves with radiographic damage assessment. Taken together, these comparisons suggest that the effect of mat incorporation depends not only on its presence in the laminate, but also on its position within the stacking sequence, which may influence local stiffness, stress redistribution, and the damage propagation path.

Overall, the complementary laminate results show that the impact and apparent damage response was not governed only by cork particle content. The matrix system, fibre orientation, and reinforcement architecture also affected the maximum force, deformation behaviour, and radiographically detected damage extent. However, because these complementary configurations involve simultaneous changes in material system, reinforcement arrangement, cork content, and in some cases specimen characteristics, the results should be interpreted as comparative trends rather than definitive isolated effects. These observations reinforce the multifactorial nature of the impact response of cork-modified glass fibre reinforced polymer laminates.

4.2.4. Tensile Behaviour of Cork-Modified Laminates and Mechanical Performance Trade-Offs

The tensile results were analysed in order to assess whether the incorporation of cork particles, which influenced the impact response and the radiographically detected apparent damage area, also affected the static mechanical behaviour of the laminates. This analysis was limited to the cork-free and 5 wt.% cork-modified configurations tested under tensile loading. Therefore, the results should be interpreted as a comparative assessment of these selected configurations rather than as a complete characterisation of all laminate systems.

The incorporation of 5 wt.% cork particles resulted in a clear reduction in tensile strength. As shown in Table 15, the mean tensile strength decreased from 252.95 MPa for the cork-free

configuration to 104.60 MPa for the 5 wt.% cork-modified configuration, corresponding to a reduction of approximately 58.6%. A similar tendency was observed for Young's modulus, which decreased from 7.51 GPa to 3.08 GPa, corresponding to a reduction of approximately 59.0%. These results indicate that the cork-modified laminate presented lower tensile load-bearing capacity and lower stiffness under static loading.

This behaviour may be associated with the introduction of cork particles as a dispersed phase within the polymer matrix, since cork particles are expected to present lower stiffness and lower tensile load-bearing capacity than both the glass fibre reinforcement and the thermosetting matrix. Therefore, their incorporation may reduce the effective stiffness and strength of the laminate under tensile loading. In addition, the presence of particles may have affected resin flow, fibre impregnation, and local homogeneity during manufacturing. As discussed previously, the addition of cork particles increased the viscosity of the resin mixture, which may have favoured local heterogeneities, particle agglomeration, or void formation. These factors can act as stress concentration regions and contribute to the reduction in tensile strength and Young's modulus.

In contrast, the strain at failure did not decrease with cork incorporation. The mean strain at failure increased from 4.25% for the cork-free configuration to 4.95% for the 5 wt.% cork-modified configuration, corresponding to an increase of approximately 16.5%. This indicates that the reduction in tensile strength and stiffness was not accompanied by a loss of deformation capacity.

These tensile results therefore indicate that cork particle incorporation produced a mechanical performance trade-off in the tested laminates: while the 5 wt.% cork-modified configuration showed a more favourable apparent impact damage response, it also exhibited lower tensile strength and stiffness under static loading. This behaviour is further discussed in relation to similar studies reported in the literature in Section 4.2.5.

4.2.5. Comparison with Similar Studies Reported in the Literature

The results obtained in the present work can be related to previous studies on glass fibre/polyester laminates and cork-modified composite systems. However, these comparisons should be interpreted mainly in terms of trends and mechanisms rather than direct numerical equivalence, since differences in material formulation, fibre architecture, manufacturing conditions, impact energy, impactor geometry, specimen configuration, and damage assessment methods can significantly affect the measured response.

Regarding the impact and damage behaviour, the reduction in the apparent radiographic damage area observed for the cork-modified laminates can be related to previous studies in which cork was shown to influence damage development in composite systems. In a study on the low-velocity impact behaviour of hybrid carbon-epoxy/cork laminates, a cork layer was inserted at a critical interface of a cross-ply carbon-epoxy laminate [64]. Although that configuration differs from the material system analysed in the present work, since it involved a

carbon-epoxy laminate with an interlaminar cork layer rather than glass fibre/polyester laminates with cork particles dispersed in the matrix, it provides relevant insight into the role of cork in impact-induced damage development.

In that study, the incorporation of the cork layer led to a distinct damage profile when compared with the monolithic carbon-epoxy laminate: while the monolithic laminate developed a longitudinal crack accompanied by extensive delamination, the hybrid carbon-epoxy/cork laminate exhibited a longer longitudinal crack but no evidence of extensive delamination at the cork layer. This behaviour was attributed to energy dissipation within a large fracture process zone developed in the cork layer, which contributed to suppressing extensive delamination [64]. Therefore, although the damage mechanisms in the present work are expected to differ due to the use of cork particles, glass fibre reinforcement and a polyester matrix, the results reported in that study support the interpretation that cork can modify damage propagation and may contribute to improved low-velocity impact behaviour, as suggested in the present work by the reduction in apparent radiographic damage area observed for the cork-modified laminates.

This interpretation is also supported by studies focused on interlaminar damage. In a study on the Mode II fracture energy of laminated composites enhanced with micro-cork particles, ENF specimens made of woven E-glass/epoxy laminates were modified with 1 wt.% and 3 wt.% micro-cork particles near the delamination interface [13]. This study is not directly equivalent to the present work, since it was based on Mode II fracture testing rather than low-velocity impact, and used an epoxy matrix instead of polyester. Nevertheless, it is particularly relevant because cork was introduced as particles within a fibre-reinforced laminate and the analysis focused directly on delamination resistance.

The results reported in that study showed that the addition of micro-cork particles increased the maximum load sustained by the ENF specimens and improved the initiation and propagation components of Mode II interlaminar fracture toughness. The most significant improvement was obtained for 3 wt.% cork particles, which increased the initiation fracture toughness by 127% and the propagation delamination toughness by 31%. The authors attributed this behaviour to several mechanisms, including crack arresting, crack kinking, alteration of the crack growth path, more stable crack propagation, and an increase in the fracture process zone length. In particular, the interaction between the crack front and the cork particles forced the crack to follow a more tortuous propagation path, increasing the energy required for delamination growth [13]. These mechanisms are relevant to the present work because delamination and matrix cracking are among the main damage mechanisms associated with low-velocity impact in laminated composites.

Therefore, although the present study did not directly measure interlaminar fracture toughness, the lower apparent radiographic damage area observed for the cork-modified laminates may be qualitatively related to the ability of cork particles to influence matrix-dominated and interlaminar damage development. Nevertheless, this interpretation should remain cautious, since the radiographic method used in this work only detects damage accessible to the penetrant and does not provide a complete three-dimensional description of the internal damage state.

As a complementary point, the tensile behaviour observed in the present work follows the general tendency reported in studies involving glass fibre/polymer composites modified with SBR or recycled rubber particles. In both cases, the introduction of a comparatively compliant particulate phase was associated with reductions in tensile strength and stiffness relative to the corresponding unmodified composites [65], [66]. These reductions have been attributed to changes in fibre–matrix bonding, load transfer, resin distribution, and material homogeneity caused by the presence and distribution of the particles. Therefore, the tensile results obtained in the present work are consistent with the broader trend observed in particle-modified fibre-reinforced composites, where the incorporation of a dispersed particulate phase may compromise static tensile performance.

4.2.6. Overall Assessment of the Results

Overall, the results obtained in this work show that the incorporation of cork particles clearly influenced the impact response and damage behaviour of the glass fibre reinforced polymer laminates. The cork-modified main laminates reached higher maximum impact forces and lower apparent radiographic damage areas than the cork-free reference laminate, with the most favourable response observed for the representative 5 wt.% configuration. This indicates that cork particles may contribute to improving the impact damage response under the testing conditions adopted in this study.

However, the results also show that the effect of cork incorporation was not linear with particle content. The 7.5 wt.% configuration did not maintain the same favourable trend observed for the 5 wt.% laminate, suggesting that there may be a more favourable range of cork particle content rather than a continuous improvement with increasing cork addition. This behaviour may be associated with a combination of material and processing factors.

On the one hand, although cork particles may contribute to energy dissipation and damage modification, cork is expected to present lower stiffness and strength than the glass fibre reinforcement and the thermosetting matrix; therefore, excessive particle contents may reduce the effective load-bearing capacity of the composite. On the other hand, higher cork contents also introduce processing-related limitations, since, as observed during manufacturing, increasing the cork concentration increased the viscosity of the resin mixture and reduced its flowability, which may have contributed to less uniform impregnation, particle agglomeration, local heterogeneity or void formation.

Therefore, the performance of cork-modified laminates appears to depend not only on the presence of cork particles, but also on the balance between particle content, material properties, dispersion quality and processing conditions.

The complementary laminate configurations also showed that the impact response was affected by other material and structural factors, including matrix system, fibre orientation and reinforcement architecture. Thus, cork particle incorporation should not be considered as an isolated parameter, but rather as one element within a broader laminate design. The final

impact and damage behaviour results from the combined influence of matrix properties, reinforcement arrangement, particle content, manufacturing quality and damage development mechanisms.

In addition, the tensile results demonstrated that the favourable impact response of the representative 5 wt.% cork-modified laminate was accompanied by reductions in tensile strength and Young's modulus. This highlights an important performance trade-off: cork particle incorporation may improve the apparent impact damage response, but it can also penalise static tensile properties. Therefore, the suitability of cork-modified GFRP laminates depends on the intended application and on the balance between impact damage tolerance, static mechanical performance and manufacturability.

In summary, the results indicate that cork particles have potential as a functional dispersed phase in glass fibre reinforced polyester laminates subjected to low-velocity impact. Nevertheless, their effective use requires optimisation of particle content, dispersion quality, resin flow, laminate architecture and processing conditions, together with complementary mechanical characterisation to ensure that improvements in impact-related behaviour do not compromise other relevant structural properties.

5. Conclusion

This chapter presents the main conclusions obtained from the experimental work developed in this dissertation. The findings are synthesised in relation to the initial objectives, with emphasis on the influence of cork particle incorporation on the LVI response, apparent internal damage development, and tensile behaviour of glass fibre reinforced polymer laminates. The main limitations of the work are also identified, and recommendations for future research are proposed.

5.1. Final Conclusions

The present dissertation investigated the influence of cork particle incorporation on the mechanical behaviour and impact damage response of glass fibre reinforced polymer composite laminates. The work focused mainly on polyester-based 0/90 woven glass fibre laminates with different cork particle contents, complemented by additional laminate configurations used to assess the influence of matrix system, fibre orientation, and reinforcement architecture. The experimental programme included low-velocity impact testing, penetrant-enhanced radiographic inspection, image-based damage quantification, and tensile testing of selected configurations.

The results obtained for the main laminate group showed that cork particle incorporation influenced the LVI response of the laminates under the adopted testing conditions. Compared with the cork-free reference laminate, the cork-modified laminates generally reached higher maximum impact force values. The most favourable response among the representative main configurations was obtained for the 0_90_6RP laminate (5 wt.% cork), which presented the highest maximum impact force and the lowest apparent radiographic damage area.

However, the improvement in impact response did not increase continuously with cork particle content. The 7.5 wt.% cork laminate showed a less favourable response than the representative 5 wt.% configuration, both in terms of maximum impact force and apparent damage area. This indicates that there may be a more favourable range of cork particle content rather than a continuous benefit with increasing cork addition. This behaviour may also be associated with possible processing-related limitations, since the incorporation of higher cork particle contents increased the viscosity of the resin mixture and may have affected resin flow, fibre impregnation, particle dispersion, and laminate homogeneity.

Conclusion

The penetrant-enhanced radiographic inspection provided important complementary information regarding the radiographically detected apparent damage developed after impact. The cork-free reference laminate presented the largest apparent radiographic damage area among the representative main configurations, while the cork-modified laminates showed lower apparent damage areas. In particular, the representative 5 wt.% cork laminate showed the lowest apparent damage area, suggesting that cork particles modified the impact-induced damage response of the laminates. Nevertheless, the radiographic results should be interpreted as apparent damage envelopes, since the technique provides a two-dimensional projection of damage accessible to the radiopaque penetrant and does not fully characterise the three-dimensional through-thickness damage state.

The complementary laminate configurations showed that the impact and damage response was not governed only by cork particle content. Matrix system, fibre orientation, and reinforcement architecture also influenced the maximum impact force, deformation behaviour, and radiographically detected damage extent. In particular, the polyester-based laminates showed a more favourable response with cork particle incorporation, whereas the epoxy-based 0/90 laminate containing 5 wt.% cork particles did not show the same improvement when compared with its cork-free counterpart. Under the conditions analysed, cork incorporation appeared more beneficial in the polyester-based laminates, where the addition of a deformable particulate phase may contribute to modifying the impact damage response. In contrast, in the epoxy-based laminates, the potential benefit of cork particles may have been limited by the intrinsic matrix behaviour, particle–matrix interaction, or processing-related effects. Therefore, cork particle incorporation should be considered as one factor within a broader laminate design, together with matrix properties, reinforcement arrangement, manufacturing quality, and damage development mechanisms.

The tensile results demonstrated that the incorporation of 5 wt.% cork particles reduced the static tensile performance of the tested laminate. The cork-modified laminate presented lower tensile strength and lower Young's modulus than the cork-free laminate, while the strain at failure increased. This indicates that the favourable impact and apparent damage response observed for the representative cork-modified laminate was accompanied by a reduction in tensile load-bearing capacity and stiffness.

Overall, the results indicate that cork particles have potential as a functional dispersed phase in glass fibre reinforced polyester laminates subjected to low-velocity impact. However, their use requires an appropriate balance between impact damage tolerance, static tensile properties, cork particle content, particle dispersion, matrix system, and manufacturing quality. The findings also highlight the importance of optimising particle content, particle size, processing conditions, and damage assessment methods in future studies.

5.2. Limitations and Future Work

The present work has some limitations that should be considered when interpreting the results and that also define possible directions for future research.

Conclusion

One of the main limitations is associated with the manufacturing process. The laminates were produced by a manual manufacturing procedure, which may introduce variability in resin distribution, fibre impregnation, laminate thickness, particle dispersion and void content. This limitation is particularly relevant for the cork-modified laminates, since the incorporation of cork particles increased the viscosity of the resin mixture, making homogeneous particle distribution and complete fibre impregnation more difficult. Future work should therefore consider more controlled manufacturing procedures, such as vacuum bagging, in order to improve laminate compaction, reduce void formation and obtain more uniform thickness and resin distribution, together with a more detailed control of resin content, fibre volume fraction and laminate thickness.

Another limitation concerns the number of specimens and laminate configurations tested. The experimental programme included a limited number of configurations and a reduced number of specimens per configuration, which restricts the statistical robustness of the results. Therefore, the trends identified in this dissertation should be interpreted as representative of the tested systems rather than as definitive general conclusions for all cork-modified GFRP laminates. Future studies should include a larger number of specimens per configuration and additional cork contents in order to confirm the existence of an optimal particle content range.

The damage assessment method also presented relevant limitations, since the penetrant-enhanced radiographic inspection provided useful information on the apparent internal damage, but it produced a two-dimensional projection and did not provide a complete three-dimensional description of the damage state through the laminate thickness. In addition, this technique only allows the detection of damage regions that are accessible to the radiopaque penetrant, meaning that cracks, delaminations or voids must be sufficiently interconnected and connected to an external opening, or present a sufficiently significant volume, to be detected. For future work, it would be relevant to complement this method with other damage assessment techniques. X-ray computed tomography would allow a three-dimensional reconstruction of the internal damage state and could reveal defects not connected to an external opening. In addition, ultrasonic C-scan inspection could enable the mapping of delaminations and internal discontinuities over the impacted area.

A further limitation is related to the penetrant application procedure. Due to the limited amount of penetrant available, the specimens could not be kept fully submerged throughout the entire infiltration stage, and the application method may not have ensured uniform penetration into all accessible damage regions. This may have influenced the visibility and apparent extent of the damage in the radiographic images. Future studies should adopt a more controlled penetrant application procedure, ensuring complete immersion, consistent exposure time and sufficient penetrant volume for all specimens.

Finally, the interpretation of the damage mechanisms was also limited by the techniques used in this work. The impact curves, visual inspection and radiographic images allowed the identification of probable damage features, such as matrix cracking, delamination, local contact damage and possible fibre damage, and enabled a comparative analysis between configurations. However, these techniques did not allow all damage mechanisms to be confirmed or separated in detail, particularly at the microscopic and through-thickness levels.

Conclusion

Future work should therefore include complementary microscopic and microstructural analyses, such as optical microscopy or scanning electron microscopy, together with interlaminar fracture toughness tests, in order to better understand the mechanisms responsible for the observed impact and damage behaviour.

Beyond the limitations and recommendations already mentioned, future research could also investigate the influence of cork particle size on the mechanical and damage response of the laminates, since this parameter may affect resin flow, particle distribution, agglomeration, and the interaction between cork particles and damage propagation mechanisms. In addition, considering previous work on glass fibre/polyester laminates modified with SBR and cork particles under tensile loading, it would be relevant to extend this comparison to low-velocity impact behaviour. This would allow cork-modified laminates to be compared with laminates modified with an elastomeric particulate phase, in order to assess whether similar impact-related benefits can be obtained and to better understand the differences between cork and SBR as matrix modifiers.

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Declaration of Integrity

I declare that I conducted this academic work with integrity. I did not plagiarize or apply any form of misuse of information or falsification of results throughout the process that led to its preparation. I declare that the work presented in this document is original and my own and has not previously been used for any other purpose. I further declare that I am fully aware of the Code of Ethical Conduct of P.PORTO, ISEP.

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Porto, June 14, 2026

Appendix A

This appendix presents the complete visual record of the main laminate configurations considered in this work. These figures include both laminates corresponding to the 5 wt.% cork configuration, namely 0_90_5RP and 0_90_6RP, complementing the images presented in Sections 3.2.2.2 and 4.1.1.1.

Figure A.1 presents the complete set of manufactured main laminate configurations before low-velocity impact testing. These images allow the visual appearance of the laminates to be compared as a function of cork particle content, including the two specimens manufactured with 5 wt.% cork particles.

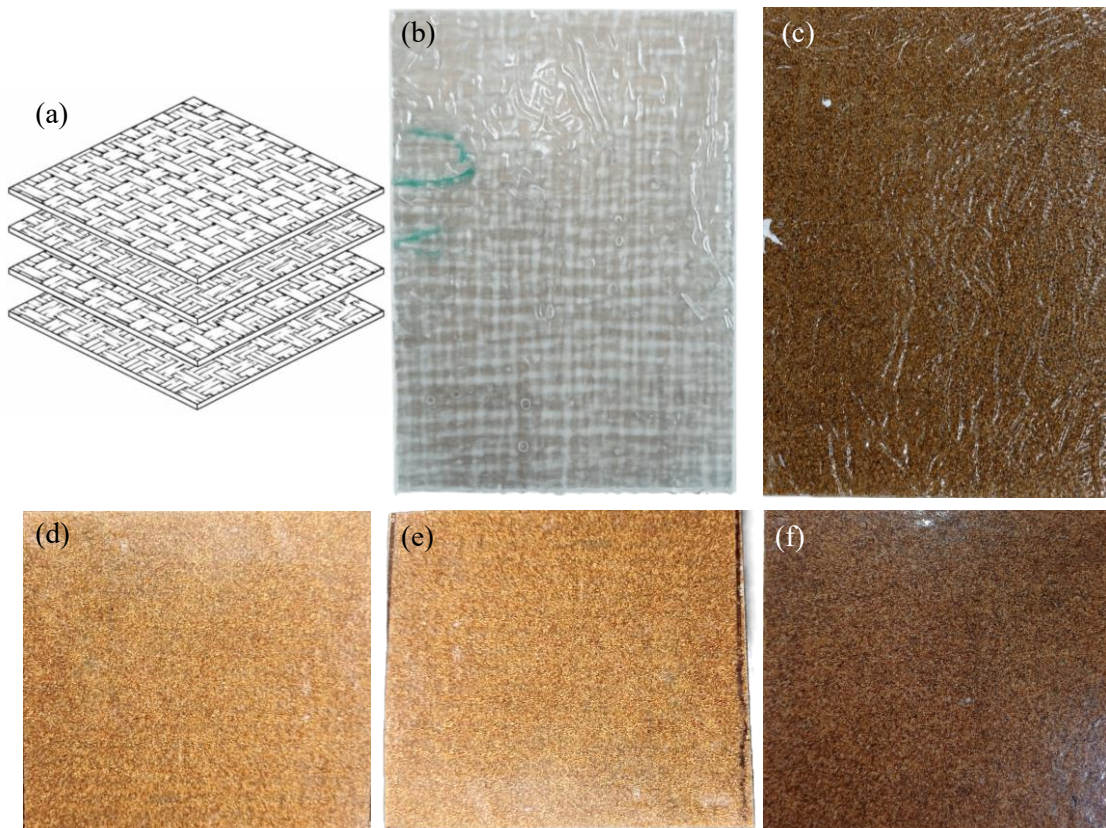


Figure A.1 - (a) Schematic representation of the four-layer 0/90 woven glass fibre reinforcement architecture; photographs of the complete set of manufactured laminates: (b) 0_90_0RP; (c) 0_90_2RP; (d) 0_90_5RP; (e) 0_90_6RP; and (f) 0_90_7RP.

The corresponding post-impact surface appearance of the same laminate configurations is presented in Figure A.2. These images provide the complete visual record of the main laminate group after low-velocity impact testing.

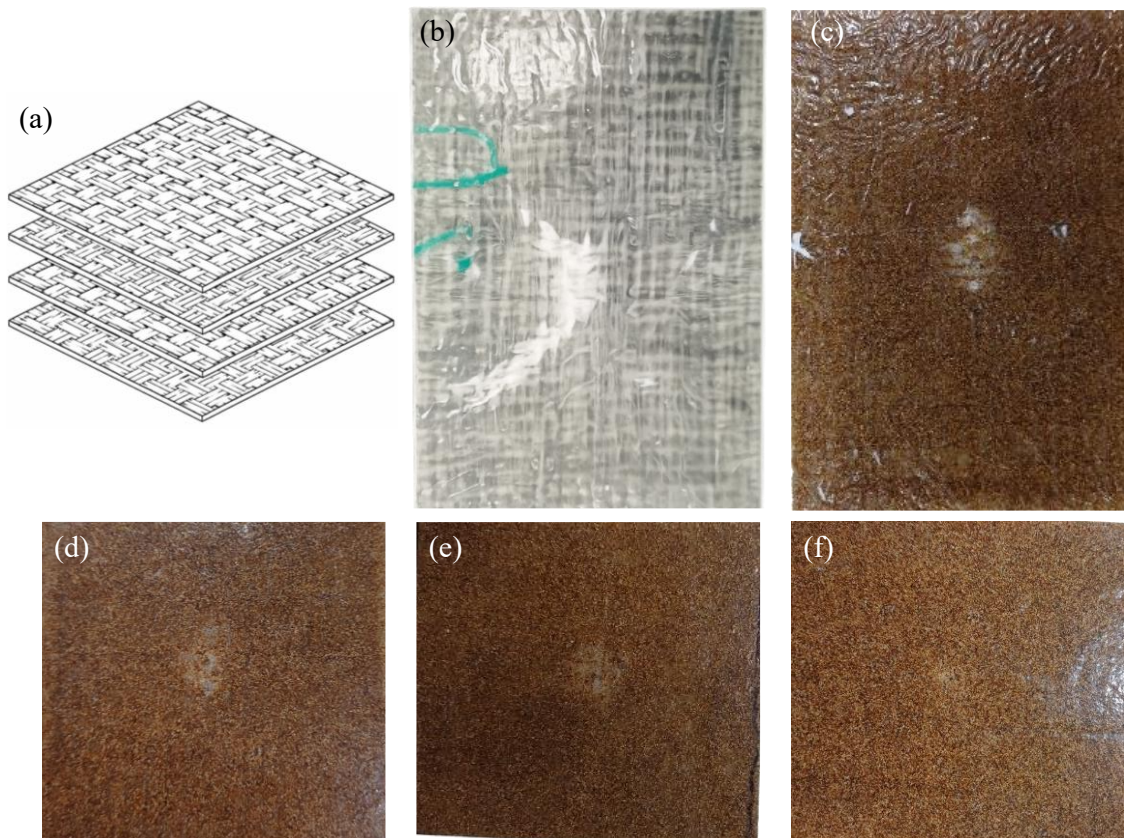


Figure A.2 - (a) Schematic representation of the four-layer 0/90 woven glass fibre reinforcement architecture; photographs of the complete set of manufactured laminates after low-velocity impact testing: (b) 0_90_0RP; (c) 0_90_2RP; (d) 0_90_5RP; (e) 0_90_6RP; and (f) 0_90_7RP.

Appendix B

This appendix presents the complete set of impact response curves obtained for the main laminate configurations subjected to low-velocity impact testing. These figures include both tests performed for the 5 wt.% cork laminate configuration, namely 0_90_5RP and 0_90_6RP, complementing the representative curves presented in Section 4.1.1.1.

Figure B.1 presents the force–time histories obtained for the complete set of main laminate configurations.

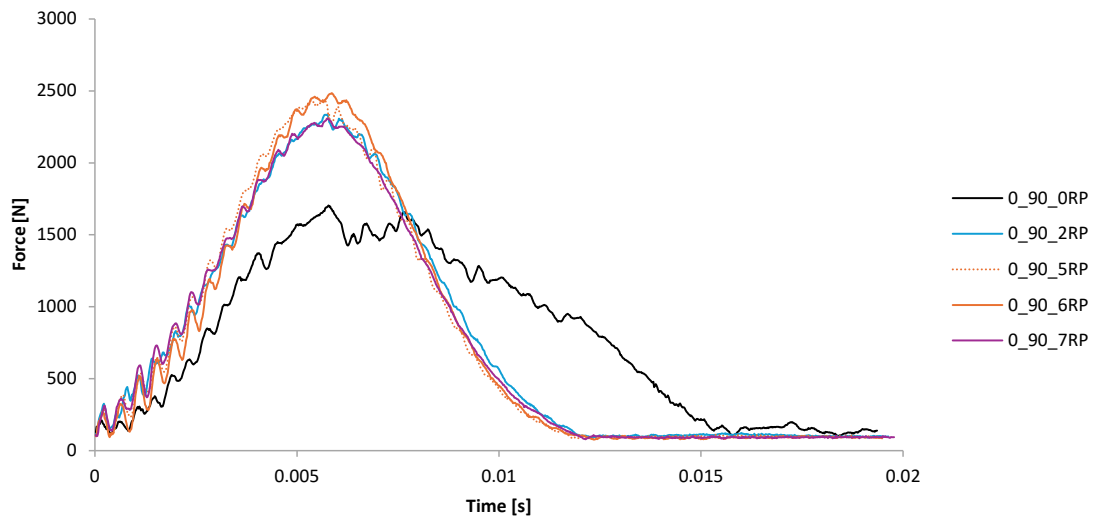


Figure B.1 - Force–time histories obtained for the complete set of main laminate configurations subjected to low-velocity impact testing.

The corresponding energy–time responses are presented in Figure B.2.

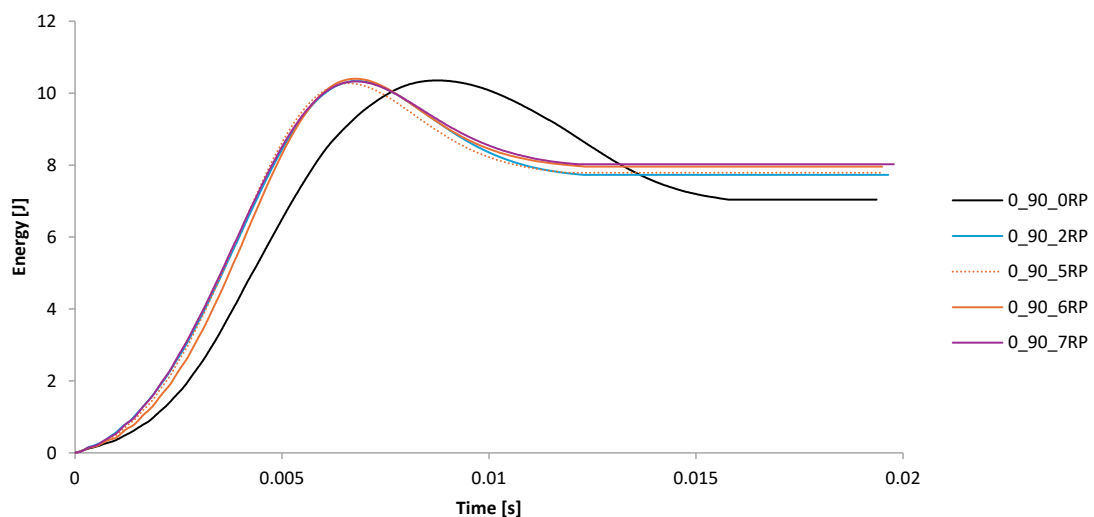


Figure B.2 - Energy–time histories obtained for the complete set of main laminate configurations subjected to low-velocity impact testing.

Figure B.3 presents the force–displacement responses obtained for the complete set of main laminate configurations. The complete responses are shown in Figure B.3(a), while Figure B.3(b) presents the response up to the maximum impact force.

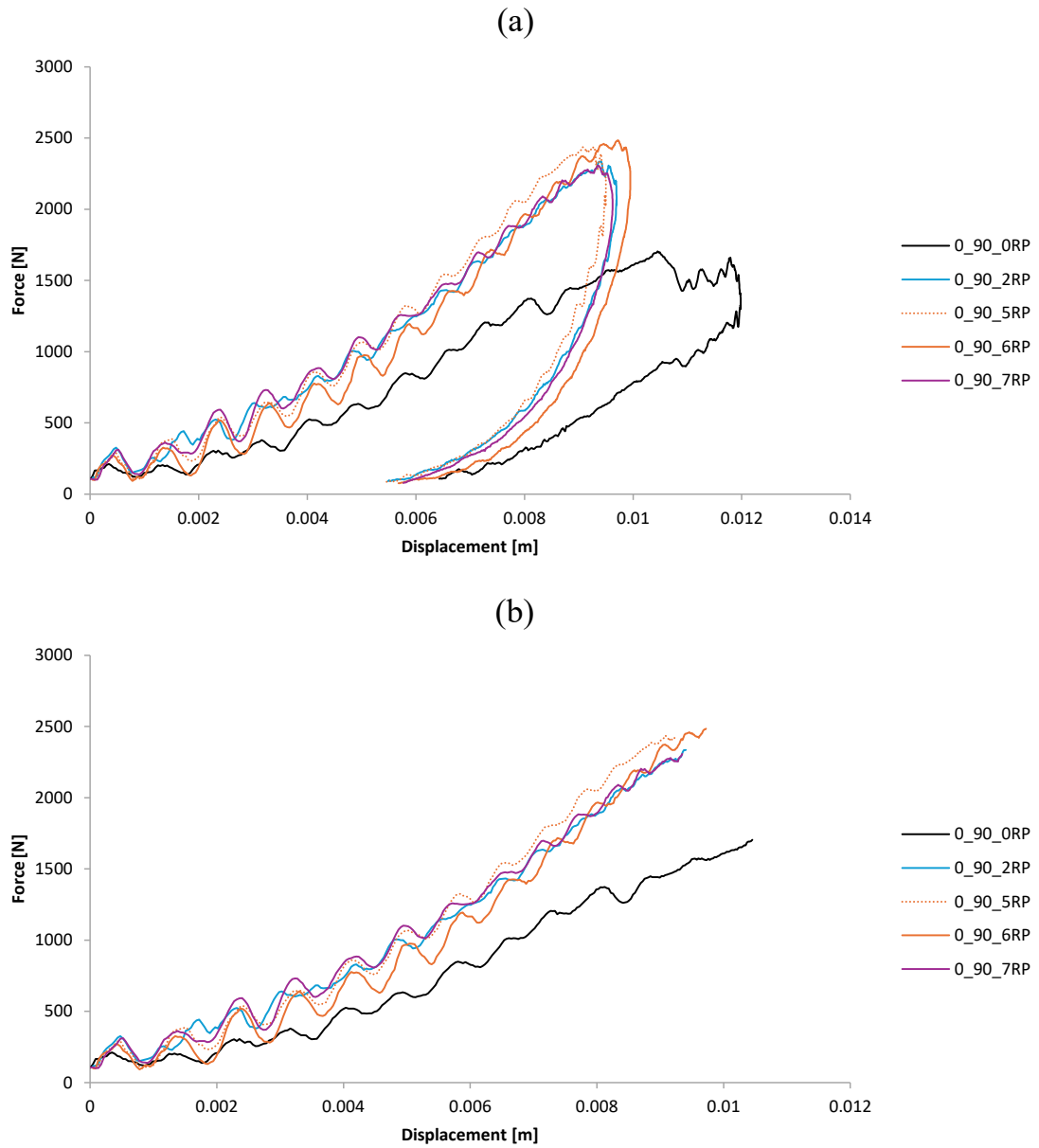


Figure B.3 - Force–displacement response obtained for the complete set of main laminate configurations subjected to low-velocity impact testing: (a) complete force–displacement response; (b) force–displacement response up to the maximum impact force.

Appendix C

This appendix presents the complete set of impact response curves obtained for the laminate configurations used to assess the influence of matrix composition under low-velocity impact loading. These figures complement the representative curves presented in Section 4.1.1.2 and provide the additional experimental responses required for a complete interpretation of the effect of matrix modification on the impact behaviour.

Figure C.1 presents the force–time histories obtained for the complete set of main laminate configurations.

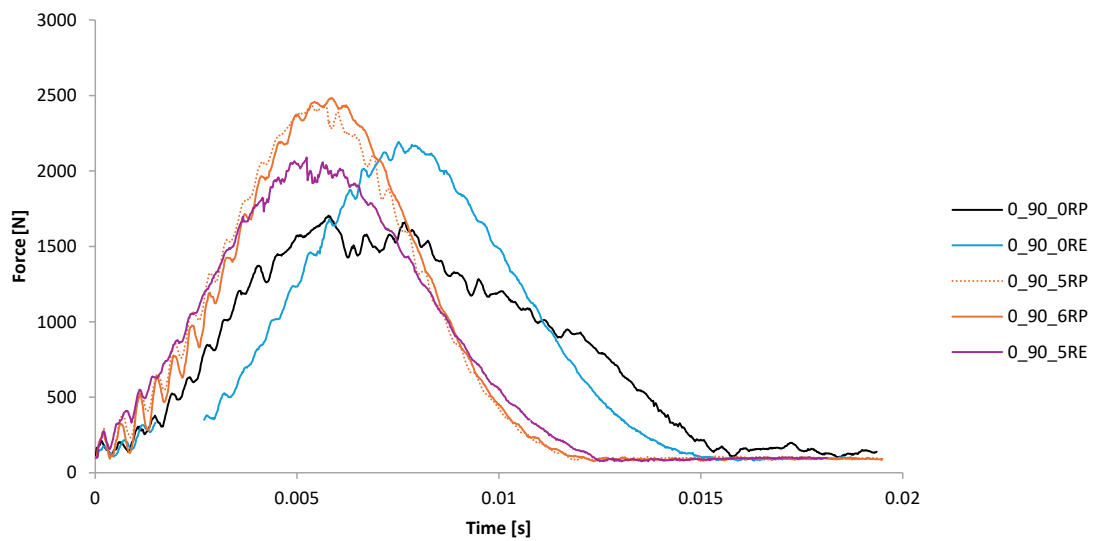


Figure C.1 - Force–time histories obtained for the laminate configurations used to evaluate the influence of matrix composition subjected to low-velocity impact testing.

The corresponding energy–time responses are presented in Figure C.2.

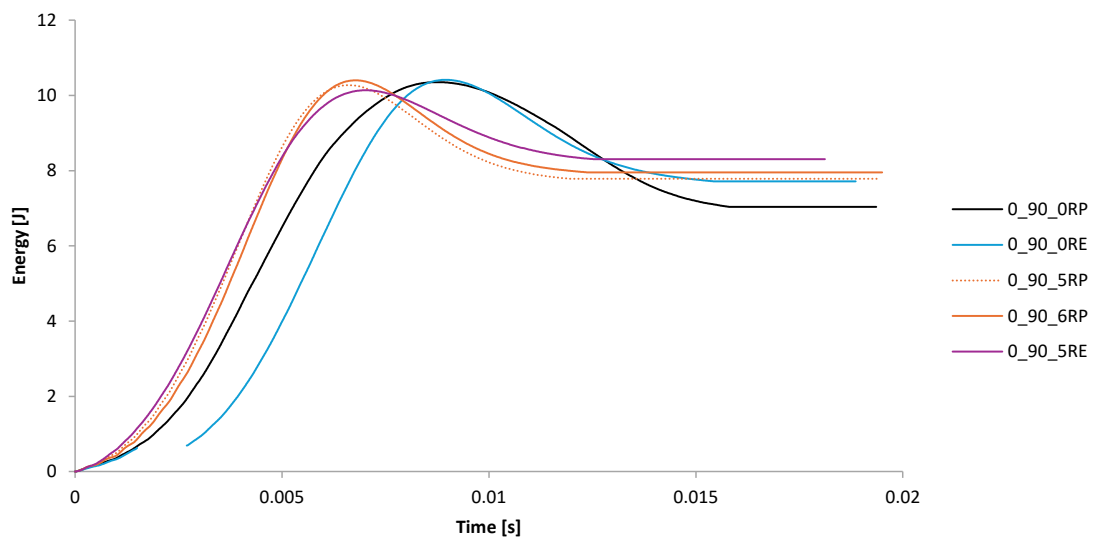


Figure C.2 - Energy–time histories obtained for the laminate configurations used to evaluate the influence of matrix composition subjected to low-velocity impact testing.

Figure C.3 presents the force–displacement responses obtained for the set of laminate configurations used to evaluate the influence of matrix composition. The complete responses are shown in Figure C.3(a), while Figure C.3(b) presents the response up to the maximum impact force.

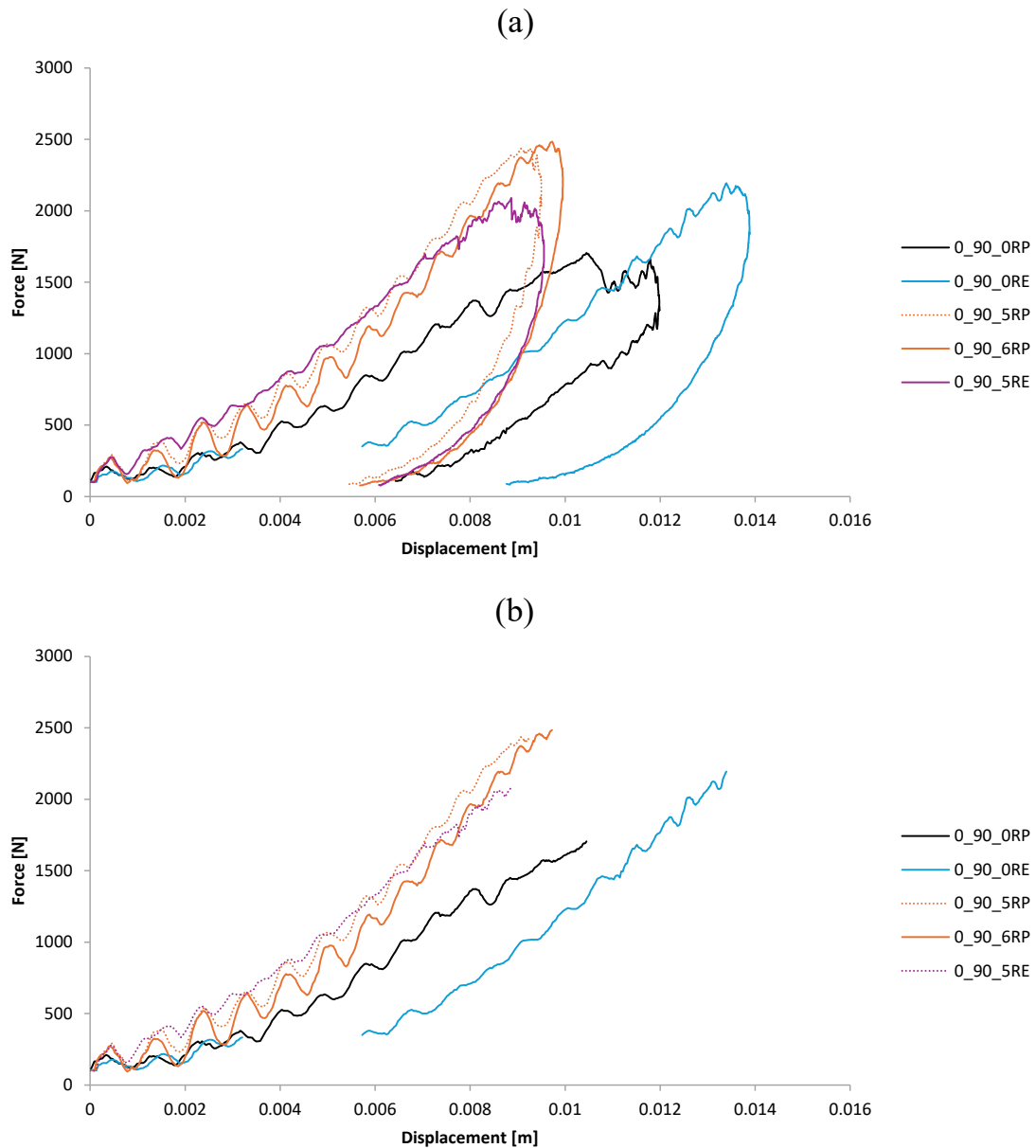


Figure C.3 - Force–displacement response obtained for the laminate configurations used to evaluate the influence of matrix composition subjected to low-velocity impact testing: (a) complete force–displacement response; (b) force–displacement response up to the maximum impact force.

Appendix D

This appendix presents the complete set of impact response curves obtained for the 5 wt.% cork laminate configurations subjected to low-velocity impact testing. These figures include both tests performed for the 5 wt.% cork laminate configuration, namely 0_90_5RP and 0_90_6RP, complementing the representative curves presented in Section 4.1.1.2.

Figure D.1 presents the force–time histories obtained for the 5 wt.% cork laminate configurations used to assess the influence of stacking sequence.

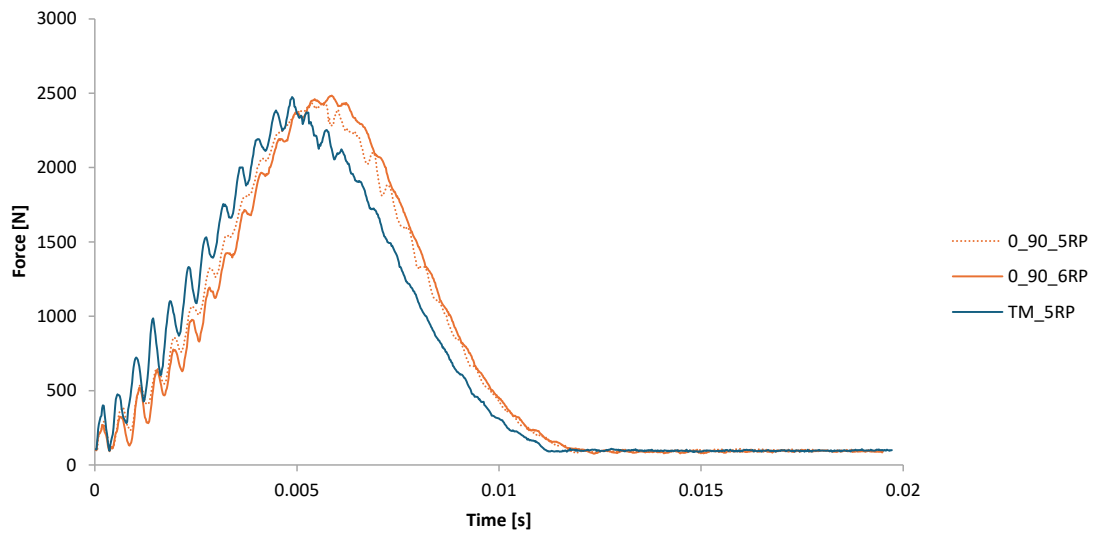


Figure D.1 - Force–time histories obtained for the 5 wt.% cork laminate configurations subjected to low-velocity impact testing.

The corresponding energy–time responses are presented in Figure D.2.

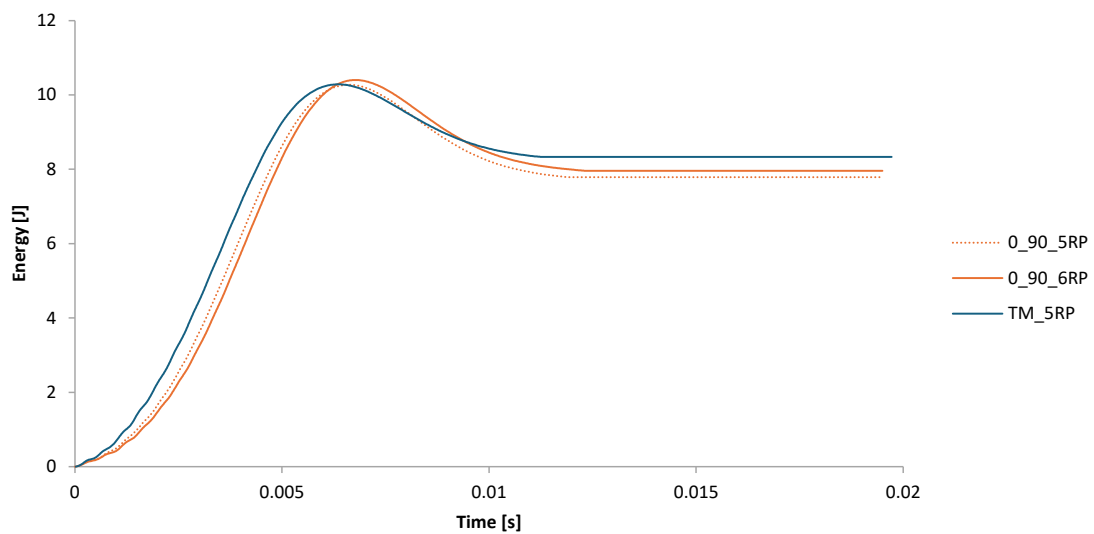


Figure D.2 - Energy–time histories obtained for the 5 wt.% cork laminate configurations subjected to low-velocity impact testing.

Figure D.3 presents the force–displacement responses obtained for the 5 wt.% cork laminate configurations. The complete responses are shown in Figure D.3(a), while Figure D.3(b) presents the response up to the maximum impact force.

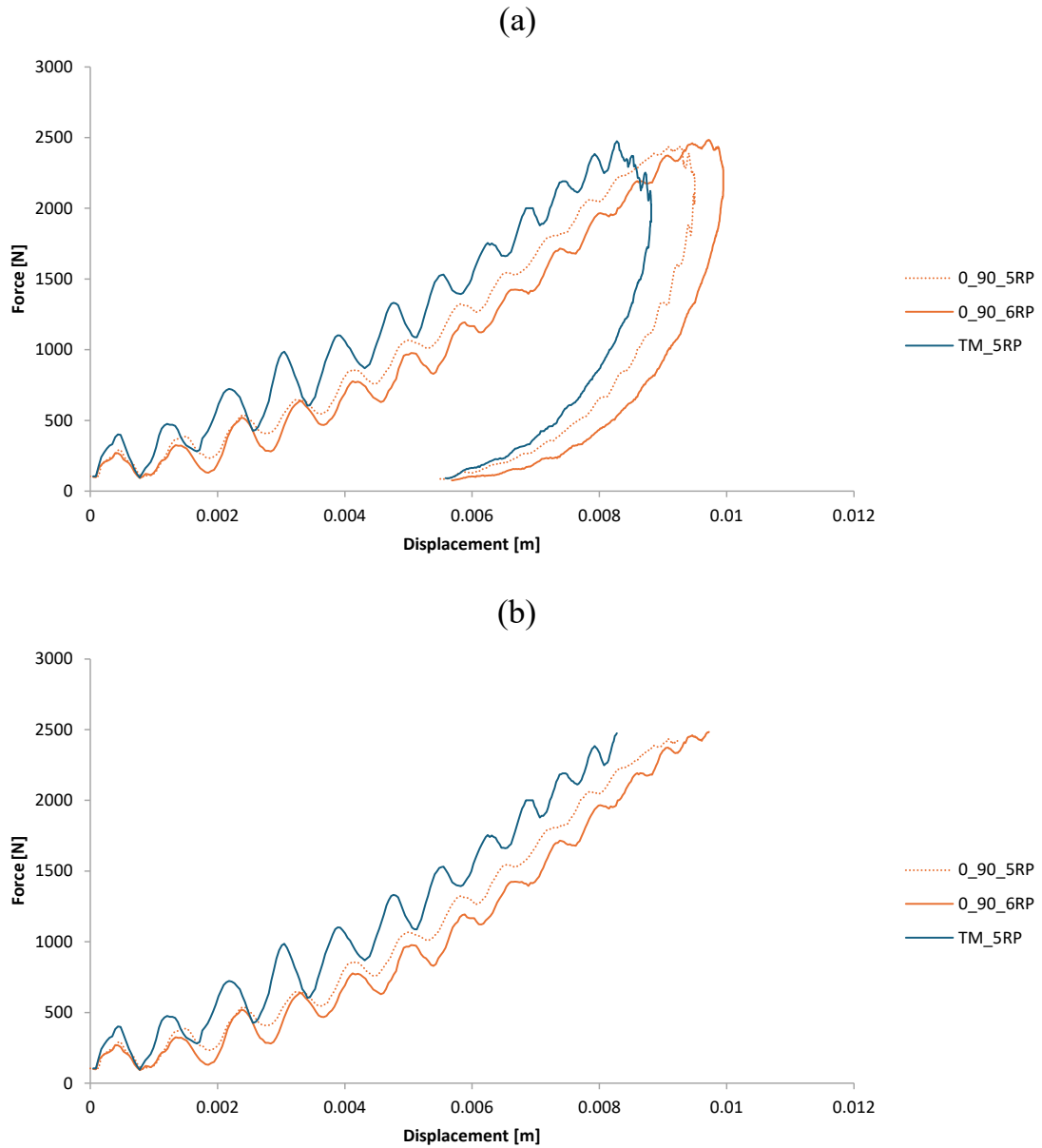


Figure D.3 - Force–displacement response obtained for the 5 wt.% cork laminate configurations subjected to low-velocity impact testing: (a) complete force–displacement response; (b) force–displacement response up to the maximum impact force.

Appendix E

This appendix presents the complete set of impact response curves obtained for the laminate configurations considered in the stacking sequence analysis subjected to low-velocity impact testing. These figures include the responses obtained for 0_90_2RP, 0_90_5RP, 0_90_6RP, 45_3RP, MT_3RP and TM_5RP, complementing the representative curves presented in Section 4.1.1.2.

Figure E.1 presents the force–time histories obtained for the complete set of laminate configurations considered in the stacking sequence analysis.

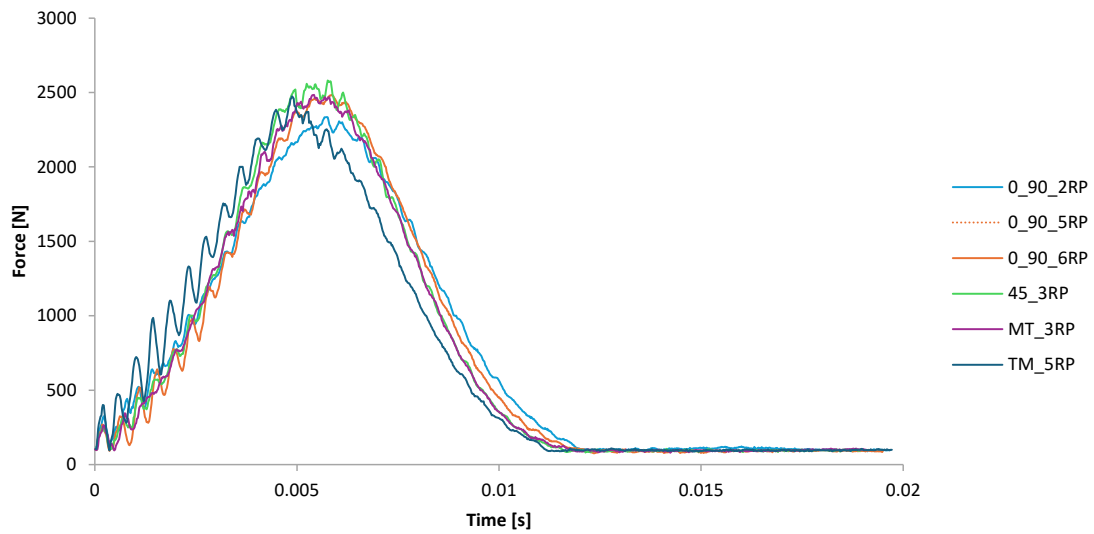


Figure E.1 - Force–time histories obtained for the laminate configurations considered in the stacking sequence analysis subjected to low-velocity impact testing.

The corresponding energy–time responses are presented in Figure E.2.

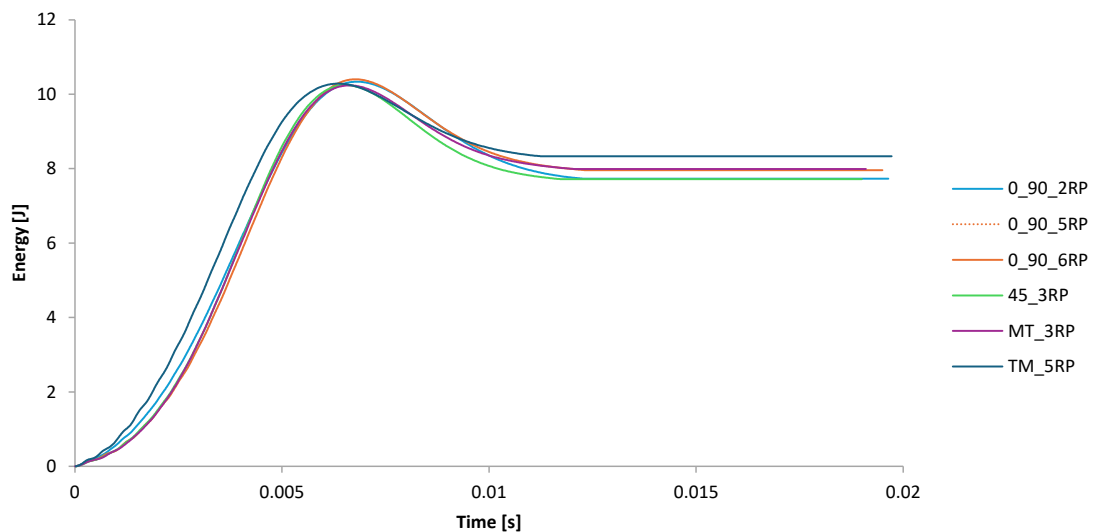


Figure E.2 - Energy–time histories obtained for the laminate configurations considered in the stacking sequence analysis subjected to low-velocity impact testing.

Figure E.3 presents the force–displacement responses obtained for the laminate configurations considered in the stacking sequence analysis. The complete responses are shown in Figure E.3(a), while Figure E.3(b) presents the response up to the maximum impact force.

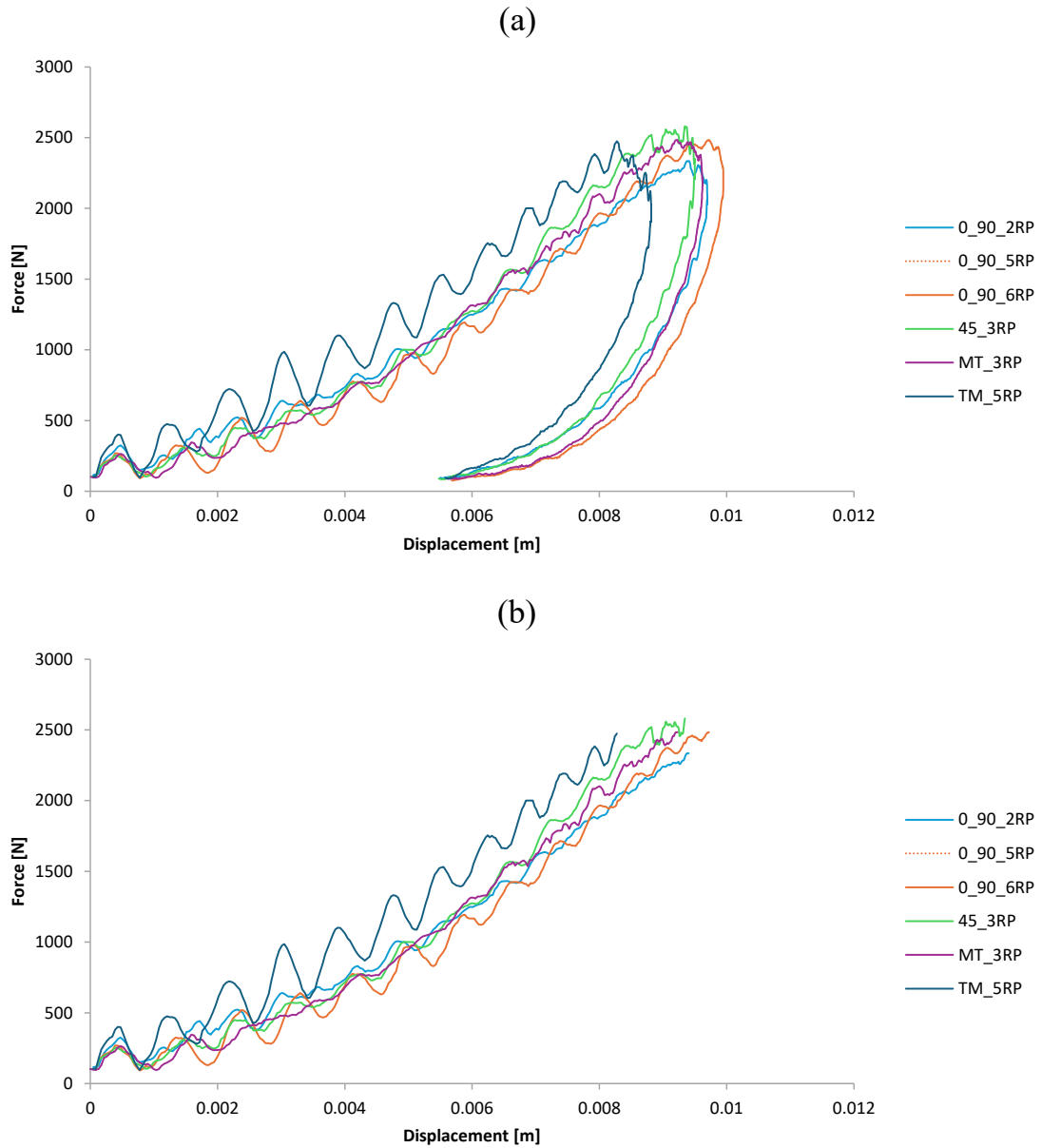


Figure E.3 - Force–displacement response obtained for the laminate configurations considered in the stacking sequence analysis subjected to low-velocity impact testing: (a) complete force–displacement response; (b) force–displacement response up to the maximum impact force.

Appendix F

This appendix presents the complementary radiographic inspection images obtained for the main laminate configurations subjected to low-velocity impact testing. These figures include the additional radiographic results obtained for the 5 wt.% cork laminate configuration, namely 0_90_5RP, complementing the representative radiographic images presented in Section 4.1.2.1.

Figure F.1 presents the radiographic images obtained for the complete set of main laminate configurations following low-velocity impact testing.

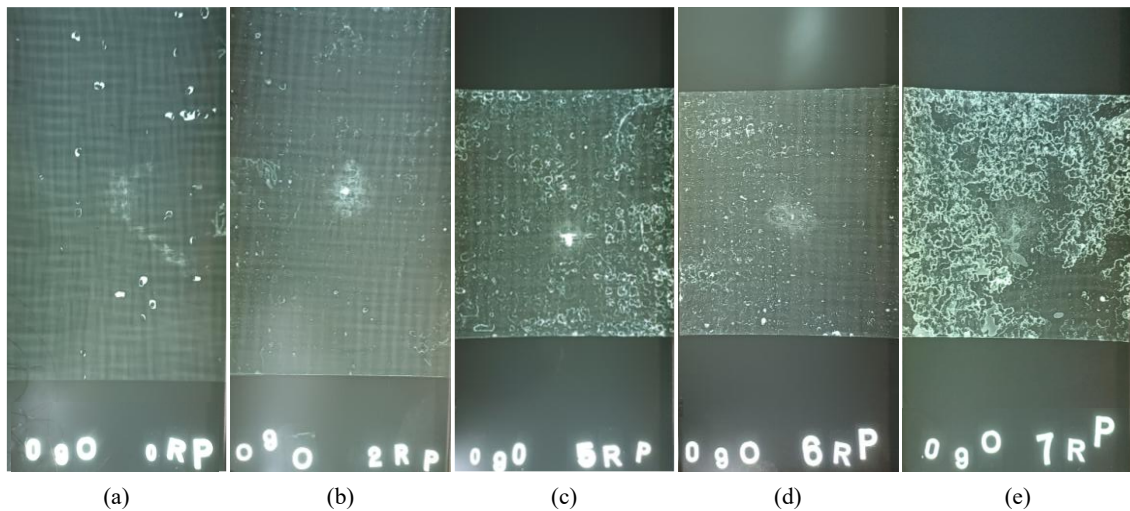


Figure F.1 - Radiographic images of the complete set of main laminate configurations following low-velocity impact testing: (a) 0_90_0RP; (b) 0_90_2RP; (c) 0_90_5RP; (d) 0_90_6RP and (e) 0_90_7RP.

To facilitate the correlation between the visible surface damage and the corresponding internal damage features identified by radiographic inspection, photographs of the impacted specimens and their respective radiographs are presented in Figure F.2.

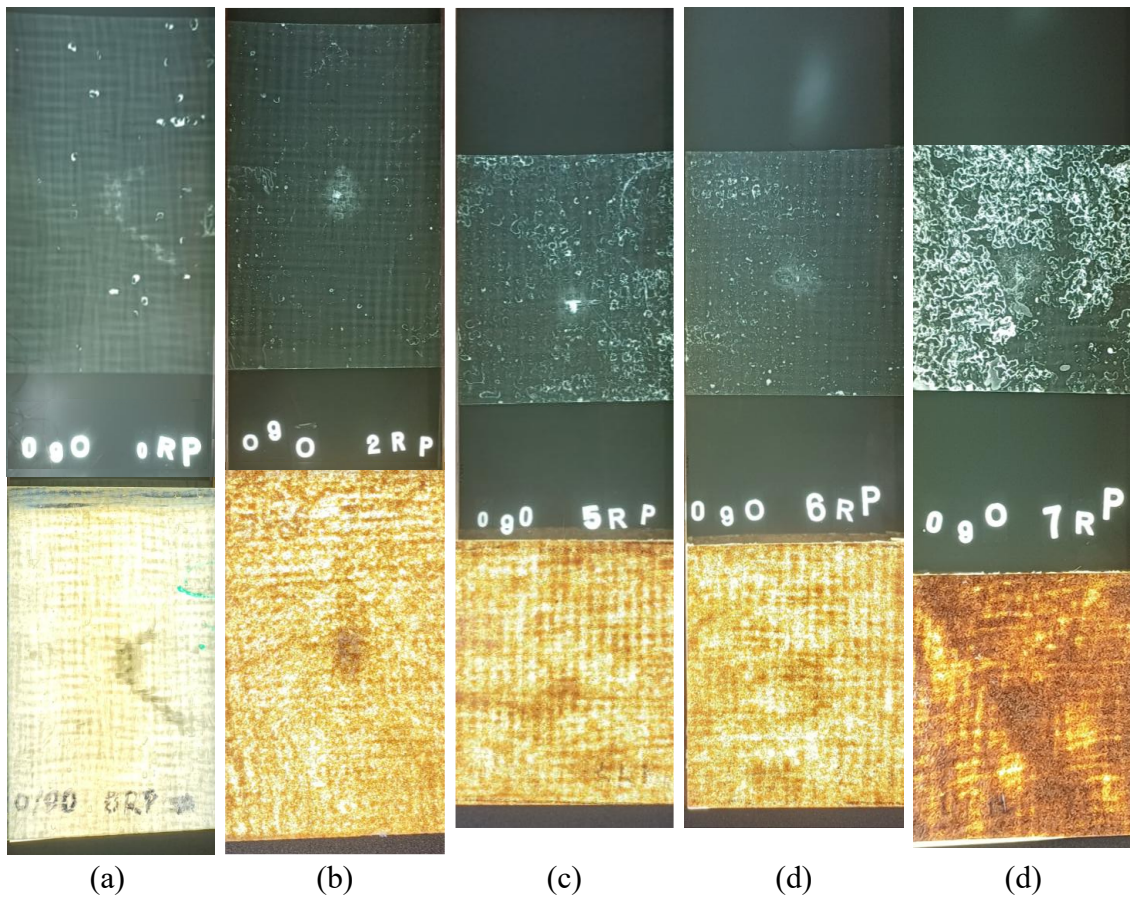


Figure F.2 - Comparison between the radiographic inspection results and the corresponding impacted specimens for the complete set of main laminate configurations: (a) 0_90_ORP; (b) 0_90_2RP; (c) 0_90_5RP; (d) 0_90_6RP; and (e) 0_90_7RP.

Figure F.3 presents the penetrant-enhanced radiographic images with the apparent damage regions delineated, illustrating the regions considered for the quantitative assessment of the complete set of main laminate configurations.

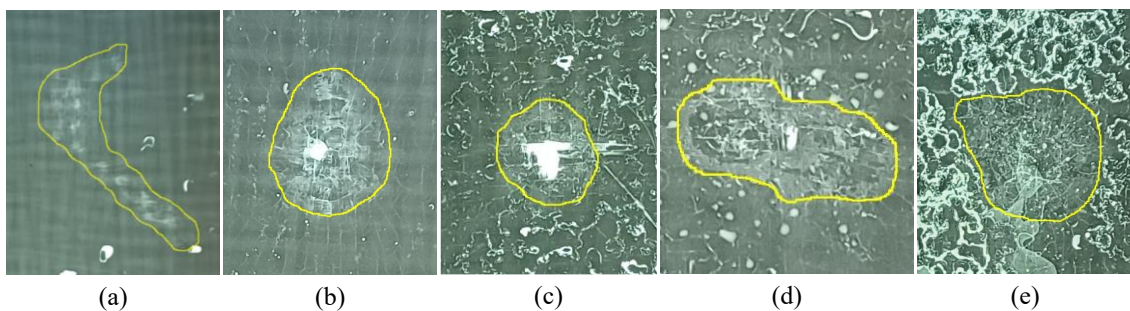


Figure F.3 - Apparent damage regions delineated on the penetrant-enhanced radiographic images of the complete set of main laminate configurations: (a) 0_90_ORP; (b) 0_90_2RP; (c) 0_90_5RP; (d) 0_90_6RP; and (e) 0_90_7RP.

Appendix G

This appendix presents the complete radiographic damage measurement data obtained for the main laminate configurations subjected to low-velocity impact testing, as shown in Table G.1. For each laminate, the maximum damage length, maximum damage width, and apparent damaged area were measured three times using Fiji software. The corresponding mean values and standard deviations were calculated to support the quantitative damage assessment presented in Section 4.1.2.1.

Table G.1 – Dimensions of the radiographically indicated damage regions for the main laminate configurations.

Laminate ID	Parameter	Trial 1	Trial 2	Trial 3	Mean	Std. Dev.
0_90_ORP	Length [mm]	46.37	46.80	46.43	46.53	0.24
	Width [mm]	37.36	37.22	36.21	36.93	0.62
	Area [mm ²]	649.53	624.76	633.17	635.82	12.60
0_90_2RP	Length [mm]	23.44	23.18	23.88	23.50	0.35
	Width [mm]	19.82	18.66	19.84	19.44	0.68
	Area [mm ²]	336.53	342.16	330.14	336.28	6.01
0_90_5RP	Length [mm]	15.32	15.17	15.40	15.29	0.12
	Width [mm]	12.78	12.63	12.86	12.75	0.12
	Area [mm ²]	154.41	149.77	157.18	153.78	3.75
0_90_6RP	Length [mm]	11.48	10.47	10.72	10.89	0.53
	Width [mm]	18.90	18.97	18.75	18.87	0.11
	Area [mm ²]	135.95	138.51	136.77	137.08	1.31
0_90_7RP	Length [mm]	21.11	20.22	20.79	20.71	0.45
	Width [mm]	20.75	21.01	21.01	20.92	0.15
	Area [mm ²]	311.57	307.55	307.26	308.79	2.41

Appendix H

This appendix presents the complete radiographic damage measurement data obtained for the complementary laminate configurations subjected to low-velocity impact testing, as shown in Table H.1. For each laminate, the maximum damage length, maximum damage width, and apparent damaged area were measured three times using Fiji software. The corresponding mean values and standard deviations were calculated to support the quantitative damage assessment presented in Section 4.1.2.2.

Table H.1 – Dimensions of the radiographically indicated damage regions for the complementary laminate configurations.

Laminate ID	Parameter	Trial 1	Trial 2	Trial 3	Mean	Std. Dev.
O_90_0RE	Length [mm]	12.70	13.30	13.15	13.05	0.32
	Width [mm]	6.48	6.65	7.32	6.82	0.44
	Area [mm ²]	70.85	68.36	70.26	69.82	1.30
O_90_5RE	Length [mm]	14.31	14.62	14.41	14.45	0.16
	Width [mm]	9.52	9.84	10.10	9.82	0.29
	Area [mm ²]	123.01	121.31	117.28	120.53	2.94
45_3RP	Length [mm]	23.45	23.06	24.18	23.56	0.57
	Width [mm]	30.45	29.95	30.30	30.23	0.26
	Area [mm ²]	421.02	403.16	407.38	410.52	9.33
MT_3RP	Length [mm]	15.48	15.48	15.00	15.32	0.28
	Width [mm]	13.73	13.86	14.12	13.90	0.20
	Area [mm ²]	166.51	159.78	165.97	164.09	3.74
TM_5RP	Length [mm]	20.26	21.35	20.85	20.82	0.54
	Width [mm]	16.40	17.28	16.99	16.89	0.45
	Area [mm ²]	260.37	266.74	262.63	263.24	3.23

Appendix I

This appendix reports the individual tensile test results obtained for the cork-free and cork-modified laminate configurations and the corresponding width and thickness measurements. For each configuration, two specimens were tested under uniaxial tensile loading, and the corresponding tensile strength, Young's modulus, and strain at failure are presented in Table I.1. These values complement the summary results reported in Section 4.1.3.

Table I.1 – Complete tensile properties obtained for the tested laminate configurations.

Cork content [wt.%]	Test Specimen No.	Tensile strength [MPa]	Young's modulus [GPa]	Strain [%]
0	1	219.2	8.07	3.60
	2	286.7	6.96	4.90
	Mean	252.95	7.51	4.25
	Std. Dev	47.73	0.78	0.92
5	1	108.7	3.19	4.90
	2	100.5	2.98	5.00
	Mean	104.60	3.08	4.95
	Std. Dev	5.80	0.15	0.07

Table I.2 provides the width and thickness measurements of the specimens considered in the tensile analysis.

Table I.2 – Width and thickness measurements of the tensile specimens considered in the analysis.

Cork content [wt.%]	Test Specimen No.	Width [mm]	Thickness [mm]
0	1	18.18	1.53
	2	17.33	1.51
5	1	17.25	3.45
	2	17.83	3.42

Appendix J

This appendix presents the complete set of individual impact parameters obtained for the main laminate configurations as a function of cork particle content. These figures include both tests performed for the 5 wt.% cork laminate configuration, namely 0_90_5RP and 0_90_6RP, complementing the representative plots presented in Section 4.2.1.

Figure J.1 presents the maximum impact force obtained for the complete set of main laminate configurations.

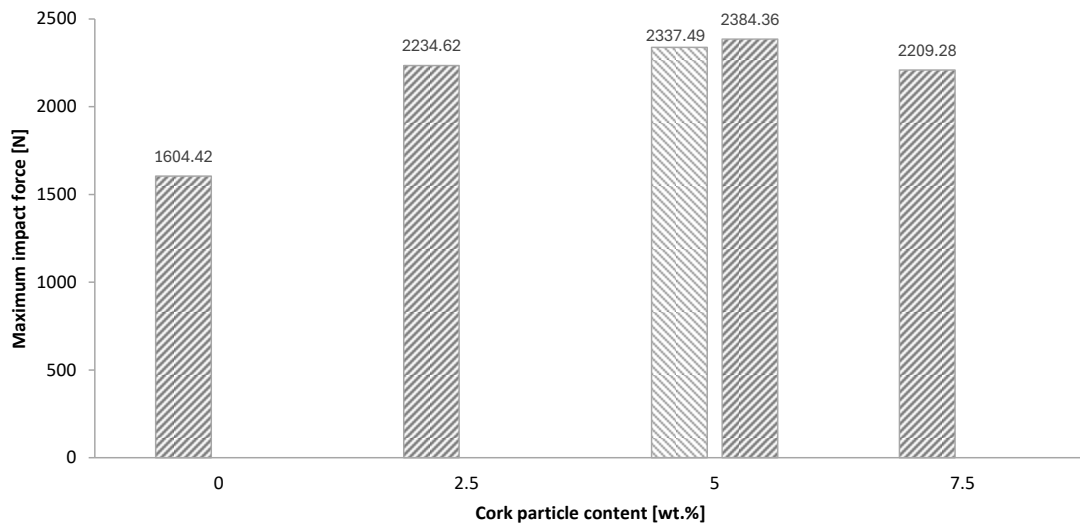


Figure J.1 - Maximum impact force as a function of cork particle content for the complete set of main laminate configurations, including both 5 wt.% cork specimens.

The corresponding maximum displacement values are presented in Figure J.2. These results complement the representative displacement trend discussed in Section 4.2.1.

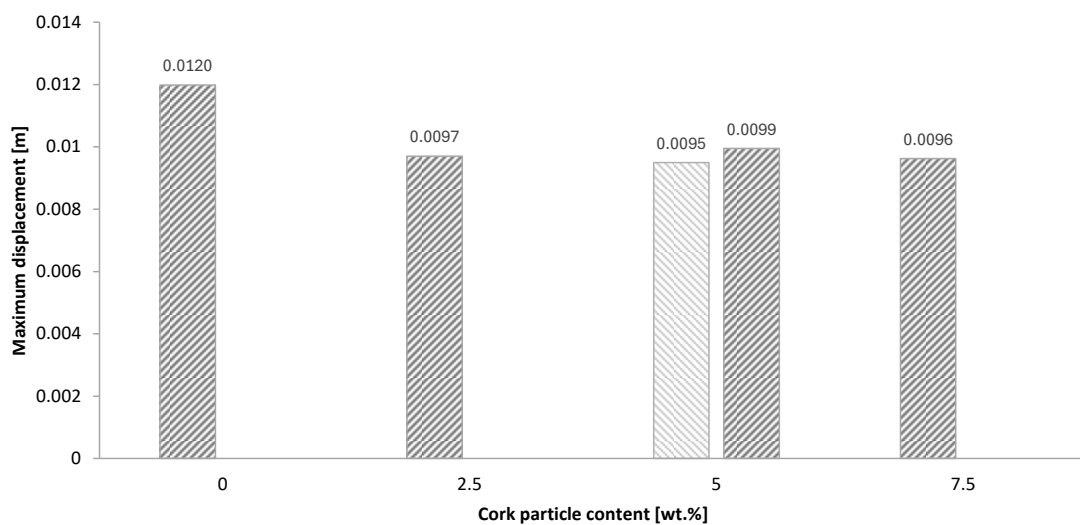


Figure J.2 - Maximum displacement as a function of cork particle content for the complete set of main laminate configurations, including both 5 wt.% cork specimens.

Appendix K

This appendix presents the complete set of radiographic damage-related results obtained for the main laminate configurations subjected to low-velocity impact testing. These figures include both specimens corresponding to the 5 wt.% cork configuration, namely 0_90_5RP and 0_90_6RP, complementing the analysis presented in Section 4.2.2.

Figure K.1 presents the apparent radiographic damage area measured for the complete set of main laminate configurations as a function of cork particle content.

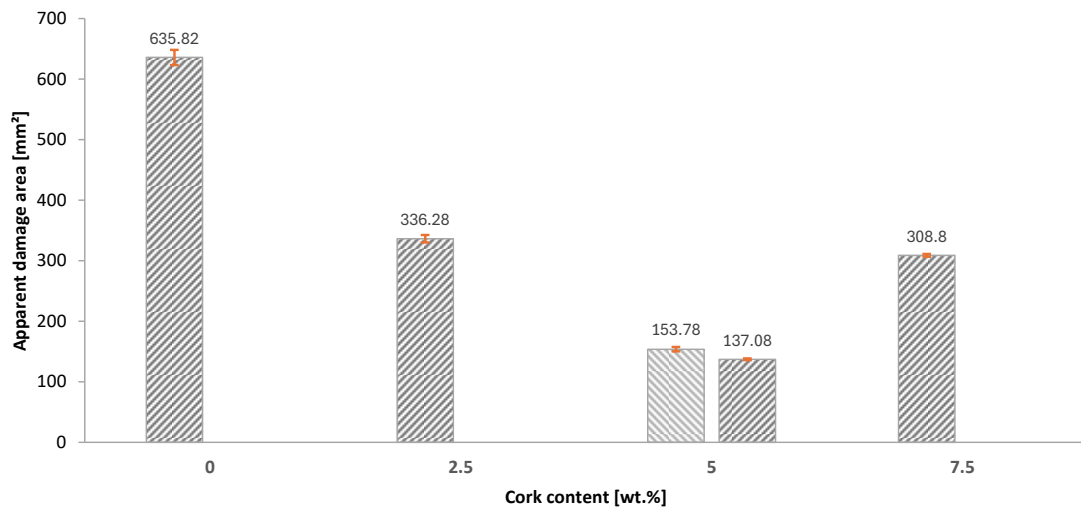


Figure K.1 – Apparent radiographic damage area as a function of cork particle content for the complete set of main laminate configurations.

The relationship between maximum impact force and apparent radiographic damage area for the same set of laminates is presented in Figure K.2. This representation complements the discussion in Section 4.2.2 by allowing the two 5 wt.% cork specimens to be directly compared with the remaining main laminate configurations.

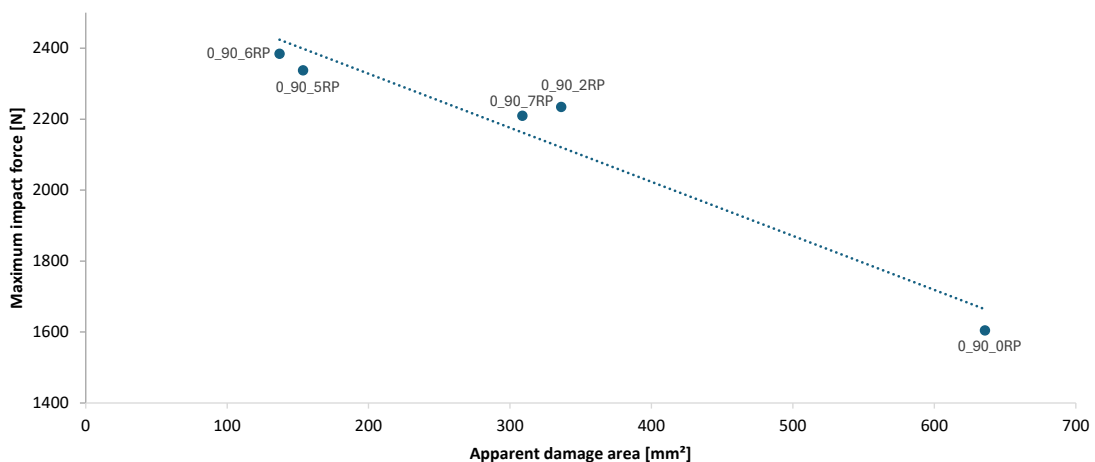


Figure K.2 – Relationship between maximum impact force and apparent radiographic damage area for the complete set of main laminate configurations, including both 5 wt.% cork specimens.

Appendix L

This appendix presents the complete comparative plots used to support the analysis of the influence of matrix system and reinforcement architecture on the impact response and apparent radiographic damage area of the tested laminate configurations, complementing the plots presented in Section 4.2.3.

Figure L.1 presents the comparison between the polyester- and epoxy-based 0/90 laminate configurations. The maximum impact force is shown in Figure L.1(a), while the corresponding apparent radiographic damage area is presented in Figure L.1(b).

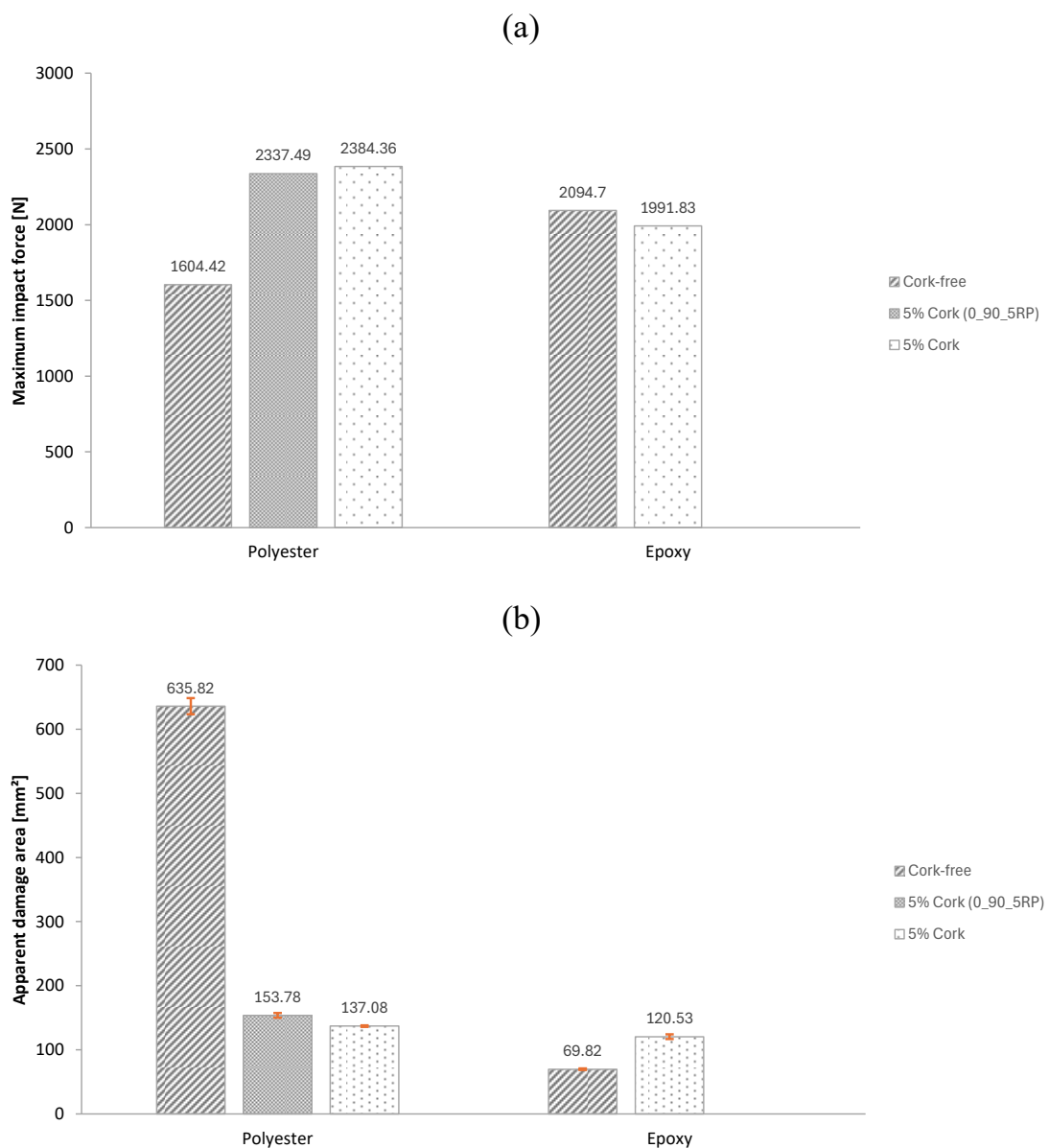


Figure L.1 – Effect of matrix system on the response of the complete set of selected 0/90 laminate configurations: (a) maximum impact force; (b) apparent radiographic damage area.

Figure L.2 presents the comparison between the selected polyester-based laminate configurations used to assess the influence of fibre orientation and reinforcement architecture. The maximum impact force is shown in Figure L.2(a), while the corresponding apparent radiographic damage area is presented in Figure L.2(b).

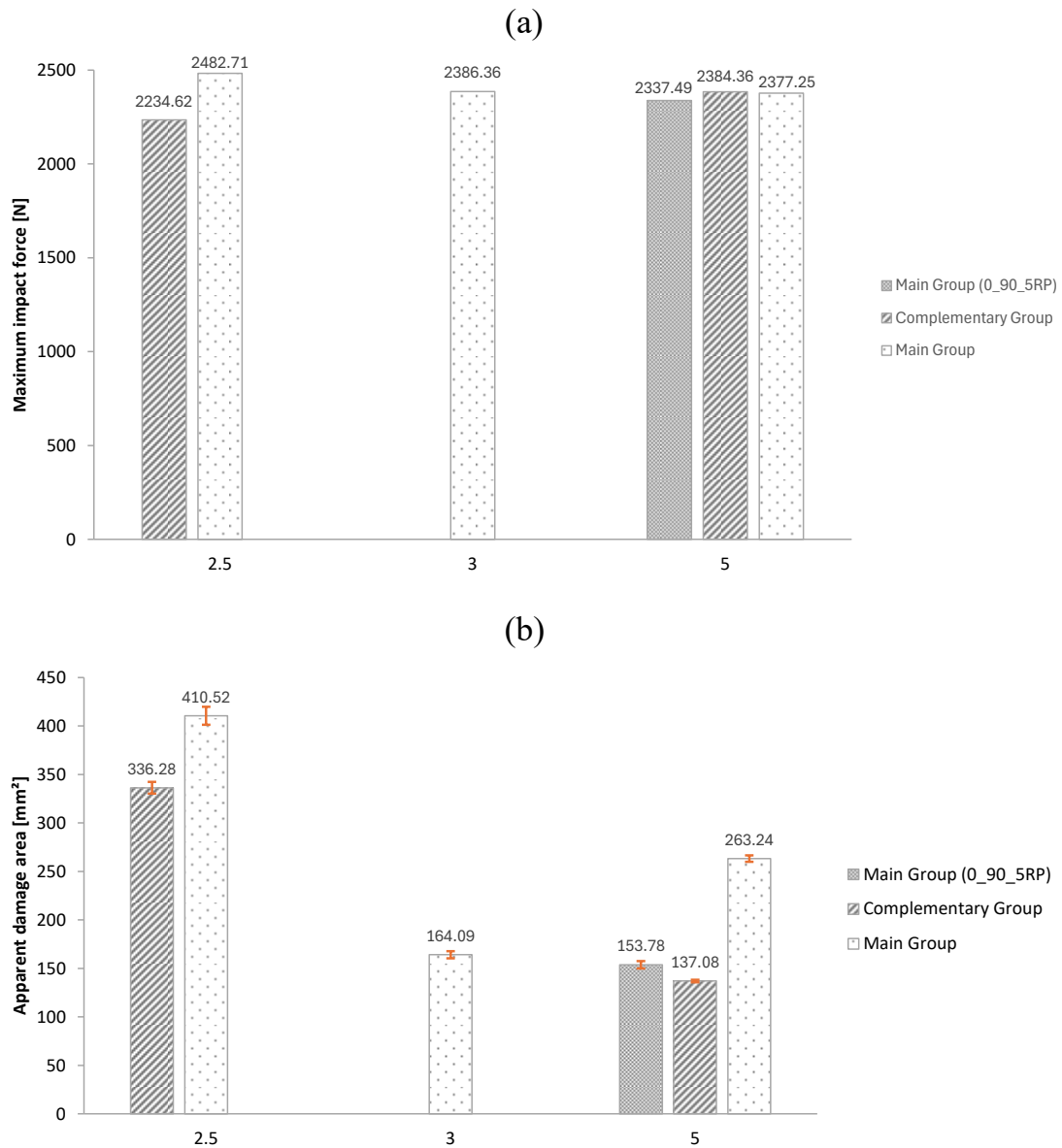


Figure L.2 – Effect of fibre orientation and reinforcement architecture on selected polyester-based laminate configurations: (a) maximum impact force; (b) apparent radiographic damage area.