

Master in Mechanical Engineering

Evaluating the performance of a novel hot-melt film adhesive in preventing delamination of CFRP and wood joints

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United Nations Sustainable Development Goals

Adopted in 2015 by all United Nations Member States, the 2030 Agenda for Sustainable Development defines 17 Sustainable Development Goals (SDGs) as a global call to action for prosperity, equality, and environmental protection. These goals aim to tackle urgent challenges such as climate change, resource depletion, and sustainable industrialization through international cooperation and innovation.

The present dissertation, dedicated to evaluating the performance of a novel thermoplastic film adhesive in CFRP and wood joints, directly contributes to several of these goals. By promoting lightweight, recyclable, and energy-absorbing adhesive solutions, this work supports the transition toward sustainable materials and engineering practices. In particular, it aligns with the following SDGs:

- SDG 9 – Industry, innovation and infrastructure
- SDG 11 – Sustainable cities and communities
- SDG 12 – Responsible consumption and production
- SDG 13 – Climate action

SDG	Target	Contribution of the dissertation	Performance indicators
9	9.4; 9.5	Development of an innovative thermoplastic adhesive for multi-material joints; use of finite element modeling to reduce physical testing and optimize design.	Peer-reviewed publications and conference presentations; number of research collaborations; validated FEM models demonstrating industrial applicability.
11	11.3; 11.6	Supports sustainable construction by enabling the use of natural substrates (wood) and recyclable adhesives.	Number of hybrid joint configurations tested; compatibility with sustainable building and eco-design practices.
12	12.2; 12.5	Promotes material efficiency and circularity through recyclable thermoplastic adhesives; enables disassembly, repair, and reuse of bonded joints.	Percentage of recyclable materials used; potential for reuse and repair in tested joints.
13	13.1; 13.2	Contributes to emission reduction by enabling lightweight structural solutions with improved energy absorption; demonstrates performance under extreme temperature conditions.	Weight reduction compared to conventional adhesives; CO ₂ -equivalent emissions avoided per application; performance metrics under low and high service temperatures.

Resumo

Esta dissertação investiga o desempenho de um novo adesivo termoplástico em filme, à base de olefina cíclica, do tipo hot-melt (HMA), na mitigação da delaminação em juntas de sobreposição simples (SLJs) fabricadas com polímeros reforçados com fibra de carbono (CFRPs) e substratos de madeira (pinheiro e carvalho). A delaminação constitui um modo de falha crítico em juntas adesivas, especialmente em SLJs, que estão tipicamente sujeitas a tensões de arrancamento sob condições reais de carregamento e que comprometem a integridade estrutural de materiais leves e anisotrópicos, como os CFRPs e a madeira. O estudo combina ensaios experimentais em condições quase-estáticas e de impacto a baixa velocidade com modelação por elementos finitos para capturar concentrações e propagação de tensões. Para as juntas em CFRP, o HMA foi comparado com adesivos epóxicos estruturais em três temperaturas de serviço ($-30\text{ }^{\circ}\text{C}$, temperatura ambiente e $80\text{ }^{\circ}\text{C}$). Os resultados demonstraram uma acentuada sensibilidade à taxa de deformação, com um desempenho notável sob impacto a temperaturas negativas - superando os epóxicos estruturais - ao mesmo tempo que manteve um modo de falha adesiva, preservando os substratos e facilitando a reparação. Por outro lado, a temperaturas elevadas o adesivo revelou-se inadequado devido à sua baixa temperatura de transição vítrea. Para as juntas em madeira, foram estudadas três configurações: referência, reforçada e híbrida. Sob carregamento quase-estático todas as juntas falharam por modo adesivo, resultando em resistências comparáveis. Sob impacto, contudo, todas as juntas falharam por delaminação na madeira, sendo que as configurações híbridas (combinações pinho-carvalho) apresentaram aumentos substanciais de até 84% na carga de falha em comparação com as juntas de referência, ganhos atribuídos a uma melhor redistribuição das tensões e ao atraso na delaminação, confirmado por simulações numéricas. De forma geral, os resultados revelam que este novo adesivo termoplástico em filme, à base de olefina cíclica, oferece uma solução leve, reciclável e com elevada capacidade de absorção de energia para juntas adesivas. Embora a sua aplicabilidade seja limitada em temperaturas elevadas, apresenta claras vantagens em aplicações com CFRP a baixas temperaturas e em estruturas híbridas de madeira sujeitas a carregamentos dinâmicos, contribuindo para o desenvolvimento de juntas adesivas mais resilientes e sustentáveis.

Palavras chave: Juntas adesivas; Compósitos CFRP; Madeira; Delaminação; Adesivo termofusível; Sustentabilidade.

Abstract

This thesis investigates the performance of a novel cyclic olefin-based thermoplastic film hot-melt adhesive (HMA) in mitigating delamination in single-lap joints (SLJs) fabricated from carbon fiber reinforced polymers (CFRPs) and wood substrates (pine and oak). Delamination is a critical failure mode in adhesively bonded joints, especially in SLJs, which are typically subjected to peel stresses under real loading conditions and which compromise the structural integrity of lightweight and anisotropic materials such as CFRPs and wood. The study combines experimental testing under quasi-static and low-velocity impact conditions with finite element modeling to capture stress concentrations and propagation. For CFRP joints, the HMA was benchmarked against structural epoxies across three service temperatures ($-30\text{ }^{\circ}\text{C}$, room temperature, and $80\text{ }^{\circ}\text{C}$). Results demonstrated a pronounced strain-rate sensitivity, with outstanding impact performance at sub-zero temperatures - surpassing structural epoxies - while maintaining an adhesive failure mode that preserves the adherends and facilitates repair. Conversely, at elevated temperature the adhesive was unsuitable due to its low glass transition temperature. For wood joints, three configurations were studied: reference, toughened, and hybrid. Under quasi-static loading all joints failed adhesively, leading to comparable strengths. Under impact, however, all joints failed by delamination in the wood, with the hybrid layups (pine–oak combinations) showing substantial gains of up to 84% in failure load compared to reference joints, attributed to improved stress redistribution and delayed delamination confirmed by numerical simulations. Overall, the findings reveal that this new cyclic olefin-based thermoplastic film offers a lightweight, recyclable, and energy-absorbing solution for bonded joints. While their applicability is limited at high temperature, they present clear advantages in low-temperature CFRP applications and in hybrid wood assemblies under dynamic loading, contributing to more resilient and sustainable adhesive joint design.

Keywords: Adhesive joints; CFRP composites; Wood; Delamination; Hot-melt adhesive; Sustainability

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Nomenclature

Acronyms

ASTM - American Society for Testing and Materials

CFRP - Carbon fiber reinforced plastic/polymer

CML - Composite Metal Laminate

CZE - Cohesive zone elements

CZM - Cohesive zone model

DIC - Digital image correlation

FEA - Finite element analysis

FEM - Finite elements method

FRP - Fiber reinforced polymer/plastic

HMA - Hot-melt adhesive

MAJ - Mixed adhesive joint

MMA - Multi-material adhesive

O-P-O - Oak-pine-oak

P-O-P - Pine-oak-pine

P- δ - Load-Displacement

R-Curve - Crack growth resistance curve

SLJ - Single lap joint

THM - Thermo-hydro-mechanical

UAS - Unmanned aerial systems

WFP - Wood failure percentage

Symbols

a - Crack length

a_{eq} - Equivalent crack length

δ - Displacement

E - Young's Modulus

E_f - Corrected bending modulus

G - Shear Modulus

G_{IC} - Fracture energy in mode I

G_{IIC} - Fracture energy in mode II

P – Load

T_g – Glass transition temperature

τ - Shear strength

γ – Shear strain

ν - Poisson's ratio

t_n^0 - Cohesive normal strength

t_s^0 - Cohesive shear strength

σ_y - Yield strength

σ_f - Ultimate strength

ε – Strain

1. Introduction

1.1. Background and motivation

Over the last several decades, the field of structural engineering has undergone a paradigm shift, with a growing emphasis on the use of high-performance, lightweight, and sustainable materials. This transition is largely driven by evolving demands in the aerospace, automotive, and transportation industries, where weight reduction, energy efficiency, and sustainability are becoming central design objectives. Within this context, carbon fiber reinforced polymers (CFRPs) have garnered significant attention due to their superior strength-to-weight ratio, high stiffness, corrosion resistance, and fatigue performance. These properties make CFRPs especially valuable for components subjected to demanding mechanical loads and environmental conditions [1], [2].

A notable example of the application of CFRP in the automotive industry is the BMW i3. This electric vehicle was the first mass-produced car to feature a passenger cell made entirely of CFRP, known as the "Life Module", Figure 1. This innovative design significantly reduced the vehicle's weight, enhancing both performance and energy efficiency. [3]



Figure 1: BMW i3 Life Module [3]

Simultaneously, increasing global attention to climate change and environmental impact has triggered a reassessment of traditional materials and production methods. In response, natural materials such as wood are experiencing a resurgence in interest - not merely for aesthetic or cost reasons but as part of a strategic movement toward bio-based and eco-friendly engineering solutions. Wood is a renewable, biodegradable, and widely available resource, and recent advancements in wood densification and bio-based adhesives have significantly improved its mechanical performance, positioning it as a viable candidate for structural applications that were traditionally dominated by metals or synthetic composites [4], [5].

One example of the increasing use of wood in modern construction is the Stockholm Wood City project, Figure 2, in Sweden. This ambitious development aims to create the world's largest urban area built entirely from timber, utilizing engineered wood products like cross-laminated timber (CLT) and glued laminated timber (glulam). The project encompasses residential, commercial, and public spaces, demonstrating the versatility and sustainability of wood in large-scale urban development [6].



Figure 2: Stockholm Wood City project in development [6]

The convergence of these two materials - CFRP and wood - represents a unique and challenging opportunity in modern adhesive joint design. While CFRP offers advanced mechanical performance, wood offers ecological sustainability and economic advantages. However, the fundamental differences in their mechanical behavior, such as anisotropy, thermal expansion, and surface characteristics, pose significant challenges in terms of adhesive bonding and joint performance.

Recently, adhesive bonding has become an indispensable joining technique in modern engineering, offering a wide array of benefits over traditional fastening methods. These include the ability to join dissimilar materials, the elimination of stress concentrations induced by mechanical fasteners, and the potential for more uniform load transfer across the bonded area. Additionally, adhesive joints help maintain the integrity of lightweight substrates by avoiding drilling, welding, or thermal treatments, which can compromise their structural properties [7], [8].

However, the mechanical performance of adhesively bonded joints is still limited by several factors, particularly when applied to composite or natural materials. The through-thickness properties of CFRPs and wood, especially in the out-of-plane direction, are relatively poor. This makes them vulnerable to delamination, peel stresses, and low impact resistance, especially in Single Lap Joint (SLJ) configurations, where eccentric load paths introduce bending moments that exacerbate stress concentrations at the bond edges [8].

To overcome these challenges in CFRP substrates, mainly to try to avoid delamination, researchers have explored various reinforcement techniques aimed at improving joint strength, energy absorption, and failure predictability. One prominent approach is the use of Fiber Metal Laminates (FMLs), which are hybrid materials composed of alternating layers of metals (typically aluminum) and fiber-reinforced composites. Studies have implemented composite metal laminate (CML) reinforcements at the adherend level, reinforcing only the outermost surface of the substrate to reduce peel stresses and delay delamination. Similarly, adhesive layer reinforcement (ALR) techniques involve the inclusion of additional adhesive plies or gradients to improve through-thickness strength and to mitigate stress concentrations at critical regions of the joint. These techniques have shown promising results under both quasi-static and dynamic loading conditions, significantly increasing failure loads and improving the overall toughness of the joints [9], [10].

In the realm of eco-friendly engineering, the integration of cork-based layers as interfacial reinforcements in wood joints has shown great potential. Cork is a naturally compressible and resilient material that can absorb energy, reduce stress gradients, and introduce a degree of ductility in otherwise brittle bonding configurations. These bio-based reinforcements also align with sustainability goals, reducing the environmental impact of bonded structures while enhancing mechanical reliability[11].

The objective of this thesis is to investigate methods capable of minimizing or eliminating delamination - a critical issue that undermines the full potential of adhesively bonded joints in wood and composite materials by causing premature joint failure. While several existing techniques, such as z-pinning, complex joint geometries and alternative reinforcement strategies, have been developed to mitigate this problem, the present study will focus specifically on exploring the effectiveness of the use of a non-structural thermoplastic, that stands out in the field of energy absorption, as the adhesive [12].

By combining the structural performance of CFRPs with the ecological benefits of wood, and enhancing them with proven reinforcement techniques, this thesis aims to bridge the gap between performance and sustainability in adhesive joint design, aligning with the global trend in sustainable engineering and supporting the development of environmentally responsible manufacturing practices. The work is expected to provide valuable insights into material compatibility, joint mechanics, and the design of hybrid solutions for next-generation structures.

1.2. Objectives and methodology

The main objective of this thesis is to try to avoid delamination in CFRP and wooden SLJs by using a non-structural hot-melt adhesive, and testing them under quasi-static and impact conditions.

In order to achieve these objectives, the presented research methodology was followed:

- An extensive literature review addressing the latest developments in hot-melt adhesive technology;

- Creation of numerical models to simulate quasi-static and impact behavior in various configurations of wooden single lap joints;
- Fabrication and experimental testing of these joints to validate the models and analyze their response under static and impact conditions.

1.3. Thesis outline

This thesis is structured into the following key sections:

- Introduction: Presents the motivation behind the research, outlines the main objectives, and describes the methodology followed throughout the study.
- Literature review: Provides an overview of the current knowledge on adhesive bonding technologies, delamination mitigation strategies, common failure modes, effects of temperature in adhesive joints and relevant loading conditions - forming the theoretical foundation of the project.
- Experimental methods: Details the experimental setup, procedures, and equipment used to carry out the tests.
- Summary of included papers: Highlights the main aims and key findings of each research paper included in the thesis.
- Conclusions: Summarizes the overall findings of the work and proposes directions for future research.
- Appended research papers: Paper A - “Comparative study of CFRP single-lap joints bonded with structural epoxies and a novel hot-melt film adhesive: effects of temperature and loading rates”; Paper B - “Strengthening the substrates of wooden single lap joints using a film adhesive to avoid delamination”.

2. Literature Review

2.1. Adhesive bonding

Adhesive bonding is a joining technique wherein an adhesive substance is applied between two substrates, and upon curing - a chemical or physical process - the adhesive solidifies to form a bond that holds the substrates together. This method is widely used across various industries due to its ability to join dissimilar materials and distribute loads uniformly [13]. Adhesive bonding offers several benefits over traditional mechanical fastening and welding techniques. This is due to the fact that adhesives can distribute loads evenly across the bonded area, reducing stress concentrations and improving fatigue performance, have a very reduced overall weight, and can preserve the integrity of the substrates, unlike mechanical fastening or welding [13], [14]. Also, adhesives are a very good option when it comes to joining dissimilar materials including metals, plastics, composites, and ceramics, which may be challenging to join using other methods. Certain adhesives can even enhance the acoustic and vibrational performance of structures, because they possess inherent damping properties [13], [14].

Understanding the mechanisms by which adhesives bond to substrates is crucial for optimizing joint performance. Four classical theories have been proposed to explain adhesion. The mechanical interlocking theory, the adsorption theory, the electrostatic theory and the diffusion theory. All of these try to clarify what forces are involved in the bond that resists separation and distributes load [15].

The mechanical interlocking theory, suggests that adhesion occurs when the adhesive penetrates into the microscopic pores and irregularities of the substrate surface, leading to physical interlocking upon curing [16]. The adsorption (physical and chemical) theory proposes that adhesion results from intermolecular forces, such as van der Waals forces, hydrogen bonding, or covalent bonding, between the adhesive and the substrate at the molecular level [16]. Both of these were afterwards contested by supporters of the electrostatic theory, which posits that adhesion is due to electrostatic forces arising from the transfer of electrons between the adhesive and the substrate, creating an electrical double layer at the interface. However, support for this theory has been declining in recent years because the predicted bond energy does not align with the higher fracture energies that have been measured experimentally [16]. Contrarily, the diffusion theory is gaining endorsement, and, applicable primarily to polymeric materials, this theory suggests that adhesion occurs when polymer chains from the adhesive and the substrate interdiffuse and entangle across the interface. It is, nonetheless, important to note that these theories are not mutually exclusive, in many practical scenarios, multiple mechanisms may contribute simultaneously to the overall adhesion [16].

Despite its advantages, adhesive bonding also presents certain limitations, such as the need to prepare the surface in order to remove contaminants achieve strong and durable bonds. Adverse environmental conditions such as high humidity, temperature extremes, and exposure to chemicals can degrade the adhesive and lower the overall joint strength. The mechanical behavior of the adhesive is also very dependent on the type of load that is applied, being very susceptible to peel stresses and very resistant to shear

loadings. Moreover, some adhesives require specific curing conditions (e.g., temperature, pressure, time), which can complicate manufacturing processes and increase production time. They are also, usually, permanent, which makes the disassembly for maintenance or even recycling very challenging [17].

Despite the use of adhesives for thousands of years [18], the invention of the first adhesive with a polymeric base was during the first decade of the 20th century, and a huge growth of the use of adhesives ever since [19]. A suitable universal criterion for joint dimensioning has yet to be established. Instead, effective design of adhesive joints necessitates a comprehensive understanding of the mechanical behavior of the adhesive and the substrates under various loading conditions. Some key considerations include joint geometry, to favor shear over peel or tensile stresses, material compatibility, which is crucial for bond integrity, fracture mechanics analysis, that can aid in predicting failure modes and improving joint reliability, and environmental testing, subjecting joints to simulated service conditions can help assess long-term performance and identify potential failure mechanisms [20].

Finally, adhesive bonding is a versatile and effective method for joining materials in various engineering applications. A thorough understanding of adhesion mechanisms, coupled with careful consideration of design and environmental factors, is essential for optimizing joint performance and ensuring structural integrity.

2.1.1. Joint configurations

Adhesive joints can be designed in various configurations, as illustrated in Figure 3. The selection of a specific joint type depends on several factors, including whether the joint serves a structural or non-structural purpose, the anticipated load conditions, the available bonding area, and practical considerations such as complexity, manufacturing time, and cost. These criteria collectively guide the decision-making process in choosing the most suitable joint configuration.

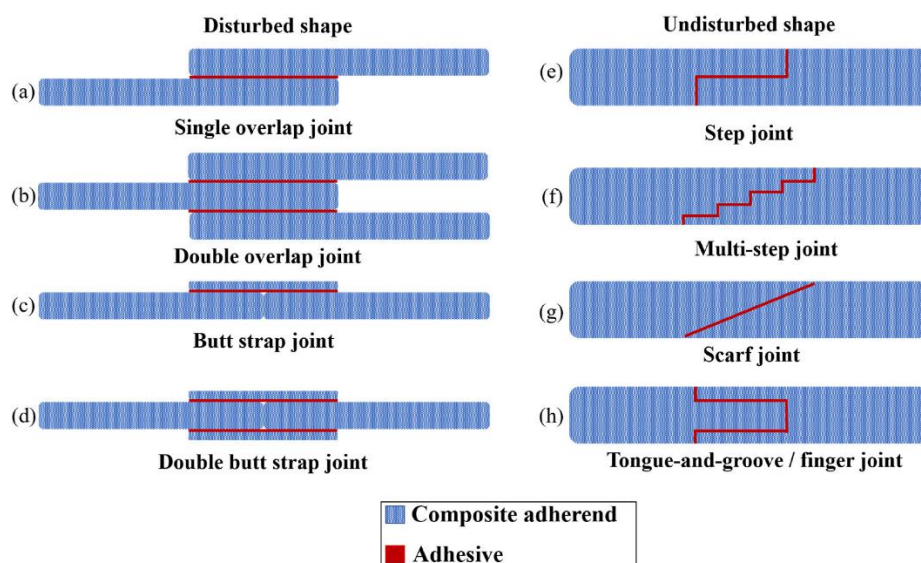


Figure 3: Common adhesively bonded joints configurations [21]

It is crucial to recognize that different types of loading affect the adhesive's behavior in distinct ways. The four primary stress types to consider are: normal (tensile and compressive), shear, cleavage, and peel. These stress modes are illustrated in Figure 4. From a design standpoint, adhesive joints should ideally be subjected primarily to shear stresses, as this promotes more uniform load distribution. In contrast, peel and cleavage stresses - especially common when flexible adherends are involved - are the most detrimental to joint strength. This is because they tend to concentrate loads along narrow regions rather than distributing them across the entire bonded area.

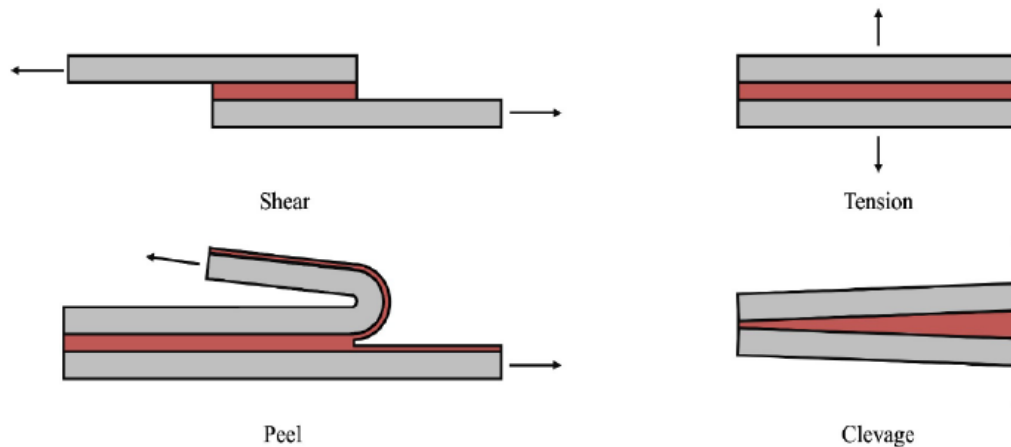


Figure 4: Types of stress in a joint (Adapted from [22])

Single lap joints are the most widely used adhesive joint configuration in practice, primarily due to their simplicity and relatively large bonding area. However, under tensile loading, SLJs tend to deform and generate bending moments, which in turn induce peel stresses that can compromise joint strength.

To address this, more advanced joint designs have been developed to reduce such stresses. Additionally, modifications to the basic SLJ configuration - such as adding adhesive fillets or tapering the adherends - can further enhance joint performance and durability [23].

2.1.2 Failure modes

There are three primary failure modes observed in adhesive joints:

Adhesive failure occurs when there is poor bonding at the interface between the adhesive and one of the substrates. This failure mode is typically identified by the complete absence of adhesive residue on one of the adherends after rupture. The most common cause is inadequate surface preparation. While some materials inherently exhibit lower adhesion, this limitation can often be addressed through appropriate surface treatments. These include degreasing, grit blasting, plasma treatment, anodizing, and the application of primers (chemical agents that enhance adhesion).

Cohesive failure within the adhesive layer indicates that the failure occurred within the adhesive itself, rather than at the interface. This type of failure is characterized by the presence of adhesive material remaining on both substrates after separation. It may

result from an unsuitable joint design or the use of an adhesive that lacks the mechanical strength to withstand the applied loads. If redesigning the joint is not feasible, selecting a more robust adhesive is necessary. Importantly, cohesive failure suggests that the bond to the substrate is sound.

Cohesive failure within the adherend is considered the optimal outcome in adhesive joint design. In this case, the failure occurs not in the adhesive or the interface, but in the substrate material itself. This indicates that the adhesive is stronger than the adherend and that the joint is no longer the weakest point in the structure. When this mode of failure is achieved, the joint can often be qualified by simply verifying that the substrate material meets the functional requirements.

These failure modes are illustrated in Figure 5. In practice, it is also common to observe mixed failures, which are combinations of adhesive and cohesive failures.

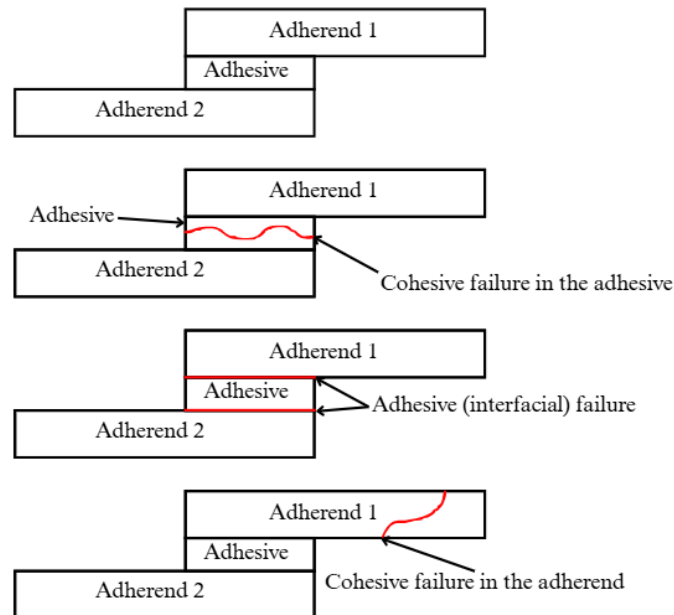


Figure 5 - Types of failure in adhesive joints adapted from [16]

2.2. Fiber reinforced plastics

Fibre-reinforced plastics (FRPs) are a class of composite materials consisting of a polymer matrix strengthened with fibrous reinforcements. The matrix is typically a thermosetting resin such as epoxy or polyester, while the most common reinforcements include carbon, glass, and aramid fibres. Among these, carbon fibre-reinforced polymer (CFRP) is widely used due to its outstanding strength-to-weight ratio and specific stiffness, making it ideal for weight-sensitive, high-performance applications [24].

FRPs are inherently anisotropic, exhibiting superior mechanical properties along the direction of the fibres and significantly reduced strength in the transverse direction. To tailor their mechanical behavior, engineers often laminate fibre layers (plies) in multiple orientations, creating quasi-isotropic or directionally optimized layups. This approach enables deterministic design, where fibre alignment is matched to anticipated load paths. Such design strategies account for various failure modes, including brittle fibre fracture, fibre pull-out, fibre-matrix debonding under tension, and matrix cracking under compression [24], [25].

Unlike metals, which follow well-defined isotropic design practices, composite materials require a multidisciplinary approach involving collaboration between structural and materials engineers. The certification and validation processes are also more demanding due to the variability in composite behavior. Despite these challenges, the use of FRPs - especially in the aerospace, Figure 6, and automotive sectors – is very significant (50% in commercial aircrafts), driven by their contribution to reducing weight and enhancing fuel efficiency or compliance with stringent emissions regulations.

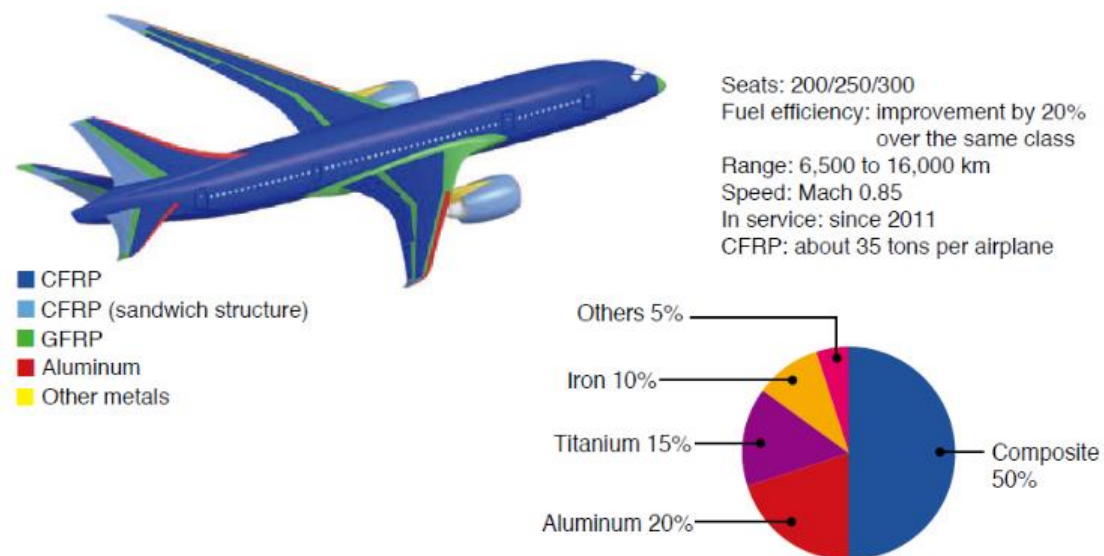


Figure 6: Material distribution and usage in a Boeing 787 commercial aircraft [26]

Aside from CFRPs, glass fibre-reinforced plastics (GFRPs) are also commonly used. Although mechanically inferior to CFRPs and slightly denser, GFRPs offer several practical advantages: they are significantly more cost-effective, more resistant to impact damage, and possess excellent thermal and electrical insulating properties. Another notable example is aramid fibre-reinforced plastic (e.g., Kevlar composites), which is well-known for its high toughness, excellent impact resistance, and use in ballistic and protective equipment [24].

2.2.1. Failure modes

In addition to the common failure modes observed in adhesively bonded joints, the use of composite materials as adherends introduces additional failure mechanisms,

notably delamination. Delamination, Figure 7, is a transverse failure mode characterized by the separation of layers within a composite laminate, often initiated by peel stresses and inadequate bonding between the fibers and the polymer matrix [27], [28]. Environmental factors, such as moisture ingress and temperature fluctuations, can exacerbate this issue, leading to a reduction in the composite's structural integrity [29].

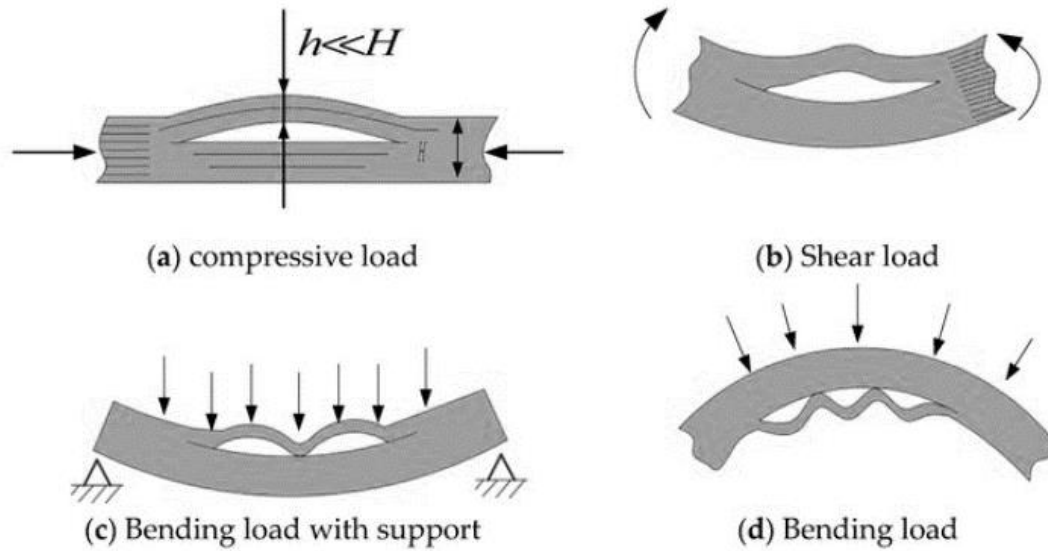


Figure 7: Delamination in composites when submitted to different loads [30]

To systematically classify and identify these failure modes, the American Society for Testing and Materials (ASTM) developed Standard D5573. This standard outlines seven distinct failure modes in adhesively bonded FRP joints: adhesive failure, cohesive failure, thin-layer cohesive failure, fiber-tear failure, light-fiber-tear failure, stock-break failure, and mixed failure, all these failure modes are shown in Figure 8. Each mode is characterized based on visual inspection of the fracture surfaces, providing a standardized approach for quality control and failure analysis in composite structures [31].

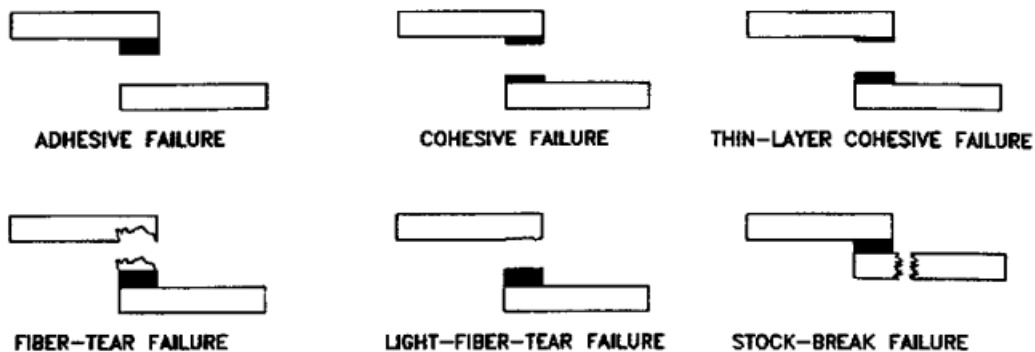


Figure 8: Failure modes in FRP joints [31]

2.3. Wood substrates

Wood is a well-recognized natural and renewable material that has been utilized for centuries across a wide range of applications, from structural frameworks in construction to paper manufacturing. It is widely available around the world and offers an advantageous strength-to-weight ratio, making it increasingly relevant in the push for global sustainability. Compared to conventional structural materials, wood and its derivatives generally have a significantly lower carbon footprint, as shown in Table 1 [32], [33].

Table 1: Net carbon emissions while producing several different materials [32]

Material	Net Carbon Emissions (kg·C/t)	Near-term net carbon emissions (kg·C/t)
Framing lumber	33	- 457
Medium-density fiberboard	60	- 382
Brick	88	88
Glass	154	154
Recycled steel	220	220
Concrete	265	265
Recycled aluminum	309	309
Steel (virgin)	694	694
Plastic	2502	2502
Aluminum (virgin)	4532	4532

It's worth noting that the terms "timber" and "lumber" are often used interchangeably to describe wood, but they differ depending on the processing stage and region. Typically, "lumber" refers to wood that has been freshly cut from the tree and still includes the outer bark layer, whereas "timber" describes wood that has been further processed - usually sawn into planks or beams for construction. However, in the United States, these definitions are reversed, with "timber" commonly referring to unprocessed logs and "lumber" used for the sawn, construction-ready product.

In order to make sure that the wood's properties and general mechanical behavior are well interpreted, it is crucial to understand its biological structure and nature.

2.3.1. Macrostructures

A cross-sectional view of a coniferous tree, specifically from the pine family, is illustrated in Figure 9. At the center lies the pith, which is encircled by two distinct zones: the heartwood and the sapwood. The heartwood, typically darker in color, consists of non-living cells that no longer participate in the transport of water and nutrients. Surrounding this is the lighter sapwood, which remains active in conducting these substances.

Adjacent to the sapwood and just beneath the bark is the cambium layer. This narrow region is responsible for the tree's growth, as it continuously generates new cells through division, contributing to both the wood and the bark.

The stem of most trees is made up of numerous concentric rings, known as annual growth rings. Each ring comprises two parts: earlywood, which forms during the beginning of the growing season and appears lighter and less dense; and latewood, which forms later and is darker and denser. The total number of these growth rings can be used to determine the age of the tree [34].

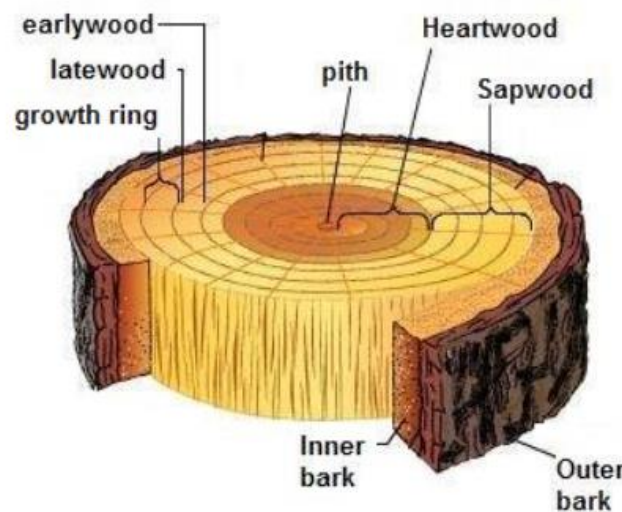


Figure 9: Cross-section of a tree stem [34]

2.3.2. Cellular structure

When examining the cellular structure of wood, notable differences arise between softwoods, like pine and spruce, and hardwoods, such as oak and beech.

Softwoods

Softwoods are composed primarily of two cell types: tracheids and parenchyma cells. Tracheids are the dominant cell type, comprising up to 95% of the wood's volume. These elongated cells, oriented parallel to the tree's stem, serve both structural and fluid transport functions. They typically range from 2 to 6 mm in length and 0.02 to 0.2 mm in width. In the earlywood (formed at the beginning of the growth season), tracheids have thin cell walls - about 2 to 3 μm - and large lumens (internal cavities), which enhance fluid conduction. In contrast, latewood tracheids have thicker walls (approximately 7 μm) and smaller lumens, contributing more to the mechanical strength of the wood [35], [36]. Parenchyma cells in softwoods are fewer in number and form the rays, which are small radial pathways that facilitate lateral transport of fluids between the tracheids [36]. Figure 10 presents SEM images that clearly show the cellular structure of a softwood species.

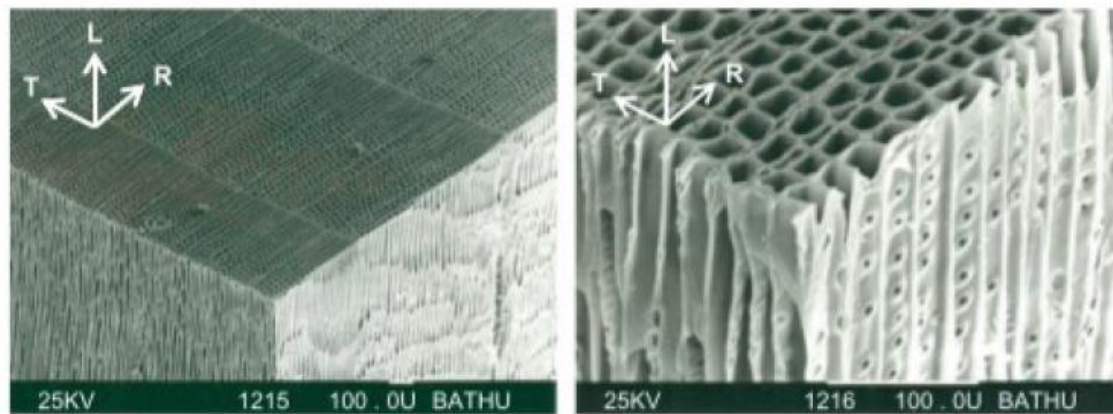


Figure 10: SEM images of Scots pine [36]

Hardwoods

Hardwoods, on the other hand, exhibit a more intricate cellular composition. Along with tracheids and fibers, they contain prominent vessels - large, tube-like cells aligned longitudinally - that function as the primary conduits for water transport. These vessels are often visible to the naked eye and distinguish hardwoods from softwoods. Additionally, hardwoods contain a greater volume of radial cells, contributing to their more complex and varied structure [33], [36]. Figure 11 displays SEM images illustrating the cellular makeup of a hardwood species.

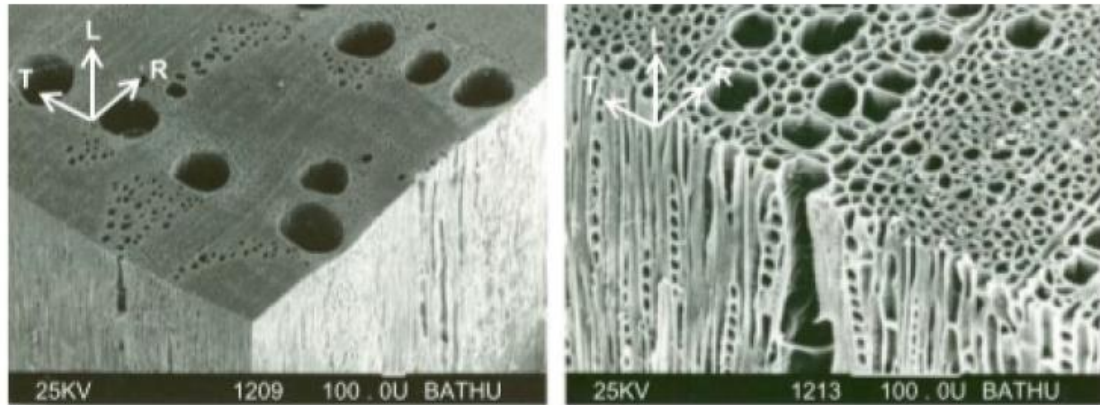


Figure 11: SEM images of English oak [36]

2.3.3. Tracheids' cell wall structure

As previously mentioned, softwoods are primarily made up of tracheids. Each tracheid cell wall consists of several layers arranged from the outer edge toward the center: the middle lamella, the primary wall, multilayered secondary walls, and a central cavity known as the lumen [36].

The middle lamella is an amorphous intercellular region responsible for bonding adjacent cells together. In the primary wall, cellulose fibers are randomly oriented. Due to the difficulty in clearly distinguishing between the middle lamella and the primary wall, they are often collectively referred to as the compound middle lamella (CML) [32]

The secondary wall is divided into three distinct layers - S1, S2, and S3 - each characterized by a highly ordered arrangement of cellulose microfibrils. The typical thicknesses of these layers are approximately 0.1 - 0.3 μm for S1, 1.0 - 5.0 μm for S2, and 0.1 μm for S3. These layers differ primarily in the orientation of their microfibrils. In the S1 and S3 layers, the microfibrils are arranged transversely in a helical pattern, with angles of 50° - 70° in S1 and 60° - 90° in S3 relative to the longitudinal axis. By contrast, the S2 layer features microfibrils also arranged helically but oriented more axially, with angles between 10° and 30° .

Due to its significantly greater thickness and favorable microfibril alignment, the S2 layer plays the most critical role in providing mechanical strength to the tree, bearing the majority of axial loads. The microfibril angle (MFA) within these layers greatly influences the mechanical properties of wood, and many correlations have been established based on MFA values [37] Figure 12 illustrates the typical structure of a softwood cell wall.

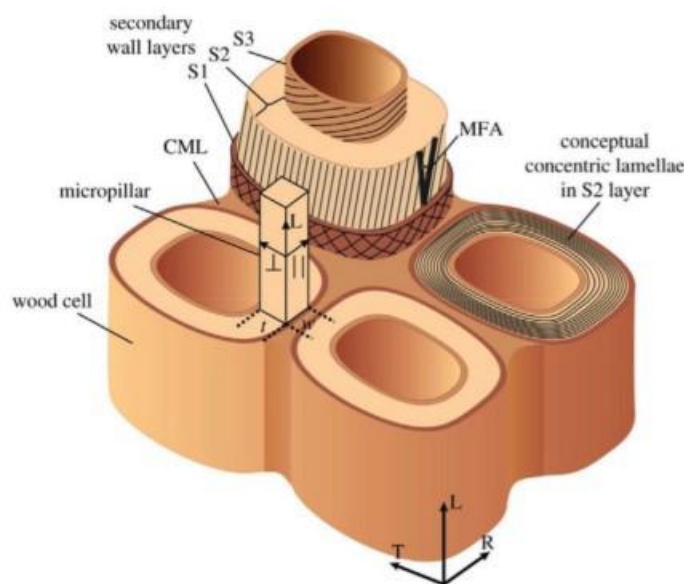


Figure 12: Schematic diagram of softwood cell wall structure [37]

2.3.4. Chemical composition

Wood can be regarded as a natural composite material made up of three primary biopolymers: cellulose, hemicellulose, and lignin. Figure 13 illustrates how these components are distributed within the structure of a softwood tracheid cell. In both the primary and secondary walls, cellulose microfibrils are embedded within a matrix of hemicellulose and surrounded by lignin. The regions between cells - known as intercellular spaces - are predominantly composed of lignin, which acts as a cementing agent, contributing to the wood's rigidity and resistance to both internal growth stresses and external mechanical loads.

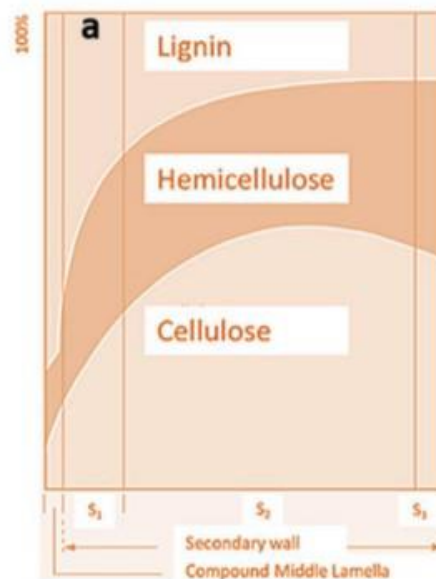


Figure 13: Main biopolymers present in softwood tracheids [37]

In this bio-composite system, cellulose microfibrils function as reinforcing fibers. They consist of multiple linear polymer chains held together by hydrogen bonds and van der Waals forces, forming larger fibrils and lamellae that impart high tensile strength to the cell wall. Hemicelluloses, made up of branched-chain polymers containing various sugar units, serve to connect cellulose with lignin. These water-permeable polymers provide flexibility and additional support to the cell wall structure.

Lignin, a phenylpropanoid polymer, plays a vital role in maintaining the structural integrity of wood. It contributes significantly to the stiffness and strength of the cell wall, while also serving a protective function by shielding cellulose and hemicellulose from enzymatic degradation and microbial attack [37]

2.3.5. Mechanical considerations

Because of its anisotropic nature, much like CFRP, the mechanical properties of wood vary significantly depending on the direction of loading, and - as a natural material - they are heavily influenced by its complex internal structure. Wood cells are primarily aligned along the grain, which corresponds to the longitudinal axis of the tree trunk. As a result, wood exhibits much greater stiffness and strength in this direction compared to the radial and tangential directions.

From a macroscopic perspective, wood is typically modeled as a cylindrical orthotropic material, with its three principal directions defined as longitudinal (L), radial (R), and tangential (T), as illustrated in Figure 14. Based on Hooke's law for orthotropic materials, describing the elastic behavior of wood requires nine independent material constants: three Young's moduli (E), three shear moduli (G), and three Poisson's ratios (ν). These parameters can be determined through experimental testing [33], [38].

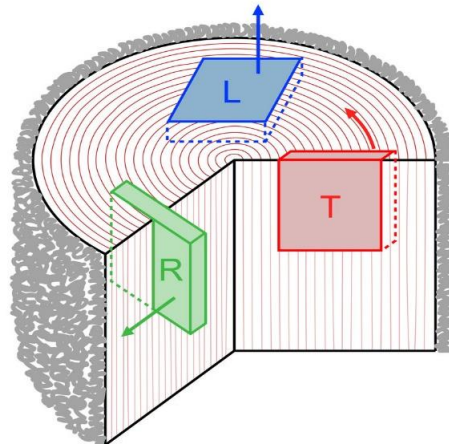


Figure 14: Principal directions defined in the anisotropic structure of wood [38], [39]

2.3.6. Adhesively bonded timber joints

Timber joints, like those in other materials, can benefit significantly from adhesive bonding. Traditionally, mechanical fasteners such as nails, bolts, and screws have been the most commonly used methods for joining wood. However, these fasteners tend to disrupt wood fibers, create localized stress concentrations, increase costs, and often allow water to penetrate the structure [38].

A key metric used to assess the quality of glued wood joints is shear strength. This property is influenced by several factors, including the physical and chemical characteristics of the adhesive, the structural and physical properties of the wood substrates, and the specific parameters of the bonding process [40]. Another widely used indicator of joint quality is the wood failure percentage (WFP), which refers to the proportion of the bonded area where failure occurs within the wood itself [41].

Because of wood's cellular structure, adhesives are absorbed into the substrate to varying degrees, largely influenced by the wood's density and porosity. Follrich et al. investigated the impact of spruce density on the quality of end joints, finding that increased density led to improved bond strength [42]. Conversely, their study on balsa wood joints revealed that while higher density resulted in a modest increase in bond strength, it also caused a sharp decline in WFP [43].

2.4. Delamination prevention

Delamination is a major failure mechanism in bonded joints, especially in substrates like CFRPs and wood, where internal cohesion is weaker in the through-thickness direction. There are several strategies to mitigate delamination in CFRP and wood SLJs, among those strategies lies adhesive selection - especially the counterintuitive benefit of more ductile, lower-strength adhesives [30].

While high-strength structural adhesives (e.g., stiff epoxies) provide high initial stiffness and load capacity, they are brittle and poor at absorbing strain energy, especially under peel or thermal cycling conditions. In contrast, more ductile, lower-modulus

adhesives (e.g., polyurethane, toughened epoxies, rubber-modified systems) offer better strain redistribution, energy absorption and compatibility with anisotropic substrates.

For example, hybridization of composites, a method to delay or even totally prevent delamination in CFRP substrates, combines fibers of different types, moduli, or diameters within the same laminate to improve mechanical performance. Hybridization strategies can involve mixing carbon, glass, Kevlar, or even natural fibers in tailored stacking sequences, which helps balance stiffness, ductility, and cost. By redistributing stresses across layers of varying properties, hybrid laminates promote more stable crack growth and delay delamination compared to non-hybrid composites. This synergistic effect, often termed the “hybrid effect”, results in improved fatigue life and energy absorption, making hybrid composites particularly attractive for applications where resistance to delamination and impact damage is critical [21].

Other delamination mitigation strategies are:

- Tapered adherend edges or scarf joints: These reduce peel stress concentrations and smooth out stress distributions.
- Hybrid bonding: Combining mechanical fasteners with adhesives can help carry peel loads away from the bondline.
- Surface treatments: Plasma treatment or peel ply improves bonding and reduces interface crack initiation.
- Moisture control: Using adhesives that remain flexible despite moisture variation (e.g., emulsion polymer isocyanates, PU) mitigates swelling-induced delamination.
- Joint design: Increasing bond area or modifying overlap geometry helps spread stress more uniformly.

In other words, delamination prevention in CFRP and wood SLJs requires balancing adhesive strength with ductility. While higher strength adhesives may seem advantageous, lower modulus, more ductile adhesives reduce peak stress transfer to the substrate, thereby preventing interlaminar or interfacial delamination. Joint geometry, substrate treatment, and moisture management further support these effects [30].

2.5. Effect of temperature in adhesive joints

Adhesive joints, while offering advantages - such as smooth stress distribution, lightweight, and joining dissimilar materials - are strongly affected by environmental temperature due to the polymeric nature of adhesives. Temperature variations influence adhesive shrinkage, viscoelastic properties, and induce thermal mismatch stresses between adherends and adhesives [44].

In the one hand, below the T_g , adhesives become increasingly brittle as molecular mobility sharply drops. This brittleness compromises their ability to absorb stress, making

joints more prone to crack initiation and propagation under mechanical loading [45]. In the other hand, as temperature rises beyond the T_g , adhesive rigidity declines: modulus, stiffness, and tensile strength degrade rapidly due to enhanced molecular motion. In epoxy-based systems, bond strength in CFRP–steel joints has been observed to diminish by over 50% at 70 °C compared to room temperature, underscoring the critical nature of operating below T_g [45].

A recent study reports that, in SJL's, joint strength decreases at both high (90 °C) and low (−40 °C) temperatures, but the same failure criteria (based on adherend yield and adhesive strain to failure) remains valid across temperatures. Joint strength drops with temperature excursions are attributed mainly to adhesive aging (near glass transition temperature - T_g - and above) and to adhesive stiffening and brittleness at low temperatures. Temperature effects are more pronounced in thicker adhesive layers, while thinner bondlines generally improve strength and thermal fatigue resistance [45].

A good strategy to mitigate the effect of temperature in the adhesive layer is the application of mixed adhesive joints (MAJ) (Figure 15). MAJs combine high and low-temperature adhesives, showing a more uniform performance across extreme temperatures, maintaining failure loads and displacement capacity by mitigating thermal-stress concentrations and providing graded compliance [44]

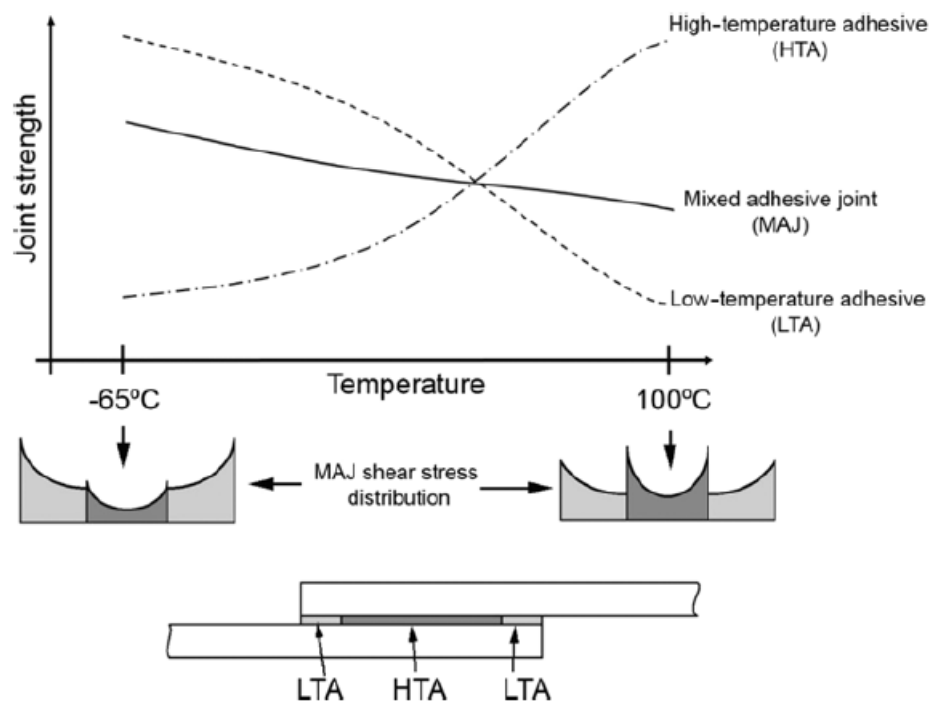


Figure 15: Mixed adhesive joint concept [44]

Mixed-adhesive systems are promising for multi-temperature applications, but require precise thermal characterization during cure (stress-free temperature of each adhesive matters).

2.6. Joint strength prediction

Accurately predicting the failure load of adhesive joints is essential for their broader adoption in structural applications. Consequently, numerous predictive models - both analytical and numerical - have been developed. However, each model typically incorporates assumptions and simplifications that confine its applicability to specific conditions.

While the models discussed here represent some of the most widely used or historically significant approaches, many other, more sophisticated formulations exist. These can accommodate a variety of material behaviors - such as linear and nonlinear elasticity of adhesives and substrates - as well as differences in adherend properties, including isotropic or anisotropic behavior and the presence of dissimilar materials. Furthermore, they may also address complex stress states, such as combined shear and peel stresses.

2.6.1. Analytical solutions

Linear Elastic Model

The simplest analytical approach for single-lap joints assumes purely shear deformation in the adhesive layer while treating the adherends as rigid. As a result, this model predicts a uniform shear stress distribution across the overlap length, which does not reflect the actual stress variation. The shear stress τ is calculated as:

$$\tau = \frac{P}{b \times l} \quad (1)$$

Where P is the applied load, b is the width of the joint, and l is the overlap length.

Volkersen Model

Introduced by Volkersen in 1938, this model extends the linear elastic approach by incorporating elastic deformation in the adherends, though it still assumes purely shear deformation in the adhesive, as shown in Figure 16 [46].

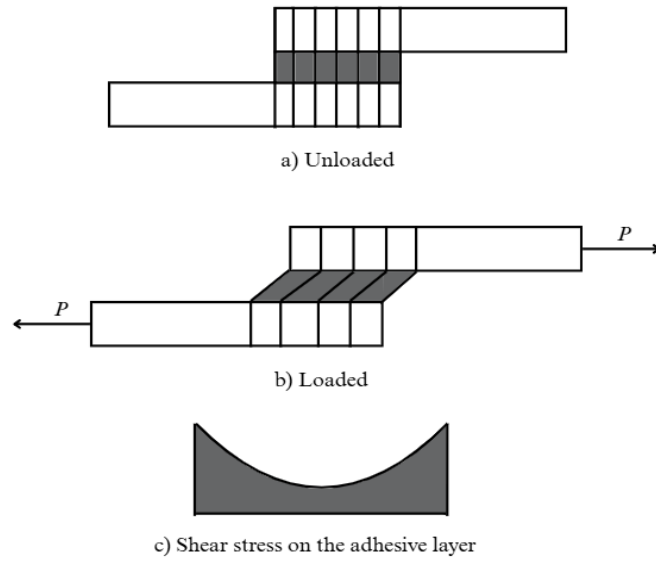


Figure 16: Differential straining and stresses acting on the adhesive layer adapted from [47]

This leads to a non-uniform shear stress distribution, with maximum values occurring near the edges of the overlap and a minimum at the center. This differential deformation introduces more realistic stress predictions compared to the constant stress assumption in simpler models [48].

Goland-Reissner Model

The Goland-Reissner model further improves upon earlier theories by accounting for bending moments and transverse forces induced by the eccentric load path, Figure 17, particularly relevant in single-lap joints [49].

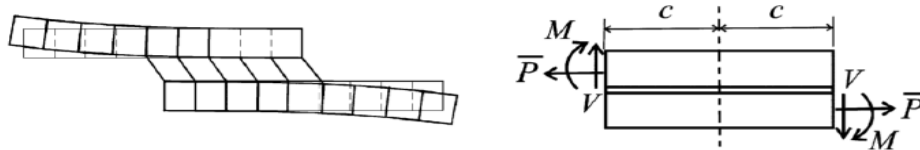


Figure 17: Graphic representation of the Goland-Reissner method [48]

This model introduces the concept of joint rotation and large deflections due to bending in the adherends, creating a geometrically nonlinear problem [48].

Consequently, when comparing to Volkersen's model, it predicts more accurate peel and shear stress distributions, with elevated stress concentrations at the overlap ends and the inclusion of peel stresses. The peel and shear stress distributions can be seen in Figure 18.

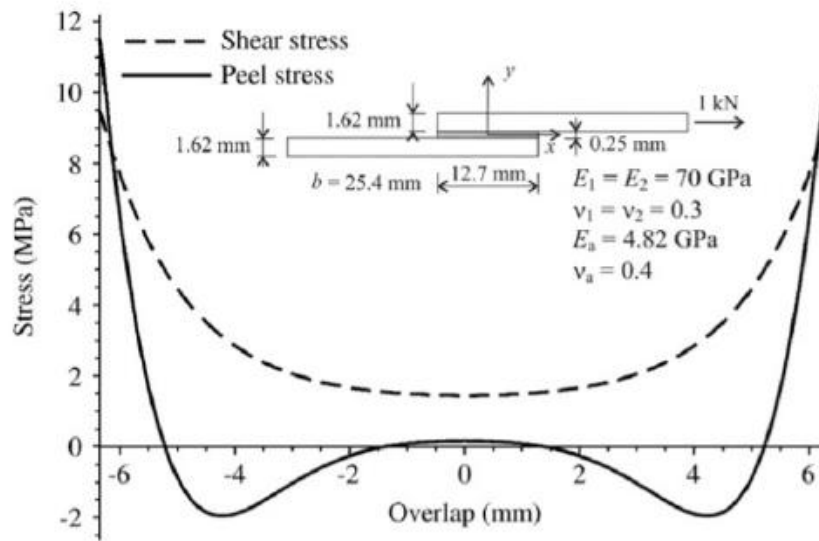


Figure 18: Shear and peel stress distributions in Goland-Reissner's method [48]

2.6.2. Numerical solutions

Recent advancements in computational power and the development of computational mechanics have significantly enhanced the capabilities of numerical methods for engineering applications. As discussed earlier, analytical models for adhesive joints grow increasingly complicated as more realistic behaviors and design factors are introduced.

In contrast, numerical methods such as the finite element method (FEM) allow for the analysis of complex joint configurations with high precision. These approaches enable the simulation of intricate stress distributions and failure mechanisms that are otherwise difficult to capture analytically (see Figure 19).

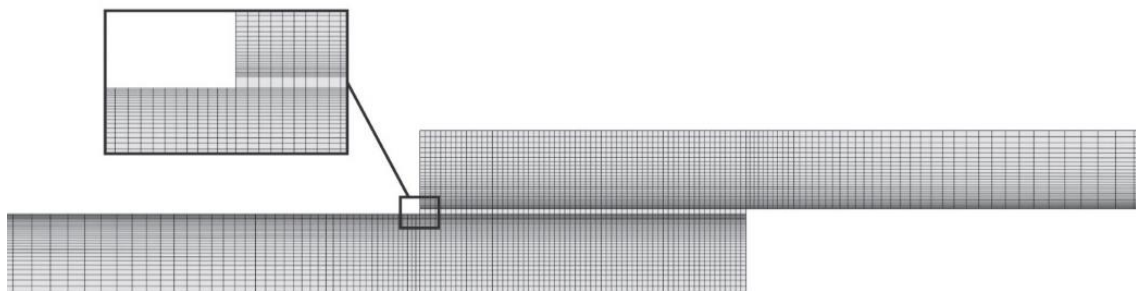


Figure 19: Finite element model of an adhesive single-lap joint [50]

Continuum mechanics vs Fracture mechanics

Continuum mechanics approaches use closed-form analytical formulations within the Finite Element Method (FEM) framework to calculate stress and strain distributions across the adhesive joint. In these models, the joint is represented using continuum elements, typically under the assumption of perfect bonding between the adhesive and adherends [52], [53]. The computed stresses and strains in the adhesive layer are then evaluated against material limits using failure criteria such as the maximum stress or maximum strain approach [54]. However, the accuracy of this method is highly sensitive to mesh refinement and the presence of stress singularities, particularly at geometric discontinuities like the edges of the overlap region [53].

In contrast, fracture mechanics treats the structure as discontinuous, explicitly accounting for the presence of defects such as cracks, delamination, or debonding. These flaws act as stress concentrators and are often the origin of joint failure [55], [56]. This method is applicable only under elastic conditions and evaluates failure based on the strain energy release rate (G). Crack propagation is predicted to occur when this rate equals or exceeds the material's critical energy release rate (G_c), which represents the material's resistance to crack growth [53], [54].

Cohesive zone modelling (CZM)

Cohesive Zone Models (CZM) synergize principles from continuum and fracture mechanics to simulate both the initiation and progression of damage in adhesive joints. Unlike traditional fracture mechanics, CZMs do not necessitate predefined cracks; instead, cohesive elements are strategically placed in regions susceptible to failure, allowing cracks to emerge and evolve organically during simulations [57].

Central to CZM is the traction-separation law, which delineates the relationship between stress (traction) and displacement (separation) across the adhesive interface. Hillerborg et al. introduced a bilinear traction-separation law, characterizing two distinct phases: an initial linear elastic response up to a peak traction, followed by a softening phase representing damage accumulation leading to eventual failure [54], [58]. The area under this curve corresponds to the material's fracture energy, a critical parameter in predicting failure. In Figure 20 is represented the evolution of the damage process zone and its relation to a traction-separation law.

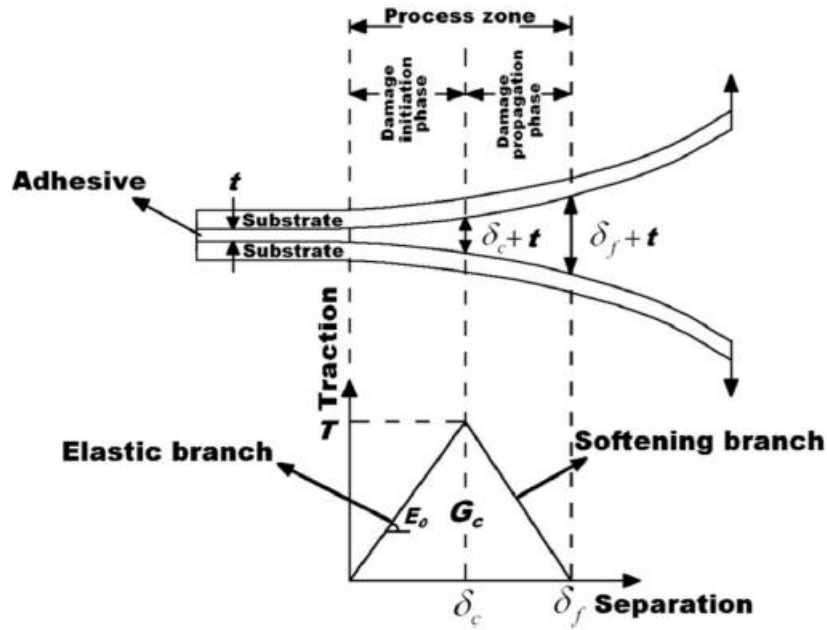


Figure 20: Damage process zone of a triangular traction-separation law [59]

Various shapes of traction-separation laws exist, including triangular, trapezoidal, (Figure 21) and exponential forms, each tailored to capture specific material behaviors. Accurate implementation requires experimental determination of material properties such as stiffness, strength, and fracture energies in Mode I (opening) and Mode II (shearing) through standardized tests like the Double Cantilever Beam (DCB) and End-Notched Flexure (ENF) tests [60].

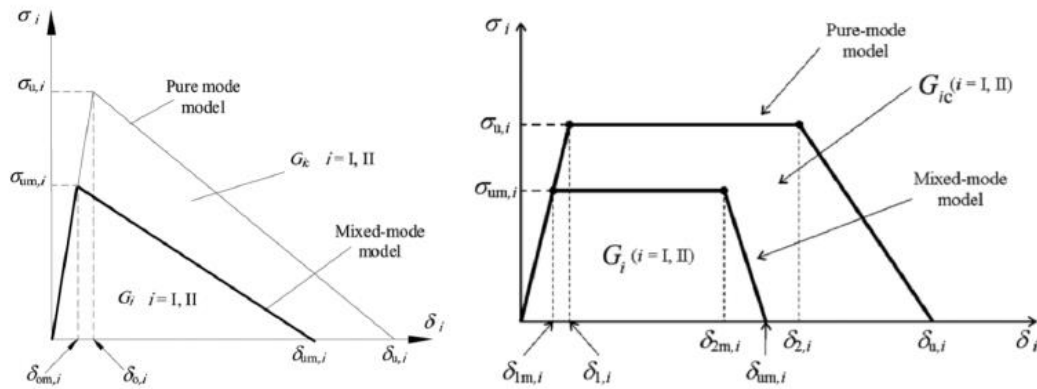


Figure 21: Triangular (left) and trapezoidal (right) traction-separation laws [55]

CZM facilitates a progressive failure mechanism, aligning with the gradual degradation observed in real-world adhesive joints. It is particularly adept at modeling delamination in composite materials. By inserting cohesive elements between composite layers, CZM can simulate interlaminar failures without relying on traditional criteria like Maximum Stress or Tsai-Wu, which may not effectively predict delamination. This

approach treats the interfaces between plies similarly to adhesive joints, enabling a unified modeling strategy for both adhesive and composite delamination failures [61].

2.7. Loading and strain-rate effects

The loading rate is a determining factor in joint behavior. Adhesives are viscoelastic materials, meaning their stiffness, strength, and energy absorption capacity vary with strain rate. Under quasi-static conditions, adhesive joints generally show lower strength but greater deformation capacity. Conversely, under dynamic or impact loading, adhesives exhibit strain-rate hardening, which increases strength but often reduces ductility. This effect is particularly relevant for thermoplastic adhesives, which are highly sensitive to strain rate and temperature [62].

Overall, understanding the combined effects of loading type (tensile, shear, bending, peel) and loading rate (quasi-static to impact) is essential for designing reliable adhesive joints. This dual perspective enables the prediction of critical failure modes and guides the development of reinforcement strategies and enhance performance under service-relevant conditions.

Impact loading

The integrity of adhesive joints under impact loading is paramount, especially in industries such as aerospace, automotive, and aeronautics, where structures are frequently subjected to dynamic forces. These industries demand a comprehensive understanding—both theoretical and experimental—of how adhesives and bonded joints behave under various impact conditions to ensure safety and performance.

While impact events are often considered rare or unpredictable, certain applications involve regular exposure to dynamic loads. In such cases, design strategies diverge: for occasional impacts, the focus is on energy absorption and controlled failure to minimize damage; for frequent impacts, the joints must exhibit resilience, maintaining integrity without damage throughout their service life [63].

Adhesives exhibit strain rate-dependent behavior, necessitating the classification of impact scenarios into low, medium, and high-velocity categories. Although exact speed thresholds vary, testing methodologies differ [64]:

- Low-velocity impacts: Typically, under 10 m/s, assessed using pendulum tests;
- Medium-velocity impacts: Up to 10 m/s, evaluated with drop-weight machines;
- High-velocity impacts: Exceeding 10 m/s, analyzed using Split-Hopkinson Pressure Bar apparatus.

These tests simulate real-world scenarios, from tool drops and minor collisions to bird strikes and high-speed crashes. Furthermore, impact tests can be categorized based on the type of stress applied: tension, compression, or torsion. Each mode provides insights into the joint's performance under specific loading conditions.

A pivotal study by Harris and Adams (1985) [65] revealed that the energy absorption capacity of a joint is more influenced by the substrate's plasticity than the adhesive's properties. Their findings indicated that joints with ductile adherends absorb more energy but fail at lower loads, whereas those with high-strength, less ductile adherends exhibit higher failure loads but absorb less energy [65].

3. Experimental Procedures

3.1. Adhesives

The adhesive used in this study was the 0.4mm thick cyclic olefin-based thermoplastic adhesive film LS-XU, which is a multi-material adhesive (MMA) developed by Zeon® Corporation (Chiyoda-ku, Tokyo, Japan). It is a hot-melt adhesive (HMA) designed for multi-material bonding applications [12].

The adhesive was cured in accordance with the manufacturer's specifications, involving a heating phase at 150 °C under a pressure of 10 bar for a duration of one hour, as shown in Figure 22. After curing, the system was allowed to cool gradually to room temperature, with both the press and heating system turned off.

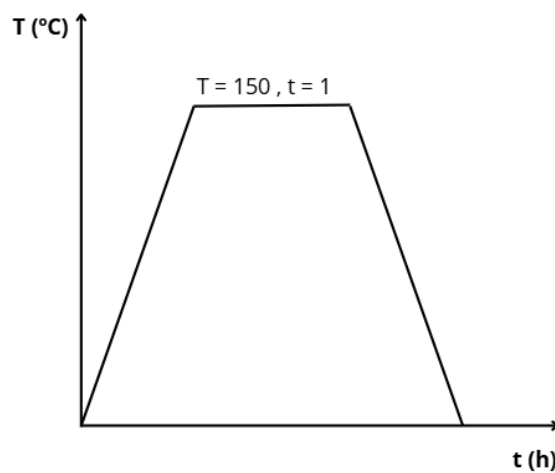


Figure 22: Cure cycle for LS-XU film adhesive

Under quasi-static loading conditions, the mechanical properties of the LS-XU adhesive have been previously characterized. A consolidated overview of the adhesive's relevant mechanical properties - pertinent to both quasi-static and low-velocity impact scenarios - is presented in Table 2

Table 2: Mechanical properties of the LS-XU adhesive

Properties	Value
E (MPa)	230.18
σ_y (MPa)	5.49
σ_f (MPa)	10.86
ν	0.47
ϵ	10.66
G (MPa)	76.67
T_f (MPa)	5.09
γ	3.54

In order to do some benchmark for the use of the LS-XU film adhesive in SLJs with CFRP substrates, two different adhesives were used under the same configurations and same testing conditions. These adhesives are the 3M Scotch AF 163-2k and the Nagase Denatite XNR 6852 E3. Both these adhesives were previously characterized and their properties were already determined and are presented in Table 3 and Table 4, respectively.

Table 3: Mechanical properties of the AF 163-2k adhesive [9], [66]

Properties	Value
E (MPa)	1520
G (MPa)	565
t_n^0	46.93
t_{s0}	46.86
Mode I fracture toughness (N/mm)	4.05
Mode II fracture toughness (N/mm)	9.77

Table 4: Mechanical properties of the Nagase Denatite adhesive [67], [68]

Properties	Value
E (MPa)	1728
G (MPa)	665
t_n^0	51.50
t_{s0}	44.90
Mode I fracture toughness (N/mm)	9.20
Mode II fracture toughness (N/mm)	51

Since this study investigates joint behavior under different temperature conditions, it is essential to consider the glass transition temperature (T_g) of each adhesive. The HMA exhibits a T_g of 85 °C, notably lower than that of the structural epoxies - 108 °C for AF 163-2k and 100 °C for Nagase Denatite.

3.2. Adherends

Three different materials were used as substrates in this study: CFRP, oak wood, and pine wood.

3.2.1. CFRP

One of the materials used in the SLJ configurations were fabricated from a composite material - Carbon Fiber Reinforced Plastic (CFRP). This material, supplied by SEAL® Texipreg, was delivered as a prepreg roll under the commercial designation HS 160 RM. It consists of a carbon-epoxy system with fibers oriented in the 0° direction. The orthotropic elastic properties of the CFRP, previously characterized by Shang et al. (2019) [69], are summarized in Table 5.

Table 5: CFRP elastic orthotropic properties [69]

Properties	Value
E_x (MPa)	109000
E_y (MPa)	8819
ν_{xy}	0.342
ν_{yz}	0.38
G_{xy} (MPa)	4315
G_{yz} (MPa)	3200
Maximum tensile strength (MPa)	40
Maximum shear strength (MPa)	35
Mode I fracture toughness (N/mm)	0.59
Mode II fracture toughness (N/mm)	1.17

The manufacturing process was carried out according to the subsequent steps:

1. The prepreg roll, stored at $-18\text{ }^{\circ}\text{C}$, was removed from the freezer and allowed to equilibrate to room temperature (RT) for several minutes.
2. The worktable and tools were thoroughly cleaned with acetone to ensure a contaminant-free environment.
3. The prepreg was unrolled, and, considering 0.15 mm of sheet thickness, twenty-one square sheets measuring $300 \times 300\text{ mm}$ were cut using a sharp X-Acto knife, to achieve the desired substrate thickness.
4. A teflon layer was removed from two adjacent sheets, and a heat gun was used to gently and uniformly warm the carbon/epoxy prepreg until it became slightly tacky.
5. Once tacky, the sheets were carefully aligned, placed on the table, and pressed together to ensure a 0° layup. A steel mould with rounded corners was used to minimize void formation. This process was repeated until all twenty-one $300 \times 300\text{ mm}$ layers were stacked.
6. A two-plate steel mould was coated with release agent and left to dry under a fume hood.
7. The stacked carbon/epoxy laminate was positioned in the mould, and calibrated spacers were placed along the edges to ensure the final plate thickness.
8. The mould was then transferred to the hot press and subjected to a pressure of 10 bar.

The CFRP prepreg was cured simultaneously with the adhesive (co-curing) to minimize energy and time consumption, as explained in section 3.3. After curing, the heating system of the hot press was switched off, and the mould was removed only once the temperature had dropped below $60\text{ }^{\circ}\text{C}$. The mould was then allowed to cool to room temperature outside the press.

3.2.1. Pine wood

In this study, pine timber (*Pinus pinaster*) was used as one of the materials for the single-lap joint (SLJ) substrates. The manufacturing process of the pine wood substrates is much simpler than that of the CFRP. The beams used to fabricate the substrates were cut using an aluminum saw, this process has to be done steadily and as slowly as possible to ensure that the cut made in the wood is clean and leaves no splinters. The cross-section of the beams is illustrated in Figure 23. It is important to note that achieving perfect symmetry of the growth rings with respect to a central vertical axis was not always possible.

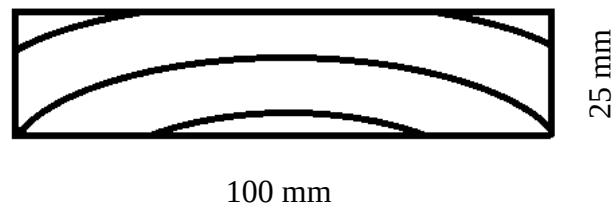


Figure 23: Illustration of the beams' cross-section dimensions and the preferable ring orientation

The elastic constants of pine wood in the longitudinal (L), radial (R), and tangential (T) directions were previously characterized by Oliveira and Moura (2007) [70] and are presented in Table 6.

Table 6: Nominal elastic properties of pine wood [70]

Properties	Value
E_L (GPa)	12.00
E_R (GPa)	1.91
E_T (GPa)	1.01
ν_{LT}	0.51
ν_{LR}	0.47
ν_{TR}	0.31
G_{LR} (GPa)	1.12
G_{LT} (GPa)	1.12
G_{TR} (GPa)	0.29
Maximum longitudinal strength (MPa)	97.50
Maximum radial strength (MPa)	7.90
Maximum transverse strength (MPa)	4.20

3.2.1. Oak wood

The second wood used in this research was oak wood (*Quercus alba*), whose beams had the same cross-sectional dimensions, and were cut following the same process, as those of the pine specimens (Figure 23). The elastic properties of oak (Table 7) were sourced from Oliveira and Moura (2007) [70] and Reiterer et al [71].

Table 7: Nominal elastic properties of oak wood [70], [71]

Properties	Value
E_L (GPa)	12.3
E_R (GPa)	2.05
E_T (GPa)	0.89
ν_{LT}	0.43
ν_{LR}	0.37
ν_{TR}	0.30
G_{LR} (GPa)	1.20
G_{LT} (GPa)	1.20
G_{TR} (GPa)	0.80
Maximum longitudinal strength (MPa)	105
Maximum radial strength (MPa)	13.80
Maximum transverse strength (MPa)	5.50

3.3. Single lap joint manufacturing

3.3.1. CFRP SLJ configuration

The single lap joints that were manufactured using the CFRP adherend had only one configuration and were based on the geometry presented in Figure 24.

Due to the thickness-supporting capability of the film adhesive, precise control of the adhesive layer thickness was not required. The SLJs were manufactured using a mould, which was coated with a release agent to prevent the CFRP from gluing to it, based on the design shown in Figure 25 and cured in a hot press. The specimens were subsequently cut to the desired length and width.

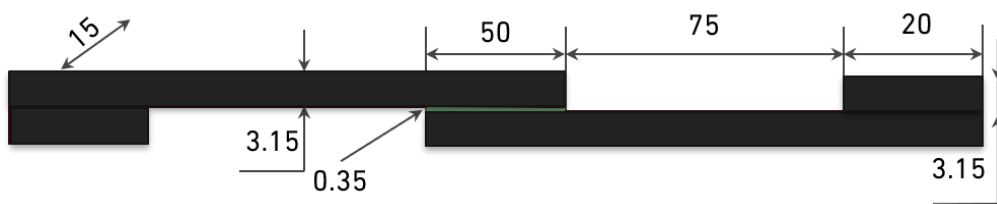


Figure 24: CFRP single lap joint geometry

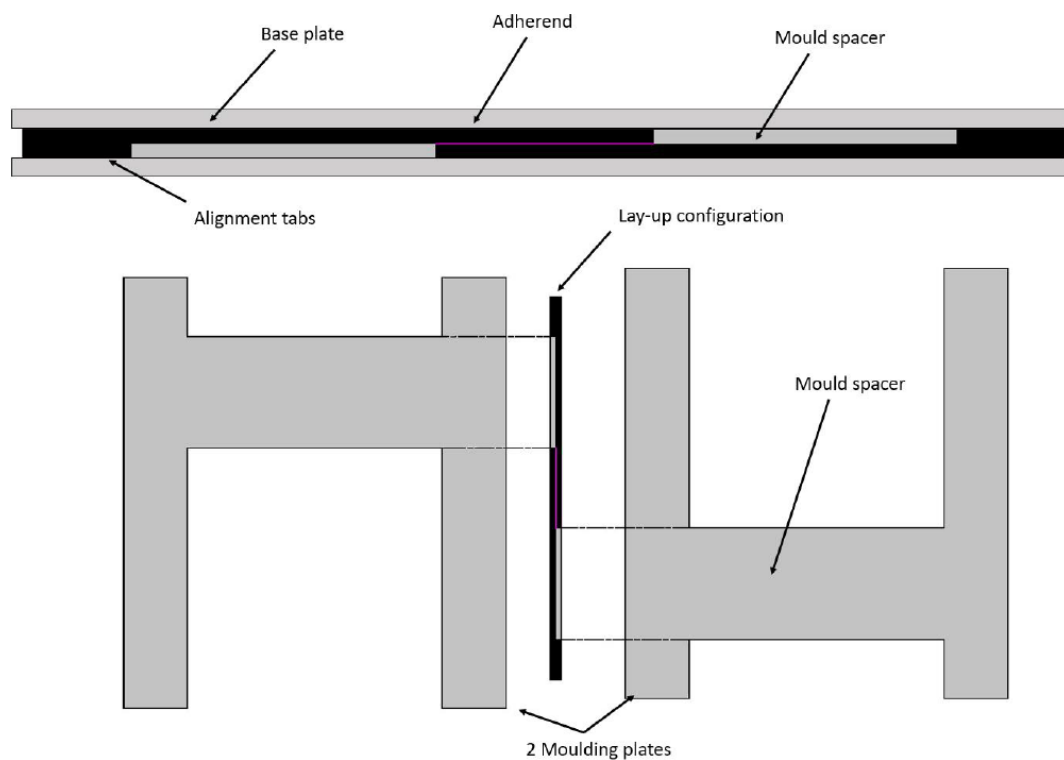


Figure 25: Manufacturing mould scheme [9]

It was found that the manufacturing approach - whether curing the adhesive and composite plies together in a single step or in two separate steps - had no significant impact on the mechanical performance of the joint when using the LS-XU adhesive. Therefore, for this adhesive, as it is a film adhesive, the single-step curing method is preferred, as it reduces both manufacturing time and energy consumption. Regarding the structural epoxies, the AF 163-2k film adhesive was also manufactured using the co-curing method, while the Nagase Denatite paste was manufactured through secondary bonding. In this approach, the CFRP adherends were also manually stacked but were cured alone at 135 °C under a pressure of 10 bar for 1 hour. The cured laminate was then cut to the adherend dimensions specified in Figure 24. In the second stage, Nagase paste adhesive was applied, and the adherends were bonded using a dedicated aluminum mold that ensured precise dimensional control, as Figure 26 shows. The assembly was cured at 150 °C for 3 hours under a pressure of 9 bar.

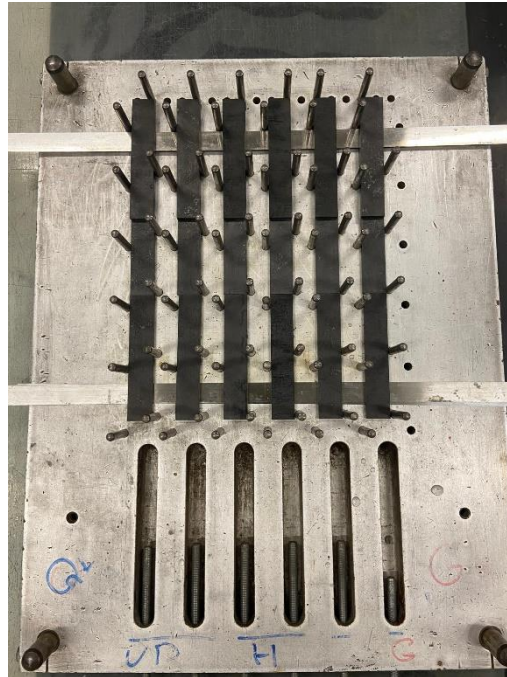


Figure 26: Aluminum mould used to manufacture CFRP joints using Nagase Denatite paste

3.3.2. Wood SLJ configurations

Three distinct configurations of wooden single lap joints (SLJs) were designed and manufactured for this study:

- **Reference configuration:** The baseline joints were fabricated from either pine or oak substrates with a uniform thickness of 6 mm. The geometry of this configuration is shown in Figure 27.
- **Toughened configuration:** These joints, also prepared with pine and oak adherends of 6 mm thickness, incorporated an additional adhesive layer extending 15 mm beyond each end of the overlap (Figure 28). This extension promoted adhesive penetration into the porous wood structure, thereby increasing the effective bonding area and reinforcing the wood cell walls. The resulting improvements in transverse strength helped reduce stress concentrations at the overlap ends, delaying crack initiation, limiting bondline crack propagation, and enhancing the joint's toughness and energy absorption capacity.
- **Hybrid configuration:** In this design, pine and oak were combined within the same substrate to produce hybrid specimens (Figure 29). Two thickness arrangements were considered: One with an oak core (4 mm) and with pine outer plies (1 mm each), forming an P–O–P configuration, and another one with pine in the core (4 mm) with oak outer plies (1 mm each), forming a O–P–O configuration. Adhesive layers were applied between the plies, with penetration further strengthening the interlaminar regions. This hybrid design aimed to improve stress distribution along the overlap length and enhance the overall load-bearing efficiency of the joints.

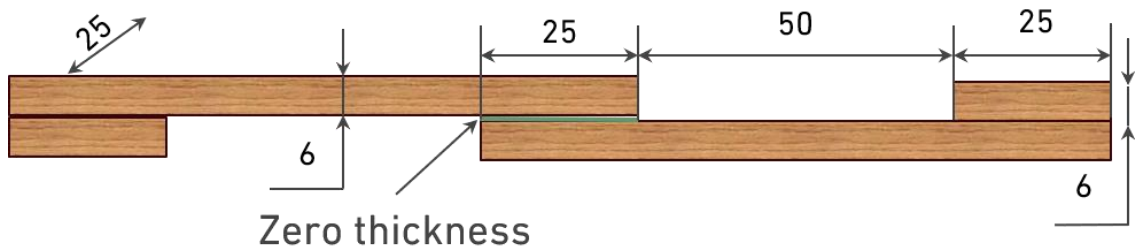


Figure 27: Geometry of the reference SLJ configuration (dimensions in mm)

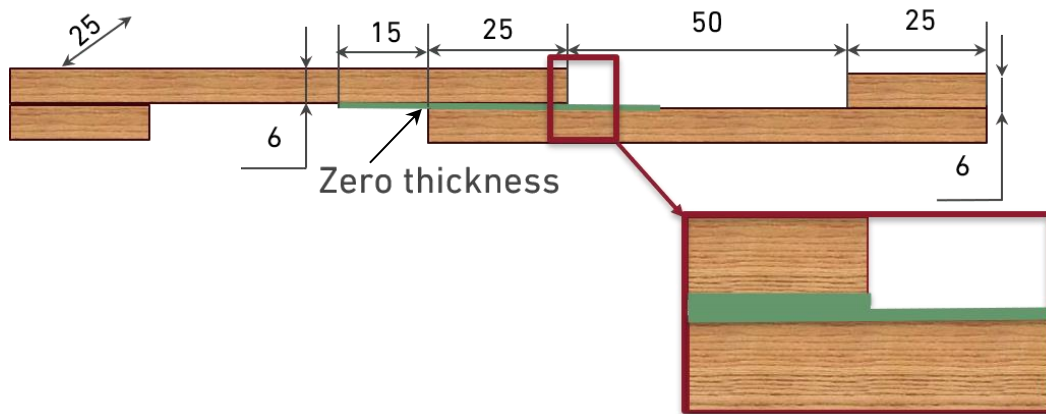


Figure 28: Geometry of the toughened SLJ configuration (dimensions in mm)

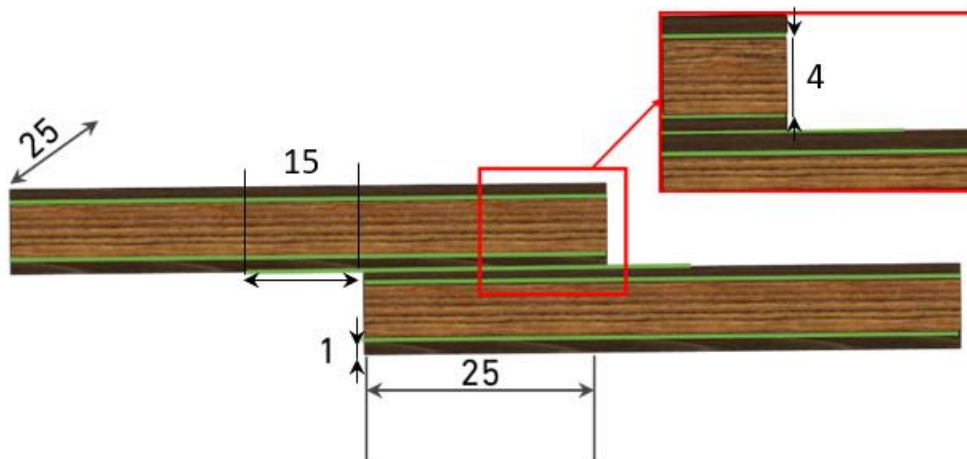


Figure 29: Geometry of the Hybrid SLJ configurations (dimensions in mm)

In order to manufacture the joints, an iron mould was used. With this mould it is possible to manufacture up to 6 specimens at a time and have a rigorous control of their width, using the pins in the mould, and of their thicknesses and length, by using previously manufactured spacers, as Figure 30 presents.

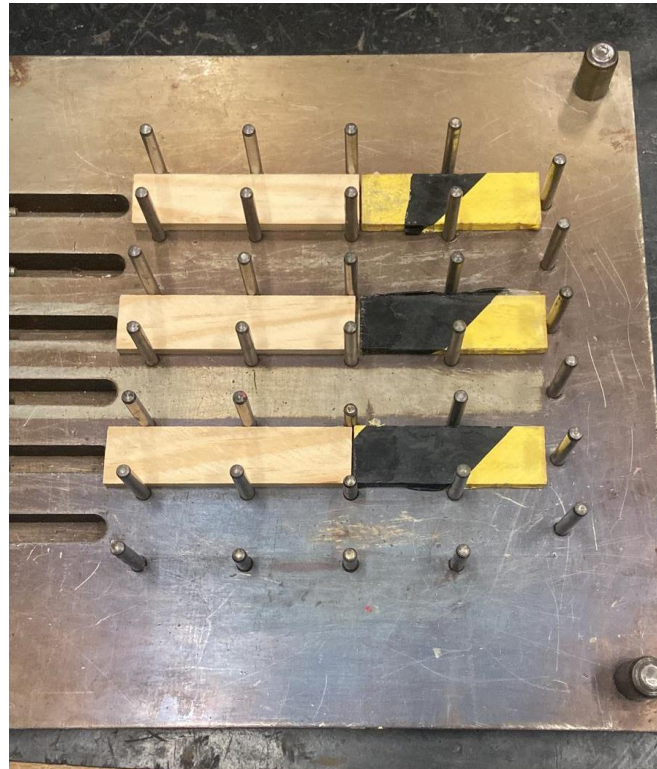


Figure 30: Iron mould used to manufacture wood specimens

The LS-XU adhesive was applied at nominally zero thickness, a condition that promotes penetration into the wood structure and minimizes the risk of insufficient adhesion. The curing conditions, in accordance with the manufacturer's recommendations for the LS-XU film adhesive, consisted of 150 °C and 10 bar for 1 hour, as previously reported.

3.4. Tensile testing

Under quasi-static loading conditions, the single lap joints were tested using an Instron 8801 servo-hydraulic testing machine equipped with a 100 kN load cell, operating at a constant crosshead speed of 1 mm/min, in accordance with ASTM D5868-01(2014) – Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding [72].

Specimens were secured using clamping fixtures, which held the free ends of each joint with four bolts manually tightened using a torque wrench. Torque was applied gradually up to 27 N·m to ensure uniform clamping pressure. Dowel pins were used to properly align the specimen with the clamps.

For the tests that were made at low and high temperature, a thermal chamber, which involved both the joint and the gripping system, was used to ensure that the temperature was uniform through the whole joint and during the entire duration of the test.

To obtain accurate load–displacement curves, the machine-measured displacement was corrected to account for the compliance of the gripping system.

3.5. Impact testing

For impact testing, a drop-weight impact machine developed by ADFEUP was utilized [73]. This equipment can release a 56 kg mass from a height of up to 1.27 m, reaching an impact velocity of 5 m/s.

In this study, tests were performed with an impact speed of 3 m/s and a drop weight of 31.3 kg, corresponding to an impact energy of 140.85 J.

For the impact testing, temperature control was achieved without the use of a thermal chamber. A thermocouple was employed to monitor the joint temperature, while heating was provided by a hot-air gun for high-temperature conditions. For low-temperature conditions, cooling was achieved using a hose connected to a liquid nitrogen tank. Once the joint reached the target temperature, the impact test was carried out.

Displacement measurements were obtained indirectly through trapezoidal time integration of the load data and were cross-validated using high-speed camera footage captured in slow motion. The high-speed camera was the Chronos 1.4 from Kron Technologies and was used to record footage at around 4500 fps.

By synchronizing the high-speed camera with the data acquisition system, it was possible to detect the exact frames where the impact occurred and where the joint failed. Using this data and a DIC (Digital Image Correlation) software Figure 31, it was possible to accurately calculate the displacement of the joint and validate the experimental results that were obtained.



Figure 31: DIC displacement measurement

Because a very high recording speed was used, additional lighting was required to ensure sufficient contrast between the black and white areas of the specimens. Achieving proper illumination was challenging, which resulted in footage that appeared foggy and unstable.

4. Summary of the Appended Papers

4.1. Paper A

Paper A investigates the effect of temperature on CFRP single-lap joints bonded with a cyclic olefin-based thermoplastic film adhesive (Zeon LS-XU), benchmarked against two structural epoxies, AF 163-2k and Nagase Denatite. Unlike traditional reinforcement methods that rely on mechanical modifications or metallic laminates, this approach explores the potential of a thermoplastic film to mitigate delamination through its energy-absorbing capacity and strain-rate sensitivity. Tests were conducted under quasi-static (1 mm/min) and impact (3 m/s) conditions at three service-relevant temperatures: sub-zero ($-30\text{ }^{\circ}\text{C}$), room temperature ($\approx 23\text{ }^{\circ}\text{C}$), and elevated temperature ($80\text{ }^{\circ}\text{C}$).

The results show that at room temperature, the Zeon adhesive exhibited significantly lower strength than the structural epoxies, but failed adhesively rather than by delamination, preserving the integrity of the CFRP adherends. At $-30\text{ }^{\circ}\text{C}$, the thermoplastic adhesive demonstrated outstanding performance under impact loading, even surpassing the benchmark epoxies in failure load, while maintaining a more favorable failure mode. At $80\text{ }^{\circ}\text{C}$, however, the Zeon film was rendered impractical due to its low glass transition temperature, failing prematurely under both quasi-static and impact conditions.

The analysis highlights the strong strain-rate dependence of the Zeon adhesive. While its quasi-static performance remained limited, its impact resistance improved considerably, narrowing the performance gap with structural epoxies and confirming its ability to absorb energy more effectively at higher loading rates.

Overall, Paper A demonstrates that the use of a thermoplastic film adhesive provides an alternative lightweight strategy for delaying delamination and enhancing energy absorption in CFRP SLJs, particularly in low-temperature and impact-prone environments. Its main limitations remain at elevated temperatures, where improvements in thermal stability would be required to expand its applicability.

4.2. Paper B

Paper B investigates a strategy to mitigate delamination in wood single lap joints by strengthening the substrates with a thermoplastic film adhesive interlayer, LS-XU from Zeon. Unlike densification or mechanical reinforcement methods, this approach leverages the energy-absorbing capacity of the thermoplastic film to delay crack initiation and improve stress redistribution. The joints were tested under quasi-static (1 mm/min) and impact (3 m/s) conditions, and three configurations were considered: reference, toughened (extra adhesive along the overlap edges), and hybrid (combining oak and pine layers to enhance stress wave propagation).

The study shows that delamination was not completely eliminated but was significantly delayed, leading to higher energy absorption, particularly under impact

loading. The toughened configuration yielded limited improvements under quasi-static conditions but increased strength for pine specimens under impact. The most effective strategy was the hybrid configuration, which delivered substantial strength gains - up to 84% compared to pine references - by distributing stresses more uniformly across the substrate layers.

A finite element model was developed and validated against experimental impact data. It revealed that in hybrid joints, stress waves propagate more uniformly through the core, while in reference joints stresses concentrate at the edges. This explains the superior impact performance of the hybrid configuration.

Overall, Paper B demonstrates that incorporating thermoplastic interlayers and hybrid wood substrates is an effective lightweight strategy to enhance the impact resistance of wood SLJs while reducing the onset of delamination.

4.3. Thesis Summary

The two studies presented in this work explored the use of a thermoplastic film adhesive to mitigate delamination in single-lap joints made from different substrates: CFRP composites (Paper A) and wood (Paper B). Although the materials and service environments differ, several common findings can be highlighted.

In both systems, the introduction of a thermoplastic interlayer changed the failure mechanism of the joints. In the case of CFRP SLJs, the LS-XU adhesive promoted adhesive failure instead of delamination in the adherends, thereby preserving the integrity of the CFRP substrates. Similarly, in wood SLJs, the presence of the film delayed delamination and increased the joints' capacity to absorb energy, particularly under impact conditions. This confirms that thermoplastic interlayers can play a significant role in controlling crack initiation and growth, independently of whether the substrate is composite or natural wood.

The effect of loading rate was also evident in both studies. The thermoplastic adhesive exhibited a pronounced strain-rate sensitivity, leading to substantial improvements in impact resistance. For CFRP joints, this was particularly visible at low temperatures, where the LS-XU adhesive not only matched but even outperformed the benchmark structural epoxies in terms of failure load under impact, as is shown in Figure 32 and Figure 33.

In wood joints, while quasi-static performance remained largely unchanged, impact performance was significantly enhanced, especially for the hybrid oak-pine configurations, as Figure 34 illustrates. These results indicate that thermoplastic interlayers are most effective under dynamic loading, where their energy absorption capacity is fully mobilized.

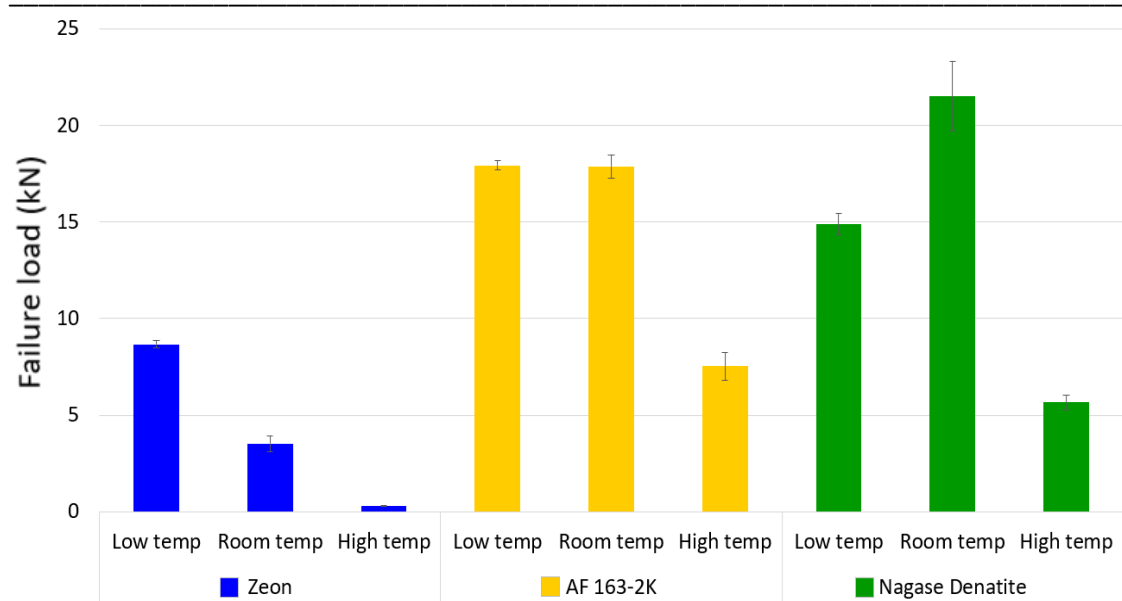


Figure 32: Summary chart of the experimental results of Paper A under quasi-static condition

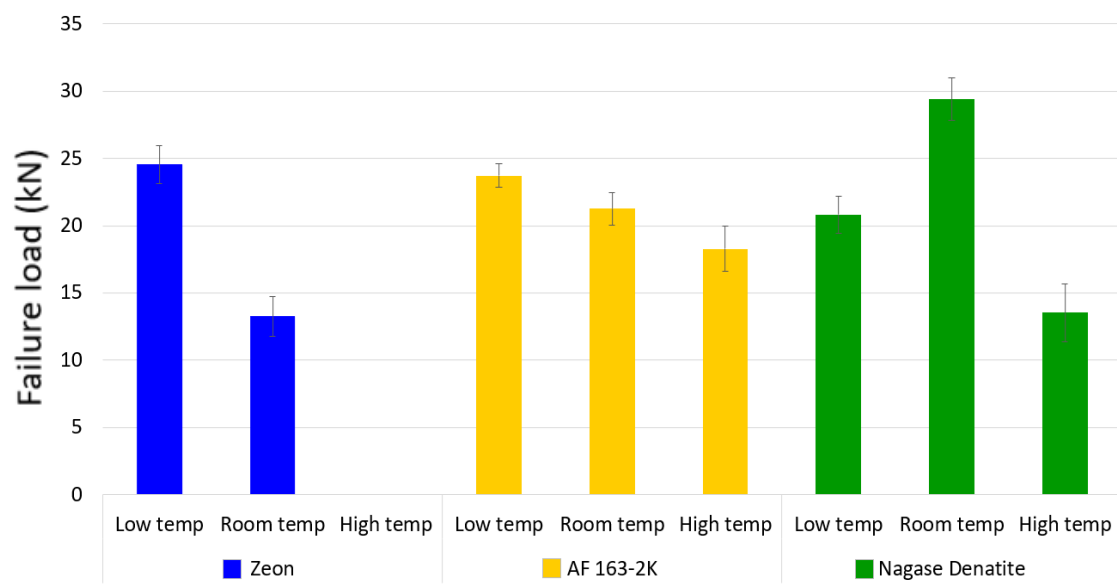


Figure 33: Summary chart of the experimental results of Paper A under impact condition

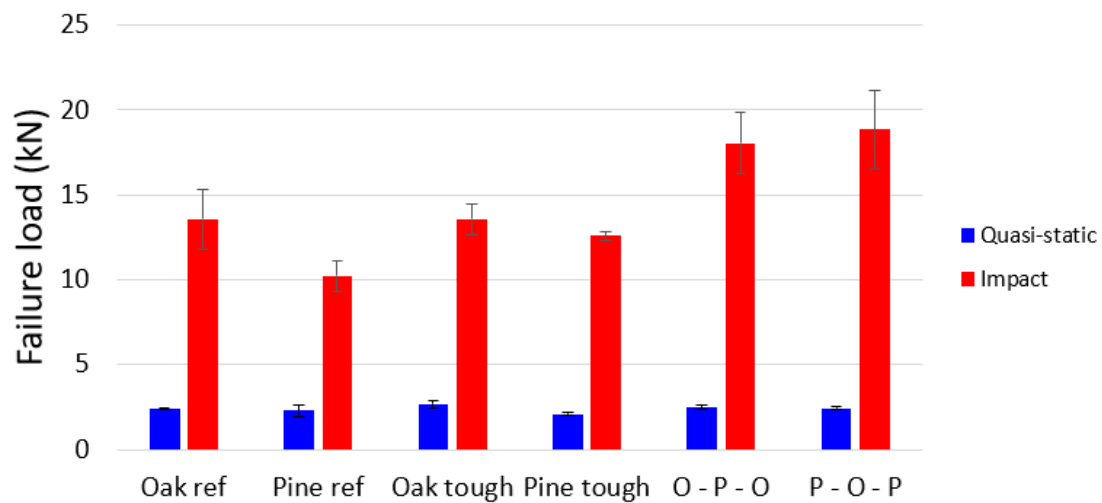


Figure 34: Summary chart of the experimental results of Paper B

Temperature effects were critical in the CFRP study but not in the wood study. The LS-XU adhesive showed excellent performance at $-30\text{ }^{\circ}\text{C}$, acceptable performance at room temperature, and a complete loss of load-bearing capability at $80\text{ }^{\circ}\text{C}$ due to its low glass transition temperature. This limitation does not arise in the wooden joints, which were tested only at ambient conditions, but it underscores the need to tailor thermoplastic chemistry to broaden their operational envelope for multi-environment service.

Finally, both works demonstrate that while thermoplastic interlayers alone cannot, in some cases, completely eliminate delamination, they can significantly delay its onset and improve the energy absorption capacity of bonded joints. This makes them an attractive lightweight reinforcement strategy. In the case of CFRPs, the main advantage lies in maintaining adherend integrity for repairability, while in wood joints the benefit is seen in stress redistribution, particularly in hybrid configurations.

Taken together, these studies establish a strong case for the broader adoption of thermoplastic adhesive films as versatile, recyclable, and process-friendly solutions to improve the performance of adhesively bonded joints across different materials and loading conditions.

5. Conclusions

This thesis investigated the potential of cyclic olefin-based thermoplastic film adhesives to mitigate delamination and improve the performance of single-lap joints (SLJs) manufactured from two distinct classes of substrates: carbon-fiber reinforced plastics (CFRPs) and wood. The adhesive performance was benchmarked against conventional structural epoxies (AF 163-2k and Nagase Denatite) in the case of CFRP joints, and compared against reference, toughened, and hybrid configurations in the case of wood joints. Quasi-static (1 mm/min) and impact (3 m/s) loading conditions were studied, and the effect of environmental temperature was assessed for CFRP joints.

- Failure mode control

In both CFRP and wood systems, the introduction of a thermoplastic film altered the failure mechanisms. For CFRP joints, Zeon LS-XU promoted adhesive failure instead of delamination, preserving the integrity of the adherends and thus facilitating reparability. In wood joints, the film delayed delamination initiation, improving energy absorption even though delamination was not completely eliminated.

- Strain-rate sensitivity

The thermoplastic adhesive displayed a marked dependence on loading rate. While its quasi-static performance remained modest, under impact conditions its relative performance improved significantly. In CFRP joints, the Zeon adhesive even surpassed the benchmark epoxies at $-30\text{ }^{\circ}\text{C}$ impact loading. In wood joints, the hybrid oak–pine configurations provided up to 84% higher failure loads than reference specimens, confirming the positive role of stress redistribution and wave propagation in dynamic conditions.

- Temperature effects in CFRP joints

Temperature strongly influenced adhesive performance. At room temperature, Zeon showed inferior strength compared to structural epoxies but still avoided delamination. At $-30\text{ }^{\circ}\text{C}$, it combined high impact resistance with favorable failure modes, making it suitable for low-temperature applications. At $80\text{ }^{\circ}\text{C}$, however, its performance was severely degraded due to its low glass transition temperature, rendering it unsuitable for high-temperature service environments.

- Energy absorption

In both CFRP and wood joints, the presence of the thermoplastic film increased energy absorption relative to reference configurations. This was particularly notable under impact conditions, where the adhesive's ductility and strain-rate sensitivity contributed most effectively.

- Overall assessment

The studies demonstrate that cyclic olefin-based thermoplastic film adhesives provide a lightweight, recyclable, and process-friendly solution to enhance the impact performance of adhesively bonded joints. Their main advantages are the preservation of adherend integrity (CFRP) and improved stress distribution (wood). Their primary limitation remains their poor thermal stability, which restricts application in elevated-temperature environments.

6. Future Work

The research presented in this thesis could be further developed through additional investigation in the following areas:

- Investigate the long-term performance of this thermoplastic film adhesive under cyclic thermal and moisture exposure and also study the effects of UV radiation, freeze-thaw cycles and biological degradation, in order to simulate real-world service environments.
- Conduct fatigue testing under cyclic loading to assess durability over the lifespan of the joint and also evaluate creep performance of the thermoplastic at varying temperatures, particularly for applications in warm or humid climates.
- Explore multi-adhesive strategies, combining structural and thermoplastic adhesives in a single joint (e.g., core ductile layer with stiff outer layers), aiming to balance strength and toughness. Investigate graded adhesive layers or multi-phase adhesives to further tailor the stress distribution and improve joint resilience.
- Extend to cohesive zone modeling and mixed-mode fracture scenarios or use XFEM (Extended Finite Element Method) to capture crack initiation without predefined paths. Incorporate temperature-dependent material models for the thermoplastic adhesive and validate with time-dependent data.
- Explore recyclability and disassembly of joints bonded with this thermoplastic film, aiming to design reversible or repairable bonded joints for circular economy applications. Conduct a life cycle assessment (LCA) comparing thermoplastic-bonded joints to conventional structural adhesives.

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Appendices

Paper A

Comparative study of CFRP single-lap joints bonded with structural epoxies and a novel hot-melt film adhesive: effects of temperature and loading rate

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Abstract: Delamination remains a critical limitation in the structural application of composite materials, particularly in adhesively bonded joints. This study investigates an alternative approach to delay delamination by using a non-structural thermoplastic adhesive to join both substrates of the joint. The proposed method does not rely on mechanical reinforcement but rather on the intrinsic properties of the thermoplastic to absorb energy and mitigate crack propagation. Single lap joints (SLJs) were tested under two displacement rates - quasi-static (1 mm/min) and impact (3 m/s) - to evaluate the strain rate sensitivity of the reinforcement. Additionally, the performance was assessed across three environmental conditions: sub-zero ($-30\text{ }^{\circ}\text{C}$), room temperature, and elevated temperature ($80\text{ }^{\circ}\text{C}$), to study thermal effects on the adhesive's mechanical behavior. Results demonstrated that delamination can be completely avoided, showing that the presence of the thermoplastic layer delayed its onset and increased the energy absorption capacity of the joint, particularly under impact and low-temperature conditions. The findings suggest that non-structural thermoplastics may offer a lightweight and effective delamination mitigation strategy for composite joints operating in variable service environments.

Keywords: CFRP; Single Lap Joint; Delamination; Adhesive Bonding; Impact; Hot melt adhesive.

1 Introduction

In recent years, composite materials have gained increasing prominence in engineering applications that demand high mechanical performance in combination with weight reduction [1,2]. Their use, once concentrated in aerospace structures, has expanded to

diverse sectors such as automotive manufacturing, renewable energy, sports equipment, and consumer electronics [3].

Among these materials, fiber-reinforced plastics (FRPs) stand out due to their high specific stiffness, excellent strength-to-weight ratio, and design flexibility, making them highly attractive for lightweight structural solutions across a broad spectrum of industries.

For instance, more recently, structural battery composites (SBCs), a component used for energy storage while also being able to carry structural loads, have emerged as a multifunctional alternative, with companies such as Airbus and Volvo actively investigating their integration into aircraft components and electric vehicle platforms to simultaneously reduce structural weight and provide onboard energy storage [4-6].

Despite these advantages, the widespread adoption of FRPs in load-bearing applications remains challenged by the development of reliable and durable joining techniques. Adhesive bonding is often preferred over mechanical fastening because composites exhibit notch sensitivity and limited tolerance to stress concentrations [7]. In addition, adhesive joints contribute minimally to structural weight, which is critical for energy-efficient applications such as electric vehicles and unmanned aerial systems [8]. However, bonded joints in composites are particularly prone to delamination, typically initiated by peel stresses or out-of-plane loading, which can lead to premature debonding between the fibers and the matrix and ultimately compromise the structural integrity of the joint [9-12].

To mitigate delamination, various reinforcement strategies have been explored, including Z-pinning [13], fiber stitching, tufting [14-16], change in stacking sequence [17], the use of interleaving layers [18], and the incorporation of fibre metal laminates (FMLs) [19-22]. While these approaches can be effective, they are not without limitations. Z-pinning, stitching, and tufting often disrupt the fiber architecture, reducing in-plane stiffness and fatigue resistance, while interleaving layers may complicate the curing process. FMLs, although highly effective in delaying crack propagation and improving damage tolerance, add significant weight and may reduce the overall specific mechanical efficiency of the joint [23,24]. Moreover, most of these methods are difficult to implement in standard industrial prepreg-based manufacturing processes [13,25].

This study explores an alternative solution based on the use of a thermoplastic hot melt adhesive (HMA) film - Zeon's cyclic olefin-based adhesive - developed for multi-material bonding. Compared to conventional epoxy adhesives, this thermoplastic film offers distinctive advantages, including high impact resistance and enhanced flexibility. Furthermore, its lightweight, non-tacky, and recyclable nature, together with its thermoplastic processability, aligns well with current demands for durable and sustainable materials in fields such as green transportation and modular construction [26].

The objective of this work is to evaluate the ability of Zeon's thermoplastic adhesive film to improve the delamination resistance of CFRP single-lap joints (SLJs) under different thermal conditions. Experimental testing is conducted at -30 °C, room temperature (≈ 23 °C), and 80 °C, representing service environments relevant to sectors ranging from cold-climate infrastructure to electronic housings exposed to elevated temperatures.

While existing reinforcement strategies have made important progress, they remain limited by weight penalties, fiber misalignment, or poor compatibility with industrial prepreg processes. In contrast, the thermoplastic adhesive investigated in this study provides a lightweight, recyclable, and process-friendly solution that not only suppresses delamination but also enhances intrinsic energy absorption of the joint under impact loading. Furthermore, by evaluating its performance across a wide temperature range

(−30 °C to 80 °C), this work offers new insights into the suitability of thermoplastic adhesives for multi-environment service conditions, an area that remains largely unexplored in the literature.

A single-lap joint (SLJ) configuration was selected for testing, given its widespread use in industry and structural simplicity. The study focuses on evaluating the failure load, failure mode, and energy absorption capacity of the joints. Joints manufactured using the new LS-XU adhesive are compared against conventional structural epoxies as a benchmark.

2 Experimental details

2.1 Adherend

The adherends used in the tested SLJ configurations were made of a composite material - specifically, a Carbon Fiber Reinforced Plastic (CFRP). This material was provided by CIT Composite Materials in Italy in the form of a prepreg roll, commercially known as HS 160 T700. It is a carbon-epoxy composite with fibers aligned in the 0° direction. The orthotropic elastic properties of the CFRP were previously identified by Campilho et al. (2005) [27] and are listed in Table A. 1

The fracture toughness of CFRP under mode I and mode II loading conditions was investigated by Machado et al. (2017) [28,29] examining how it varies with temperature and strain rate. The fracture energies under quasi-static conditions were experimentally determined and then a logarithmic trend was used to estimate these properties for low-velocity impact scenarios. The tensile and shear strength values for CFRP were obtained from research conducted by Shang et al. (2018) [25] The key cohesive properties of the CFRP are also outlined in Table A. 1.

Table A. 1: CFRP elastic orthotropic properties [25,27-29]

Properties	Value
Longitudinal Young's modulus (MPa)	109000
Transverse Young's modulus (MPa)	8819
Poisson's ratio (x to y direction)	0.342
Poisson's ratio (y to z direction)	0.38
Shear modulus in the x-y plane (MPa)	4315
Shear modulus in the y-z plane (MPa)	3200
Maximum tensile strength (MPa)	40
Maximum shear strength (MPa)	35
Mode I fracture toughness (N/mm)	0.59
Mode II fracture toughness (N/mm)	1.17

2.2 Adhesives

The adhesive used in this study was a 0.4 mm thick cyclic olefin-based thermoplastic film (LS-XU), a multi-material adhesive (MMA) developed by Zeon® Corporation (Chiyoda-ku, Tokyo, Japan). It is a hot-melt film designed for multi-material bonding applications.

Processing followed the manufacturer's specifications: curing at 150 °C under 10 bar for 1 hour, followed by gradual cooling to room temperature with the press and heating system switched off.

In parallel with this work, the mechanical properties of the HMA were characterized under quasi-static conditions. Table A. 2 summarizes the properties most relevant to its performance in quasi-static loading as well as its shear properties.

Table A. 2: Elastic properties of the hot-melt adhesive film

Properties	Value
Young's modulus (MPa)	230.18
Yield strength (MPa)	5.49
Ultimate tensile strength (MPa)	10.86
Poisson's ratio	0.47
Strain at failure	10.66
Shear modulus (MPa)	76.67
Maximum shear strength (MPa)	5.09
Shear strain at failure	3.54

In order to do some benchmark and find out if this new cyclic olefin-based Zeon adhesive can compete with the different adhesives available in the market and be an option to substitute them, two different structural epoxy adhesives were used under the same testing conditions. These adhesives are the 3M Scotch AF 163-2k, an "epoxy structural adhesives in film form" [30] and the Nagase Denatite XNR 6852 E3, a paste adhesive designed for CFRP-CFRP and CFRP-metal interfaces [23]. Both these adhesives were previously characterized and their properties are presented in Table A. 3 and Table A. 4, respectively.

Table A. 3: AF 163-2k mechanical properties [23,31]

Properties	Value
Young's modulus (MPa)	1520
Shear modulus (MPa)	565
Tensile strength of the adhesive layer (MPa)	46.93
Shear strength of the adhesive layer (MPa)	46.86
Mode I fracture toughness (N/mm)	4.05
Mode II fracture toughness (N/mm)	9.77

Table A. 4: Nagase Denatite XNR 6853 E3 mechanical properties [32]

Properties	Value
Young's modulus (MPa)	1728
Shear modulus (MPa)	665
Tensile strength of the adhesive layer (MPa)	51.50
Shear strength of the adhesive layer (MPa)	44.90
Mode I fracture toughness (N/mm)	9.20
Mode II fracture toughness (N/mm)	51

As this study focuses on the response of the joint when submitted to various different temperatures, it is important to note the different glass transition temperature (T_g) given by the datasheet of each adhesive under study. The HMA presents a T_g of 85 °C, which is much lower than that of both structural epoxies – 108 °C for the AF 163-2k and 100 °C for the Nagase Denatite.

2.3 Single lap joint: geometry and manufacture

The geometry of the manufactured SLJs were as shown in Figure A.1. This reference configuration was used for the three different adhesives under study - in exception to the adhesive thickness, which was 0.2 mm for the benchmark - in order to compare the results of the newly developed thermoplastic adhesive against two well-known structural epoxies that are substantially used in the industry nowadays.

The manufacturing process for SLJs with film adhesives was co-curing, which means the stacked CFRP and adhesive were cured simultaneously. It began with stacking the CFRP laminate using the hand lay-up method until the desired thickness was reached, considering the 0.15 mm thickness of each prepreg layer for the adherends. An aluminum mold coated with release agent was then used to ensure easy removal after curing, while shim tapes served as spacers to precisely control the adhesive layer thickness. The stacked laminate was then bonded together and subjected to the curing process. Following the manufacturer's specifications, the curing conditions for the Zeon and AF 163-2K film adhesives were 150 °C and 130 °C, respectively, under 10 bar for 1 hour. However, the paste Nagase adhesive could not be manufactured using the co-curing approach, and therefore the secondary bonding approach was adopted to prepare the SLJs with this adhesive. In this approach, the CFRP adherends were first stacked manually and cured at 135 °C under 10 bar for 1 hour. The cured CFRP laminate was then cut to the adherend dimensions shown in Figure A. 1. In the second stage, the Nagase paste adhesive was applied, and using a specific aluminum mold that enabled precise dimensional control, the cured CFRP adherends were joined together with the paste adhesive at 150 °C for 3 hours under 9 bar pressure. Furthermore, it is important to mention that there is no significant effect on the strength of the joints when changing the curing approach, namely co-curing and secondary bonding [23].

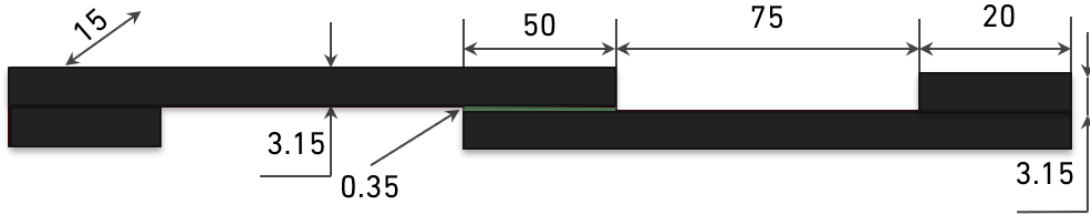


Figure A. 1: Single lap joint geometry (dimensions in mm)

2.4 Testing conditions

Five specimens were tested for each loading condition and temperature setting in this study.

For the quasi-static tests, single-lap joints (SLJs) were evaluated using an Instron 8801 servo-hydraulic testing machine equipped with a 30 kN load cell. The experiments were conducted at a constant displacement rate of 1 mm/min in accordance with ASTM D5868-01 (2014) [33].

Impact testing was performed on a custom-built drop-weight machine [34], capable of releasing a 56 kg mass from a maximum height of 1.27 m, corresponding to an impact velocity of 5 m/s. In this study, a 10 kg mass was dropped at 3 m/s, generating an impact energy of 108 J.

Displacement was determined through trapezoidal integration of the load–time curves and validated using high-speed video recordings combined with Digital Image Correlation (DIC) for improved accuracy. For this procedure, the specimens were painted white and afterwards they were once again painted with a black speckle, in order to contrast with the previous white paint applied. This way the high-speed camera could select the black dots from the speckle and capture them in different frames of the video, measuring their exact displacement between the frames under study.

Furthermore, all tests were performed at three distinct temperatures: -30 °C, room temperature (approximately 23 °C), and 70 °C. A thermal chamber was used to isolate the specimens and ensure that the target temperature was consistently maintained during testing.

3 Results

It should be noted that the results for both quasi-static and impact loading at room temperature using the structural epoxies AF 163-2k and Nagase Denatite were previously reported by Morgado (2019) [23], therefore, they do not present standard deviation in their P- δ graphs. Those results will be compared with the results in this study.

3.1 Room temperature ($\approx 23^\circ\text{C}$)

The load–displacement curves for the three adhesives under quasi-static loading at room temperature are illustrated in Figure A. 2. The HMA film exhibited an average failure load of 3.53 ± 0.41 kN, which is considerably lower than the values obtained with the structural adhesives - 17.48 kN for AF 163-2k and 19.87 kN for Nagase Denatite - highlighting its weaker mechanical performance.

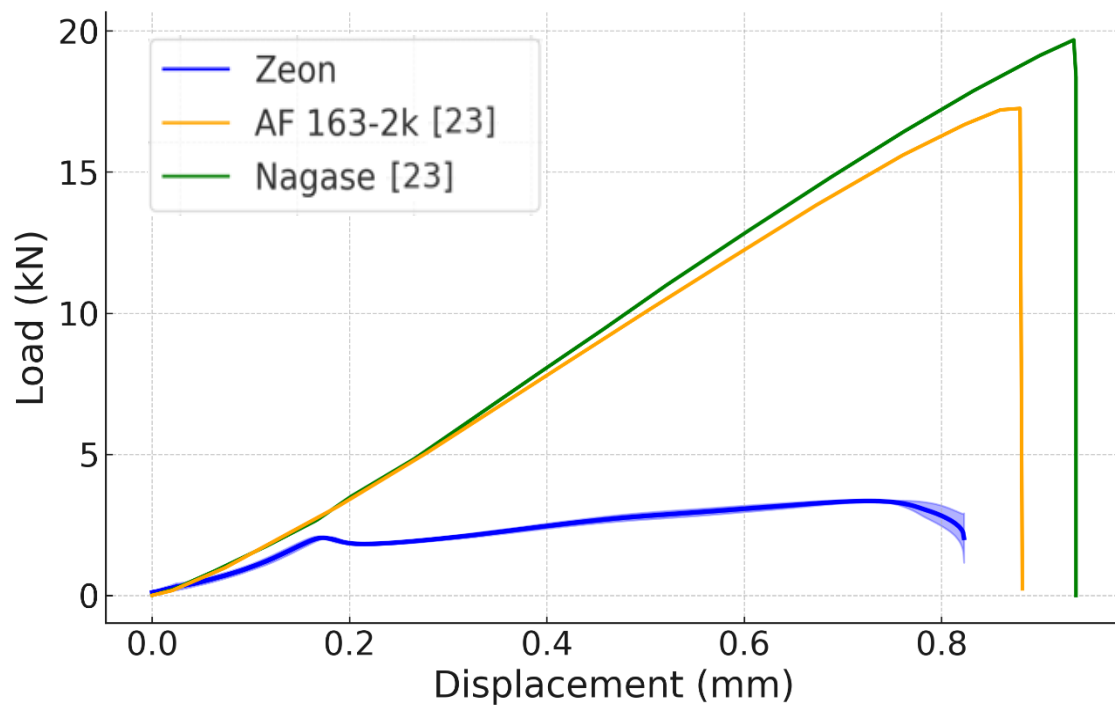


Figure A. 2: Experimental P- δ curves under quasi-static and room temperature conditions for the HMA and for both epoxies (reported by Morgado (2019) [23])

Despite this lower strength, the HMA demonstrated a distinct failure mode compared to the structural adhesives. Whereas the joints bonded with AF 163-2k and Nagase Denatite both failed by delamination of the CFRP, the ones that were manufactured using the cyclic olefin-based HMA failed adhesively. This failure mode preserves the integrity of the CFRP adherends and offers practical advantages, as the joint can be more easily repaired through rebonding or reapplication of the adhesive. The observed failure modes for all three adhesives are shown in Figure A. 3.

A scheme of the crack path for the three different specimen types is provided in Figure A. 4.



a) Zeon LS-XU

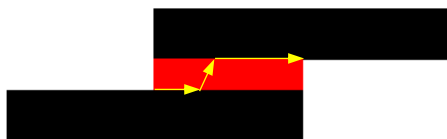


b) AF 163-2k [23]

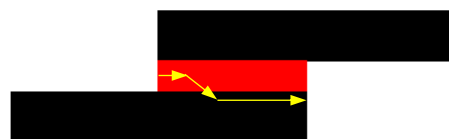


c) Nagase Denatite [23]

Figure A. 3: Failure modes obtained using the three different adhesives under quasi-static and room temperature conditions



Adhesive a)



Adhesives b) and c)

Figure A. 4: Crack path scheme for the three different adhesives under quasi-static and room temperature conditions – a) Zeon LS-XU; b) AF 163-2k; c) Nagase Denatite

Regarding the performance of the joints at room temperature under impact conditions, the average failure load was 13.25 ± 1.46 kN when using the HMA, 21.27 ± 1.20 kN for the joints with the structural AF 163-2k film and 29.40 ± 1.60 kN while using the Nagase Denatite epoxy, as Figure A. 5 illustrates. Once again, due to its weaker mechanical properties, the joints that were manufactured using the HMA, could not compete against the joints that were manufactured using structural epoxies.

Even though the HMA joints showed a reduced failure load relative to both structural adhesives, they presented adhesive failure while the joints that used both structural adhesives failed by delamination in the CFRP layer, as shown by Figure A. 6. As discussed before this is a preferable failure mode because it does not damage the CFRP adherend and is also much easier to repair.

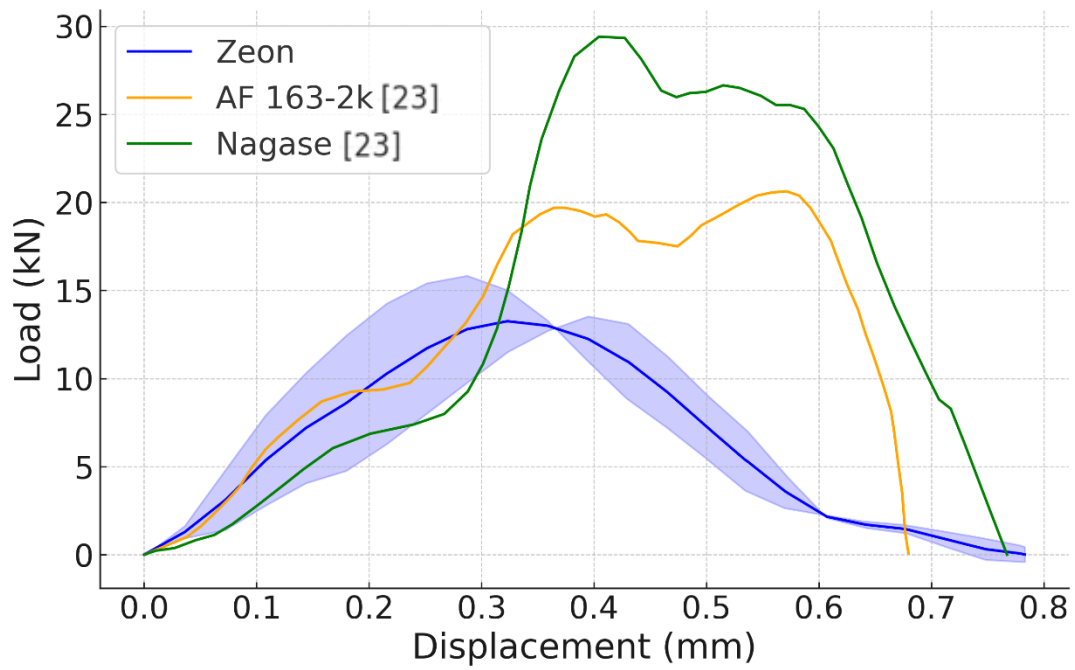
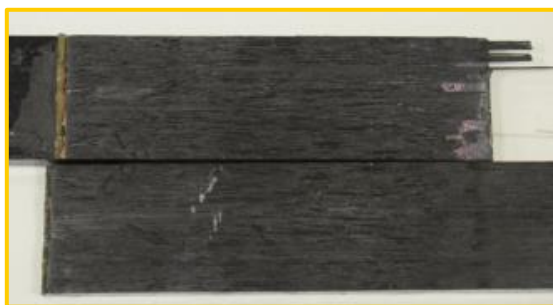


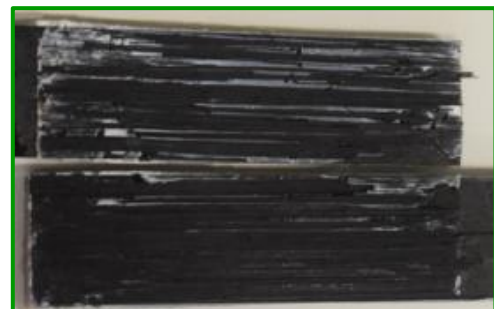
Figure A. 5: Experimental P- δ curves under impact and room temperature conditions for the the HMA and for both epoxies (reported by Morgado (2019) [23])



a) Zeon LS-XU



b) AF 163-2k [23]



c) Nagase Denatite [23]

Figure A. 6: Failure modes obtained using the three different adhesives under impact and room temperature conditions

In order to better understand the failure mode of the joints while using the three distinct adhesives, a scheme of the crack paths is depicted in Figure A. 8.



Figure A. 8: Crack path scheme for the three different adhesives under impact and room temperature conditions – a) Zeon LS-XU; b) AF 163-2k; c) Nagase Denatite

Overall, the specimens bonded with the HMA film showed unsatisfactory performance at room temperature, as their load-bearing capacity was significantly lower than that of the benchmark structural adhesives. However, unlike the other two adhesives, which failed by delamination, the HMA exhibited adhesive failure - a more favorable outcome since it preserves the integrity of the CFRP adherends.

The performance of the joints bonded with the HMA against the benchmarks – AF 163-2k and Nagase Denatite – can be seen in Figure A. 9. The increase of the failure loads for the three adhesives when the loading condition changes from quasi-static to impact is related to the strain rate dependency of polymers, which is even more accentuated in the HMA – with a rise of 275.35% in the failure load from static to impact loading – while the AF 163-2k epoxy adhesive only improves 21.68% and the Nagase Denatite epoxy improves 47.96%, showing its ability to perform better under impact.

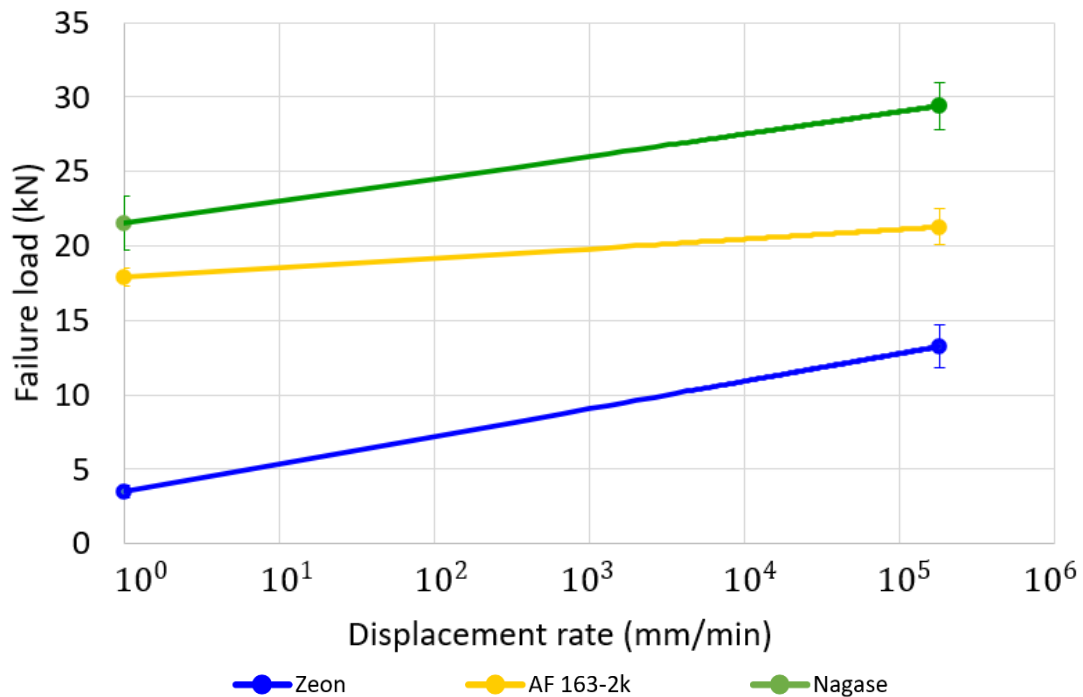


Figure A. 9: Summary of failure load of the HMA against benchmark at room temperature

Regarding the energy absorption of the specimens that were tested, it is important to state the smaller discrepancy, when compared with the failure load, between the HMA and both structural epoxies. In this case, the HMA provided a 63.89% increase from the static to the impact conditions, the structural film AF 163-2k showed a 13.80% increase and slightly lower than the 20.44% increase of the Nagase Denatite Figure A. 10 depicts

a summary of the energy absorption at room temperature under quasi-static and impact conditions.

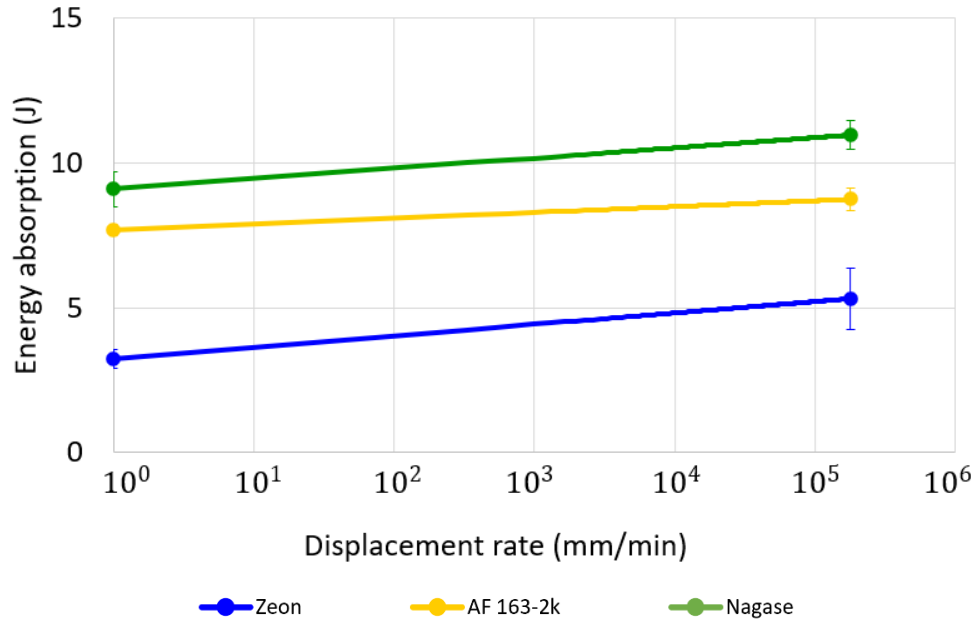


Figure A. 10: Summary of the energy absorption of the HMA against benchmark at room temperature

3.2 Low temperature (-30 °C)

At sub-zero temperature, in this case -30 °C, the performance of the three different adhesives under static testing are presented in Figure A. 11. The joints using the HMA film achieved an average failure load of 8.67 ± 0.18 kN, markedly lower than the values recorded for the specimens that used the structural adhesives, 17.93 ± 0.23 kN for AF 163-2k and 14.88 ± 0.54 kN for Nagase Denatite, underscoring, once more, its inferior mechanical performance.

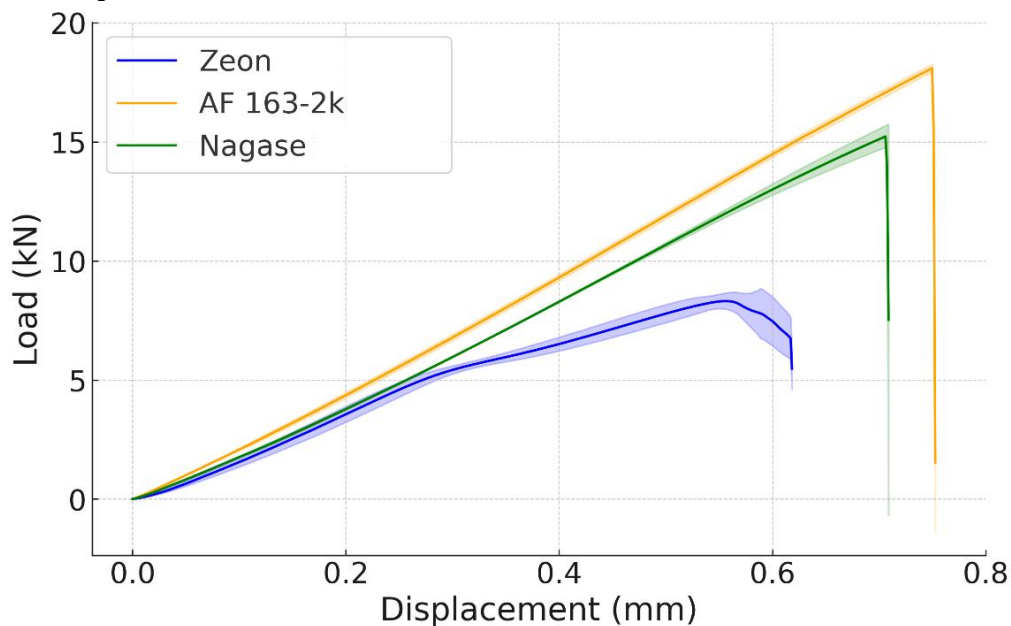


Figure A. 11: Experimental P-δ curves under quasi-static and low temperature conditions for the three distinct adhesives

Although the failure load of the HMA remains significantly lower than that of the benchmark adhesives, the observed improvement, when compared with the results obtained at room temperature, highlights its ability to be used at low temperatures. When lowering the temperatures, the adhesives tend to become stiffer and less ductile, which explains the lower displacement when compared to the results obtained at room temperature.

Anew, the joints manufactured using the HMA presented adhesive failure, while the joints that used the benchmark adhesives showed failure by delamination in the CFRP. This is favorable due to the reasons that were previously reported in section 3.1.

Figure A. 12 depicts the failure mode obtained when using the three different adhesives and Figure A. 13 shows an illustration of the crack path to provide a better visualization of the failure mode that was achieved.



a) Zeon LS-XU



b) AF 163-2k



c) Nagase Denatite

Figure A. 12: Failure modes obtained using the three different adhesives under quasi-static and low temperature conditions

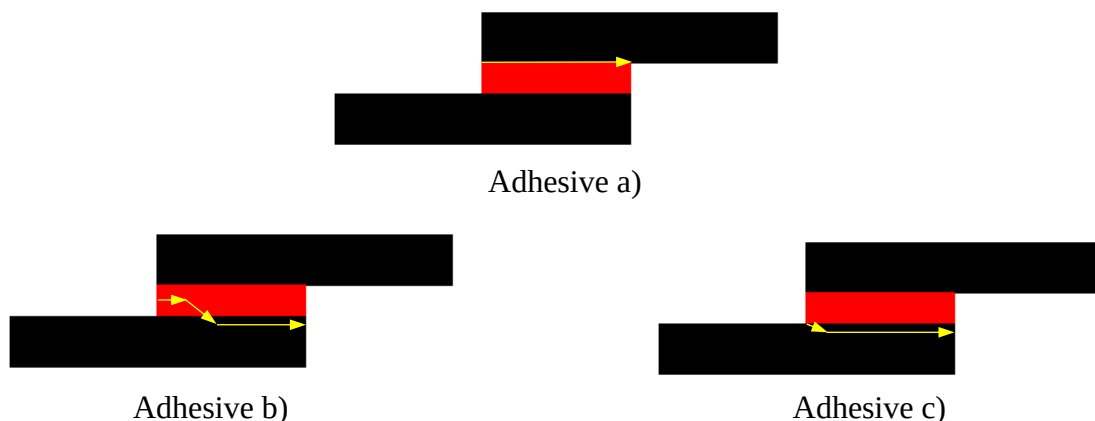


Figure A. 13: Crack path scheme for the three different adhesives under quasi-static and low temperature conditions – a) Zeon LS-XU; b) AF 163-2k; c) Nagase Denatite

When it comes to the behavior of the joints at $-30\text{ }^{\circ}\text{C}$ under impact loading conditions, the load-displacement curves for the three adhesives are illustrated in Figure A. 14. This set of conditions enabled the new HMA to deliver an outstanding performance, combining its high energy absorption capacity under impact loading with its suitability for sub-zero service temperatures.

The failure load for the joints where the HMA was applied was slightly higher than the joints where both the benchmark structural adhesives were applied, reaching values of $24.54 \pm 1.44\text{ kN}$, while the AF 163-2k showed a failure load of $23.74 \pm 0.91\text{ kN}$ and the Nagase Denatite presented a failure load of $20.84 \pm 1.37\text{ kN}$.

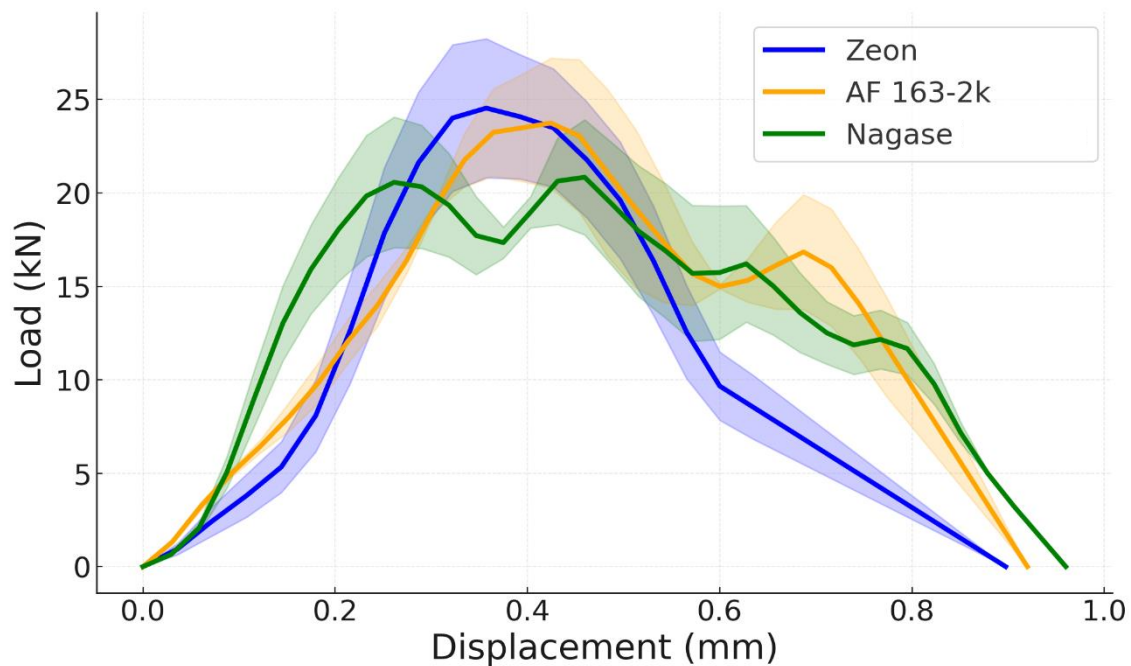


Figure A. 14: Experimental P- δ curves under impact and low temperature conditions for the three distinct adhesives

Furthermore, when analyzing the failure mode of the three different specimens (Figure A. 15 and Figure A. 16), the ones that employed the HMA presented the more acceptable failure mode. The joints where the HMA was used demonstrated an adhesive failure mode while, once again, the two structural adhesives showed failure by delamination in the CFRP, making the HMA the most suitable adhesive to use under impact loading at low temperature conditions.



a) Zeon LS-XU

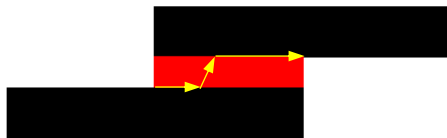


b) AF 163-2k

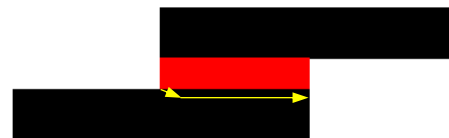


c) Nagase Denatite

Figure A. 15: Failure modes obtained using the three different adhesives under impact and low temperature conditions



Adhesive a)



Adhesives b) and c)

Figure A. 16: Crack path scheme for the three different adhesives under impact and low temperature conditions – a) Zeon LS-XU; b) AF 163-2k; c) Nagase Denatite

On the whole, when considering low service temperatures and specifically under impact conditions, the specimens that used the HMA showed a remarkable performance. Not only can this adhesive compete with the benchmarked structural adhesives when it comes to the loads it can withstand, but it also shows a more acceptable failure mode than the other two adhesives that were studied, which demonstrates that there also is room for improvement at the interface layer of the joint.

A summary of the performance of the three different adhesives at $-30\text{ }^{\circ}\text{C}$ is depicted in Figure A. 17. At low temperature, as observed under room temperature conditions, the HMA exhibited the greatest relative improvement when transitioning from quasi-static to impact loading, with an increase of 183.13%. In comparison, the AF 163-2k showed an improvement of only 32.37%, while the Nagase Denatite increased by 40.04%. These results show, once again, that HMA is the most strain rate dependent adhesive of all three.

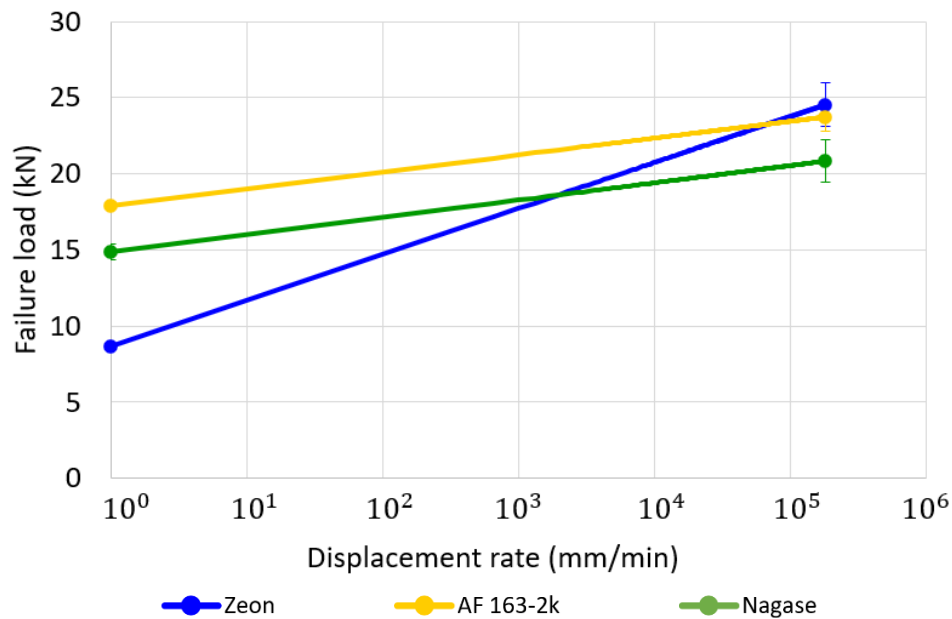


Figure A. 17: Summary of HMA against benchmark at low temperature

With respect to the energy absorption of the tested specimens, it is worth noting that the relative improvement when transitioning from quasi-static to impact loading is, once more, higher for the HMA when comparing with both epoxies. The HMA presents a 182.67% increase, while the AF 163-2k and the Nagase Denatite show 81.31% increase and 130.83% increase, respectively. Figure A. 18 summarizes the energy absorption results obtained at room temperature under both quasi-static and impact conditions.

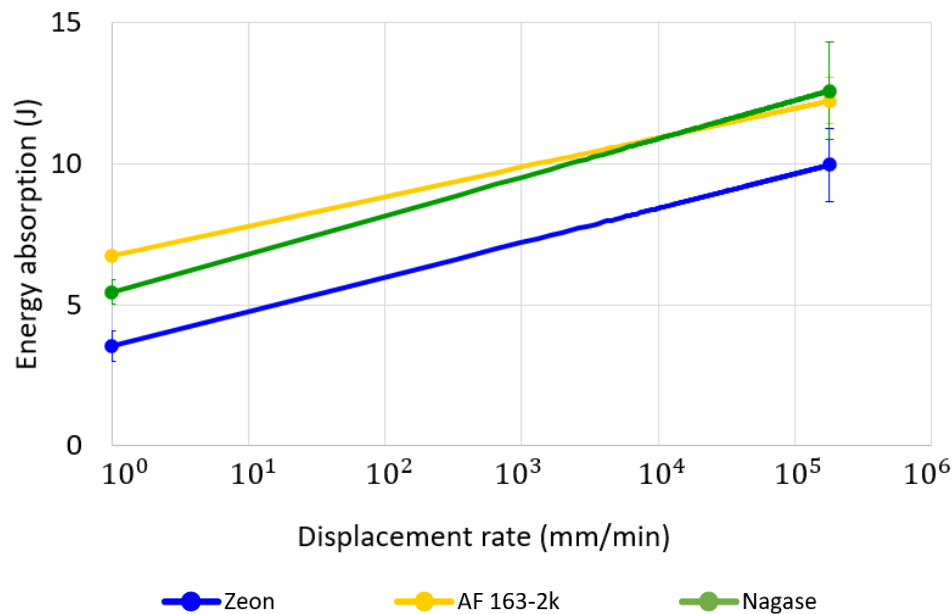


Figure A. 18: Summary of the energy absorption of the HMA against benchmark at low temperature

Although the specimens bonded with the non-structural HMA exhibited lower energy absorption than those manufactured with the structural epoxies - primarily due to the reduced displacement observed under impact loading - these results remain noteworthy,

as the HMA still demonstrates a competitive performance when compared with the benchmark materials.

3.3 High temperature (80 °C)

At high temperature (80 °C), the quasi-static performance of the three adhesives is shown in Figure A. 19. The joints where the HMA film was used reached an average failure load of 0.30 ± 0.02 kN, which is considerably lower than the values obtained with the structural adhesives: 7.53 ± 0.71 kN for AF 163-2k and 5.67 ± 0.38 kN for Nagase Denatite. These results, not only highlight the inferior mechanical strength of the HMA compared with the benchmark structural adhesives, but they also tell that the HMA is practically unusable at higher temperatures due to its low T_g (around 85 °C), while both structural adhesives also start to degrade they can still manage to withstand, somewhat, higher loads because their glass transition temperature is slightly higher (108 °C for the AF 163-2k epoxy and 100 °C for the Nagase Denatite epoxy).

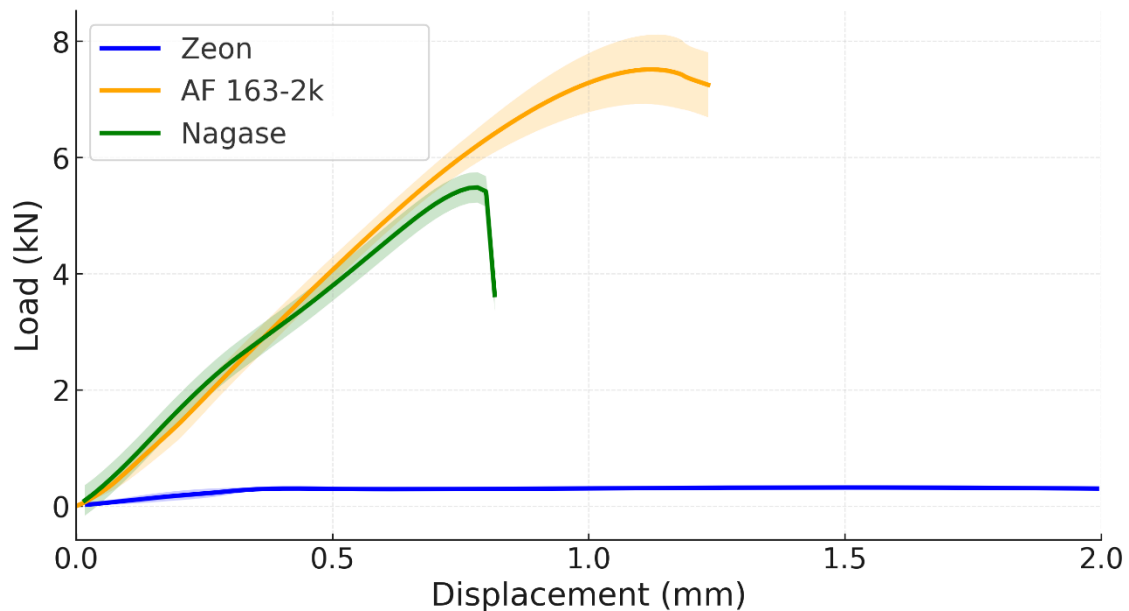


Figure A. 19: Experimental P- δ curves under quasi-static and high temperature conditions for the three distinct adhesives

Contrarily to the previous results, all three of the different manufactured specimens, presented similar failure mechanism. The failure mode in the joints that were bonded with the HMA was cohesive failure in the adhesive, the joints that used both structural epoxies presented a mixed failure mode – adhesive and cohesive in the adhesive – as Figure A. 20 illustrates. Figure A. 21 also depicts a representative drawing of the crack path in the three different adhesives.

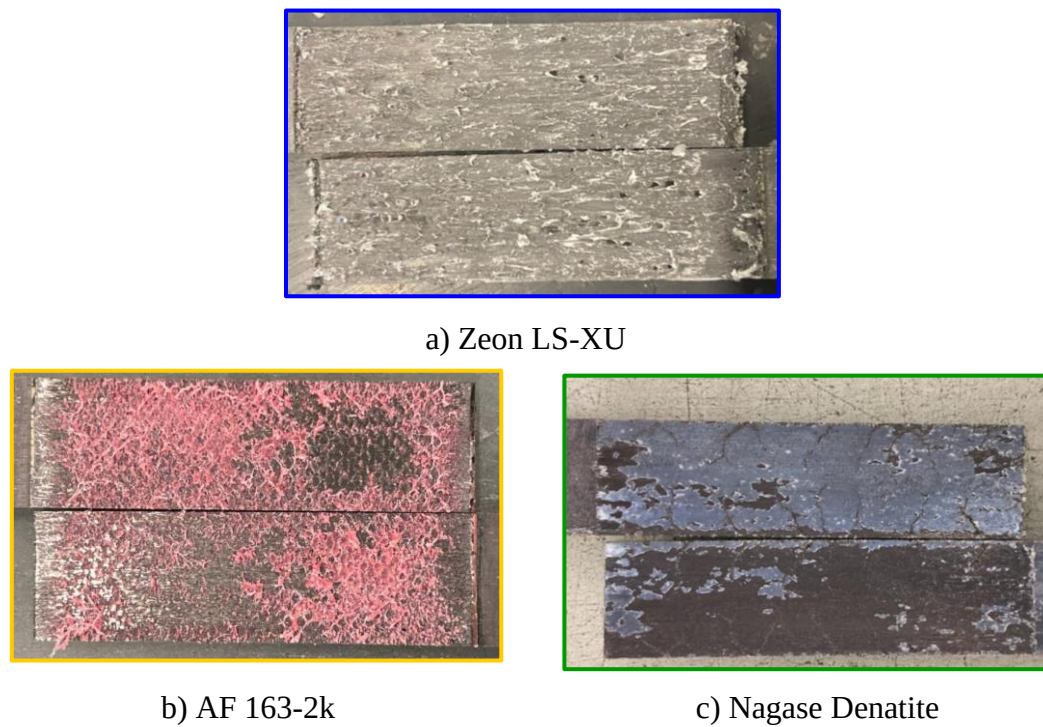


Figure A. 20: Failure modes obtained using the three different adhesives under quasi-static and high temperature conditions



Figure A. 21: Crack path scheme for the three different adhesives under quasi-static and high temperature conditions – a) Zeon LS-XU; b) AF 163-2k; c) Nagase Denatite

At 80 °C, under impact loading, the load–displacement curves for the two structural adhesives are shown in Figure A. 22. At 80 °C, the HMA film displayed severely reduced mechanical properties. The joints bonded with this adhesive could not be tested, as failure occurred prematurely under the self-weight of the drop-weight machine's grip, even before the impact test could be initiated. Since the joint could not be tested, there is not a representative load-displacement curve for the new HMA, still, as the grip weighs, 1.5 kg it is possible to estimate a failure load of 15 N, an impact failure load could not be obtained.

Nevertheless, the joints bonded with the AF 163-2k epoxy adhesive reached an average failure load of 18.28 ± 1.67 kN, slightly higher than those bonded with the Nagase Denatite epoxy, which exhibited a failure load of 13.52 ± 2.14 kN, as Figure A. 22 illustrates.

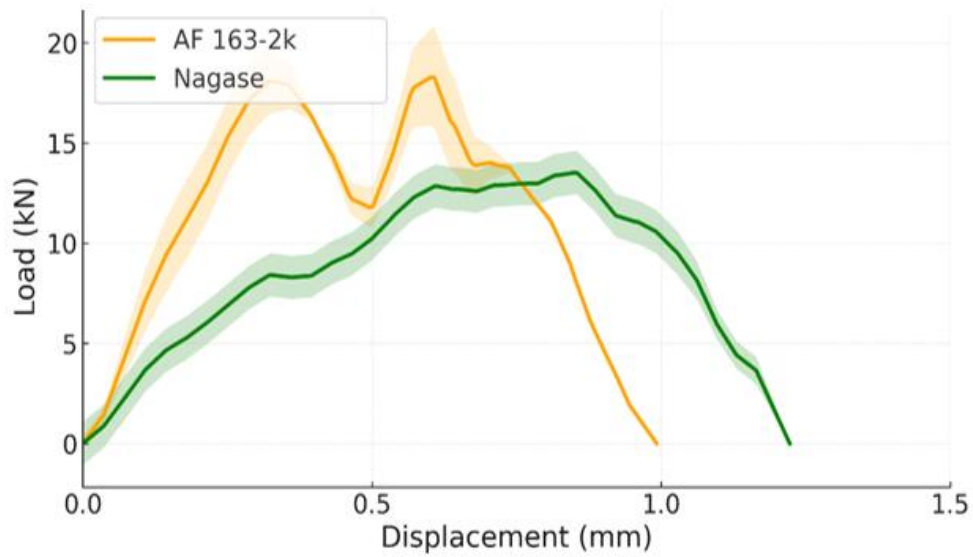
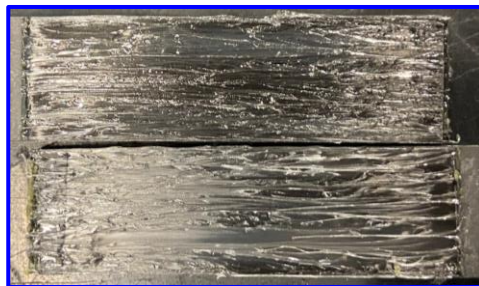


Figure A. 22: Experimental P- δ curves under quasi-static and high temperature conditions for the three distinct adhesives

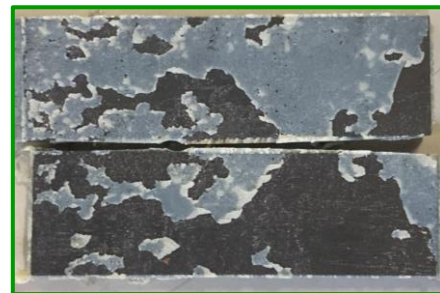
Moreover, the failure mode analysis (Figure A. 23) revealed that specimens with the HMA failed cohesively in the adhesive layer, as well as the joints that were manufactured using the AF 163-2k film adhesive, whereas the specimens using the Nagase Denatite epoxy failed adhesively. This makes the HMA impractical at high service temperatures, corroborating with the results obtained for the quasi-static loading conditions, as it barely has any strength. Regarding both epoxies, while the failure load is lower than the cases of low and room temperature, their failure mode is no longer delamination in the CFRP which preserves the capability of rebonding as a possible solution. The same can be observed in Figure A. 24.



a) Zeon LS-XU



b) AF 163-2k



c) Nagase Denatite

Figure A. 23: Failure modes obtained using the three different adhesives under impact and high temperature conditions



Figure A. 24: Crack path scheme for the three different adhesives under impact and high temperature conditions – a) Zeon LS-XU; b) AF 163-2k; c) Nagase Denatite

In conclusion, the new HMA is practically unworkable at high temperatures, mostly due to its relatively low glass transition temperature. Under the same high temperature conditions, this adhesive reveals a significant limited performance when compared with the two benchmarked structural adhesives.

A recapitulation of the performance of the three adhesives that were being studied at high temperatures is shown in Figure A. 25 and Figure A. 26.

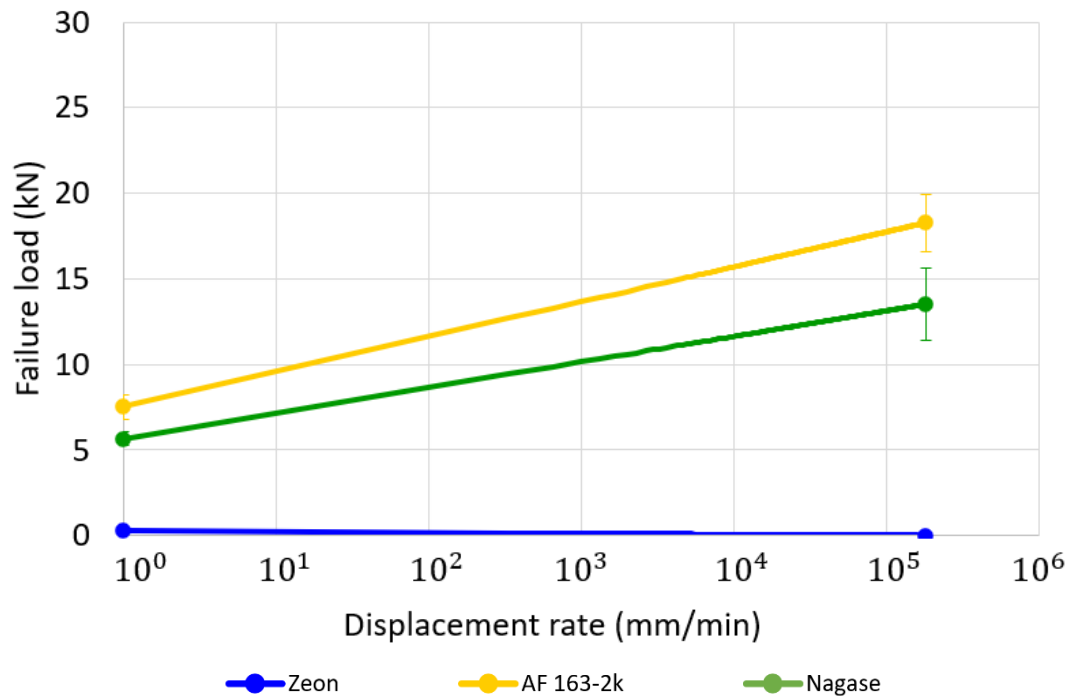


Figure A. 25: Summary of HMA against benchmark at low temperature

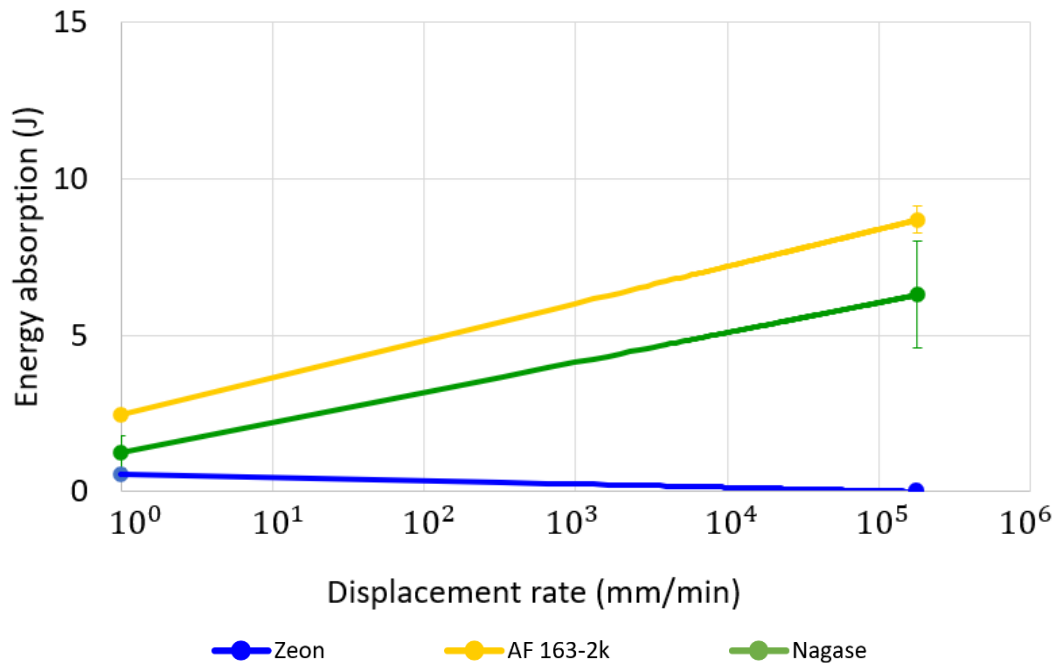


Figure A. 26: Summary of the energy absorption of the HMA against benchmark at low temperature

The subsequent images provide a synthesis of the experimental outcomes achieved in this investigation. Firstly, Figure A. 27 provides a concise overview of the quasi-static performance of each adhesive used in this study, with respect to both failure load and failure mode.

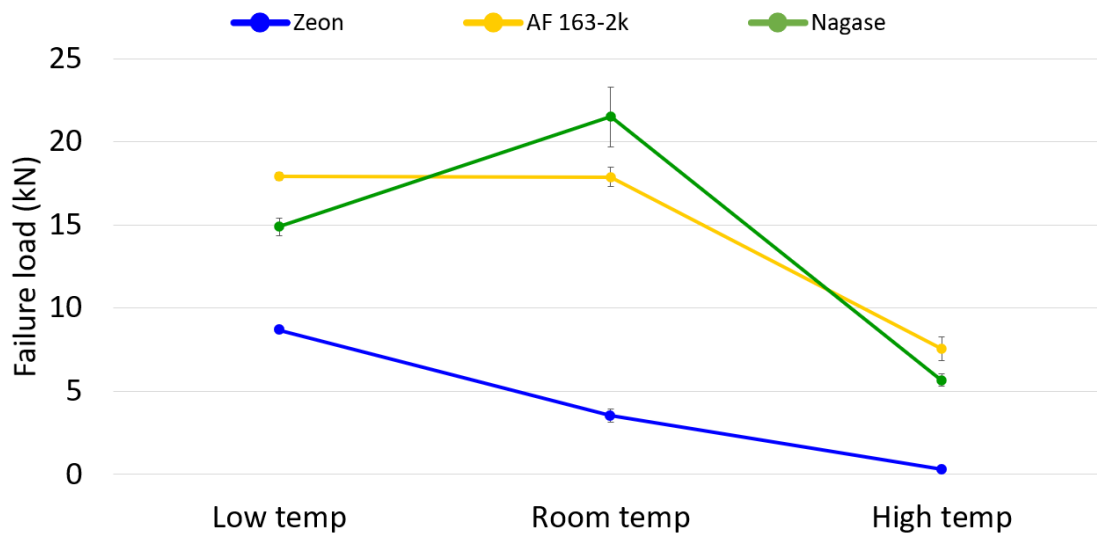


Figure A. 27: Summary chart of the experimental results under quasi-static conditions

The results clearly demonstrate that the new HMA performs way better at sub-zero temperatures, but they also demonstrate that, even though the non-structural film adhesive

behaves well at low temperature, it still cannot compete with both benchmark structural adhesives – AF 163-2k and Nagase Denatite.

Nonetheless, it is important to highlight the distinct failure mode exhibited by the joints bonded with the HMA. Unlike the structural adhesives, which failed by delamination at both low and room temperatures, the HMA joints did not experience this type of failure. Instead, the use of the new HMA film preserved the structural integrity of the CFRP adherends, providing notable advantages such as simplified repair procedures through rebonding or even reapplication of the adhesive.

Similarly, Figure A. 28 summarizes the corresponding results under impact loading. As expected, all configurations exhibited higher failure loads compared to their quasi-static performance, reflecting the strain-rate sensitivity of the adhesives. Furthermore, it can be concluded that the new HMA is more strongly influenced by strain rate than both structural epoxies, which explains its better behavior under impact conditions.

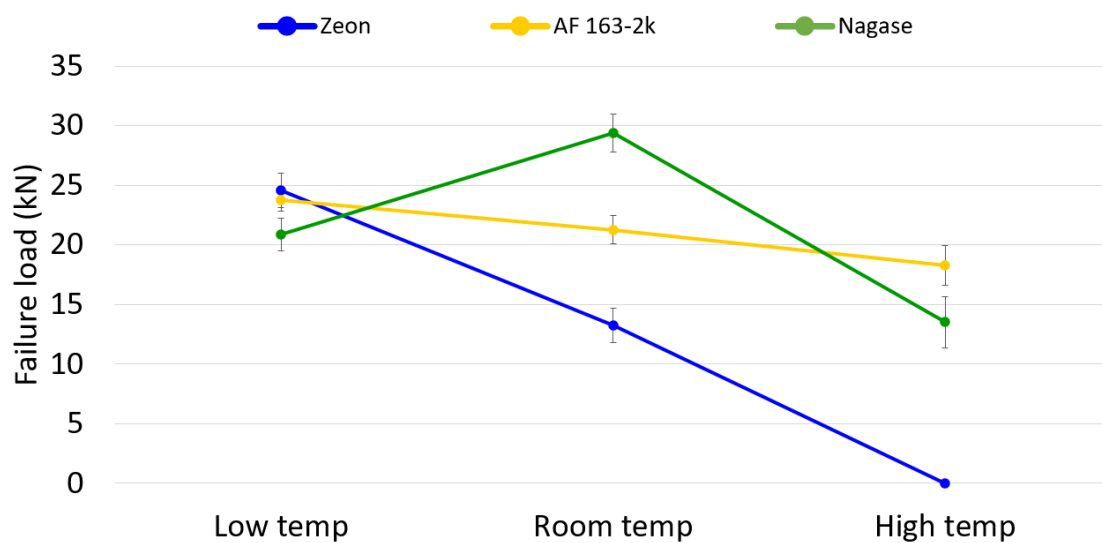


Figure A. 28: Summary chart of the experimental results under impact condition

Finally, the HMA film showed a superlative performance under impact and low temperature conditions when compared with both benchmark epoxies, revealing its capabilities absorb impact energy and its enhanced properties at low temperature.

4 Conclusions

This work investigated the effect of temperature on the performance of CFRP single-lap joints bonded with a novel cyclic olefin-based thermoplastic adhesive (Zeon LS-XU) and benchmarked against two structural epoxies, AF 163-2k and Nagase Denatite. Tests were performed under quasi-static and impact conditions at -30°C , room temperature, and 80°C .

- At room temperature, the HMA exhibited a significantly lower failure load compared to both structural epoxies. However, unlike the epoxies that failed by

delamination, the HMA joints failed adhesively, thereby preserving the integrity of the CFRP adherends and enabling simpler repair strategies.

- At sub-zero temperature ($-30\text{ }^{\circ}\text{C}$), the HMA adhesive showed markedly improved performance. Under impact loading, its joints even surpassed the benchmark adhesives in failure load, while maintaining adhesive failure as the dominant mode. This highlights the potential of Zeon LS-XU for low-temperature service environments where impact resistance is critical.
- At elevated temperature ($80\text{ }^{\circ}\text{C}$), the HMA proved unsuitable due to its low glass transition temperature ($\sim 85\text{ }^{\circ}\text{C}$). Joints bonded with this film failed prematurely, confirming that its use should be avoided in high-temperature service conditions.
- Strain-rate sensitivity was evident across all adhesives, with higher failure loads recorded under impact loading compared to quasi-static tests. The HMA, in particular, demonstrated pronounced strain-rate dependence, showing relatively better performance in impact than in quasi-static loading.
- Overall, while the HMA cannot compete with structural epoxies in terms of absolute strength across all conditions, it demonstrated outstanding potential at low temperature and under impact loads, with the additional benefit of avoiding delamination.

The results suggest that cyclic olefin-based hot-melt adhesives may provide a lightweight, recyclable alternative for applications requiring energy absorption and repairability, particularly in cold environments. Further optimization - such as increasing glass transition temperature or tailoring film thickness - could extend their applicability to broader service conditions.

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Paper B

Strengthening the substrates of wood single-lap joints using a novel hot-melt film adhesive to avoid delamination

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Abstract: Delamination remains one of the main challenges limiting the structural use of wood, particularly in adhesively bonded joints. This work explores an alternative method to delay delamination by introducing a non-structural thermoplastic adhesive as an interlayer to reinforce wooden substrates. Rather than relying on mechanical reinforcements, this approach takes advantage of the thermoplastic's inherent ability to absorb energy and slow crack growth. Single-lap joints (SLJs) were tested under two loading rates - quasi-static (1 mm/min) and impact (3 m/s) - to study the effect of strain rate on joint performance. Tests were also conducted using different configurations, namely two reference configurations, two toughened configurations which use extra 15 mm of adhesive in each side of the overlap and also two hybrid configurations that use both oak and pine wood, in order to better propagate the stress wave along the joint. The results showed that, although delamination was not completely eliminated, the presence of the thermoplastic layer delayed its initiation and significantly improved the joints' energy absorption capacity. Also, the use of the hybrid configurations exhibited an improvement in the strength of the joint especially under impact conditions. Furthermore, a finite element elastic model was developed and a stress analysis was performed, in order to demonstrate why the hybrid joints have more uniform stress distributions and subsequently displayed higher strengths. These findings indicate that incorporating non-structural thermoplastic interlayers can be an effective and lightweight strategy for reducing delamination in wood joints subjected to variable service conditions. The most effective strategy was the hybrid configuration under impact conditions, which delivered substantial strength gains - up to 84% compared to reference configurations - by propagating the stress wave through the core layer of the substrate.

Keywords: Wood adhesive joint; Single lap joint; Delamination; Adhesive bonding; Hybrid wood substrates; Impact; Numerical.

1 Introduction

Adhesive bonding technology is gaining prominence as a compelling alternative to traditional mechanical joining methods across numerous industries, including automotive, aerospace, and electronics. Compared to conventional joining techniques such as riveting or fastening, adhesive bonding offers notable advantages: it enables a continuous bond line, facilitating more uniform stress distribution and enhancing both load transfer and fatigue resistance. These features contribute to reduced overall weight and cost. Moreover, adhesive bonding allows for the joining of dissimilar materials and offers greater flexibility in joint design [1-3].

Wood, a naturally anisotropic material, presents an environmentally sustainable option for a variety of structural applications—even in domains where materials like steel, aluminum, or concrete have long been dominant. Its renewed appeal stems from its low carbon footprint and renewable nature, particularly when sourced through responsible forestry practices that safeguard long-term biodiversity and forest health [4,5]. Among the most attractive candidates for engineering applications are fast-growing wood species, valued for their rapid renewability. However, these woods often present limited mechanical performance, making them less suitable for demanding applications without further enhancement [2,6,7].

Wood structures are particularly sensitive to discontinuities such as holes, notches, or penetrations created by nails and screws. These discontinuities introduce local stress concentrations that cut through the fibers, disrupting the natural load-carrying capacity of the cellular structure and often leading to premature or even catastrophic failure. Moreover, the geometry of wood and its fiber orientation must be carefully considered, since mechanical behavior is strongly direction-dependent [8]. Recent studies highlight that introducing defects or altering the substrate microstructure accelerates delamination and weakens adhesive joints, further underlining the importance of avoiding stress concentrators in load-bearing wooden assemblies [4,9,10].

Wood joints play a pivotal role in structural integrity and are commonly achieved through adhesive bonding. A key metric in assessing joint quality is shear strength, which is influenced by the adhesive's chemical and physical properties, the wood's microstructure, and the process parameters [11,12]. The wood failure percentage (WFP) is another widely used indicator; higher WFP values generally reflect stronger joints, where failure occurs predominantly in the wood itself rather than at the adhesive interface [13,14].

In previous studies, strategies such as wood densification via thermo-hydropneumatic (THM) treatments have been used to improve mechanical properties and bonding performance [15-17]. However, such processes are often associated with drawbacks like moisture sensitivity and set-recovery, which can lead to dimensional instability under cyclic environmental conditions [16,18]. While these methods offer material enhancement, they also introduce complexity and limitations in real-world applications [18].

In contrast, the present study explores an alternative approach that avoids the use of densified wood. Instead, different configurations of natural wood substrates with the use of a new hot melt adhesive (HMA) are proposed and investigated with the goal of minimizing delamination in adhesively bonded joints. This focus addresses one of the key

failure modes in wood bonding - delamination - by examining how layer arrangement influence joint performance.

In this work, novelty lies in the combined use of a cyclic olefin-based hot-melt adhesive film and hybrid pine–oak arrangements. In the one hand, this study provides a more lightweight option by using an HMA and alternating layers of pine and oak wood, avoiding the drawbacks of wood densification such as set-recovery, dimensional instability, and high processing demands. In the other hand, it offers a much simpler manufacturing process than wood densification and other methods, that preserves the natural structure of wood while improving the joints mechanical properties.

Although, the toughening and hybrid strategies barely presented any improvement in the joint's properties under quasi-static loading, when the hybrid configurations were tested under impact, there was a gain of up to 84% in terms of failure load when compared to the reference configurations. While, delamination under impact loading was never eliminated, this improvement in the joint's behavior shows the efficacy of this method.

SLJs were chosen for their relevance in industrial applications and ease of experimental standardization. The evaluation involves both experimental testing and numerical modeling using finite element analysis (FEA) to predict joint behaviour and stress concentrations in the joint. Through this work, the potential of Zeon's thermoplastic adhesive film to improve structural reliability and mitigate delamination in bonded composite assemblies is critically assessed [19].

2 Experimental details

To systematically evaluate the performance of the proposed reinforcement strategies, a comprehensive experimental procedure was designed. This included the preparation of single-lap joints using pine and oak substrates, bonded with a thermoplastic hot-melt adhesive film, under different joint configurations. Mechanical testing was performed under both quasi-static and impact loading conditions to capture the strain-rate sensitivity of the adhesive–wood interface. The following section details the materials, manufacturing procedures, and testing protocols employed.

2.1 Adherends

2.1.1 Pine wood

In this study, pine timber (*Pinus pinaster*) was one of the materials used for the SLJ substrates. The beams used to produce the adherends for the single lap joints had a cross-section as showed in Figure B. 1, although the thickness varied when manufacturing the hybrid specimens (1 and 4 mm). It should be noted that achieving perfect symmetry of the growth rings relative to a central vertical axis was not always feasible.

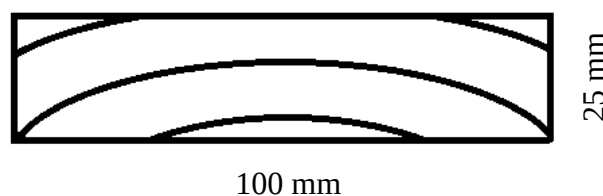


Figure B. 1: Illustration of the beams' cross-section dimensions and of the preferable ring orientation

Oliveira and Moura (2007) [20] have previously published the values of the nine elastic constants and strength properties on the longitudinal (L), radial (R) and tangential (T) directions for pine wood. These properties are summarized in Table B. 1

Table B. 1: Nominal orthotropic properties of pine wood [20]

Properties	Value
E_L (GPa)	12.00
E_R (GPa)	1.91
E_T (GPa)	1.01
ν_{LT}	0.51
ν_{LR}	0.47
ν_{TR}	0.31
G_{LR} (GPa)	1.12
G_{LT} (GPa)	1.12
G_{TR} (GPa)	0.29
Maximum longitudinal strength (MPa)	97.50
Maximum radial strength (MPa)	7.90
Maximum transverse strength (MPa)	4.20

The notation adopted in the table is defined as: Longitudinal Young's modulus (E_L), radial Young's modulus (E_R), transverse Young's modulus (E_T), Poisson's ratio (ν), shear modulus in the longitudinal-radial plane (G_{LR}), shear modulus in the longitudinal-transverse plane (G_{LT}), shear modulus in the transverse-radial plane (G_{TR}), maximum longitudinal strength (σ_L), maximum radial strength (σ_R), maximum transverse strength (σ_T).

2.1.2 Oak wood

The second material utilized during this research was oak wood (*Quercus alba*) was one of the materials used for the SLJ substrates. The cross-section dimensions of the oak wood beams were the same as the pine wood ones (Figure B. 1). The elastic properties of oak wood were obtained from the Oliveira and Moura [20] and Reiterer et al. [21] and are presented in the table below (Table B. 2)

Table B. 2: Nominal orthotropic properties of oak wood [20,21]

Properties	Value
E_L (GPa)	12.3
E_R (GPa)	2.05
E_T (GPa)	0.89
ν_{LT}	0.43
ν_{LR}	0.37
ν_{TR}	0.30

G_{LR} (GPa)	1.20
G_{LT} (GPa)	1.20
G_{TR} (GPa)	0.80
σ_L (MPa)	105
σ_R (MPa)	13.80
σ_T (MPa)	5.50

2.2 Adhesive

The 0.4mm thick cyclic olefin-based thermoplastic adhesive film named LS-XU is multi-material adhesive (MMA) developed by Zeon® Corporation (Chiyoda-ku, Tokyo, Japan) and was used in this study, it is a hot-melt film designed for multi-material bonding applications.

The adhesive was processed according to the manufacturer's guidelines, curing at 150 °C at 10 bar for 1 hour, followed by a gradual cooling at ambient temperature with the press and heating system being turned off.

For quasi-static conditions, the mechanical properties of the HMA have been characterized parallel to this work. A summary of the mechanical properties relevant to the adhesive performance under quasi-static conditions as well as the remaining shear properties required for the numerical simulation of the single-lap joint are provided in Table B. 3

Table B. 3: Elastic properties of the hot-melt adhesive film

Properties	Value
E (MPa)	230.18
σ_y (MPa)	5.49
σ_f (MPa)	10.86
ν	0.47
ϵ	10.66
G (MPa)	76.67
T_f (MPa)	5.09
γ	3.54

The symbols in the table are defined as: Young's modulus (E), yield strength (σ_y), ultimate tensile strength (σ_f), Poisson's ratio (ν), strain at failure (ϵ), shear modulus (G), shear strength (T_f), shear strain at failure (γ).

2.3 Single lap joint: geometry and manufacture

Three distinct configurations of wooden single lap joints (SLJs) were designed and manufactured for this study.

Reference configuration – The first configuration, referred to as the reference joint, was fabricated using either pine or oak substrates with a uniform thickness of 6 mm. The geometry of this configuration is presented in Figure B. 2.

Toughened configuration – The second configuration, also prepared with both pine and oak adherends of 6 mm thickness, incorporated an additional adhesive layer extending 15 mm beyond each end of the overlap (Figure B. 3). This design aimed to take advantage of adhesive penetration into the porous wood structure. Such penetration increases the effective bonding area and locally reinforces the wood cell walls, which improves transverse strength in the overlap region. As a result, stress concentrations at the overlap ends can be reduced, delaying crack initiation, limiting propagation along the bondline, and ultimately enhancing the joint’s capacity for energy absorption and toughness.

Hybrid configuration – The third configuration combined pine and oak within the same adherend, producing hybrid specimens (Figure B. 4). Two thickness arrangements were manufactured: (i) oak in the core (4 mm) with pine plies on the outer surfaces (1 mm each), forming an O–P–O configuration, and (ii) pine in the core (4 mm) with oak plies on the outer surfaces (1 mm each), forming a P–O–P configuration. Adhesive layers were applied between the different wood plies, with penetration further strengthening the interlaminar regions. The hybrid design was intended to improve stress distribution along the overlap length and increase the overall load-bearing efficiency of the joints.

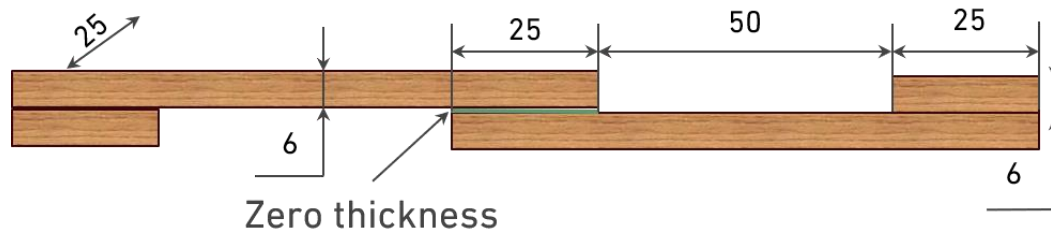


Figure B. 2: Geometry of the reference SLJ configuration (dimensions in mm)

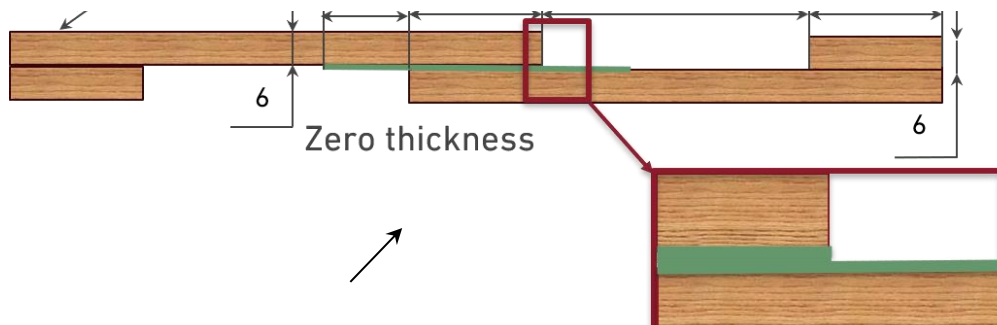


Figure B. 3: Geometry of the toughened SLJ configuration (dimensions in mm)

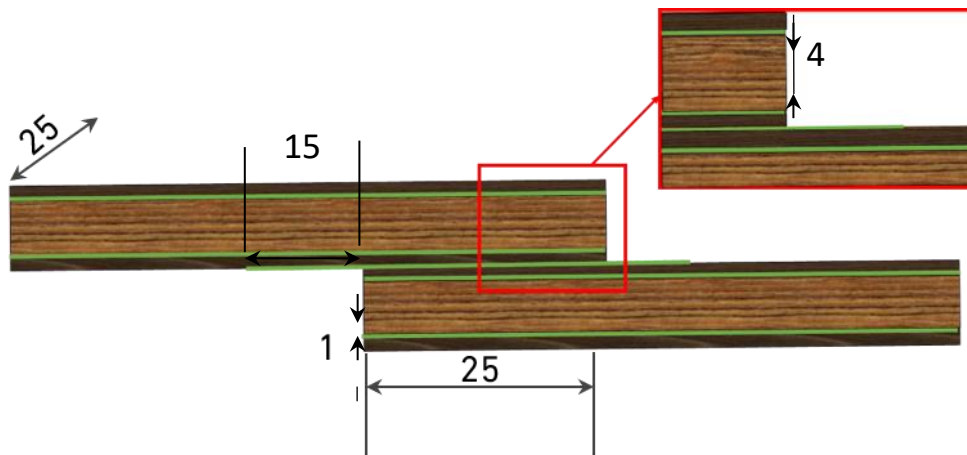


Figure B. 4: Geometry of the Hybrid SLJ configurations (dimensions in mm)

The manufacturing process for the SLJs bonded with HMA film followed a controlled procedure. An iron mold coated with release agent was employed to facilitate removal of the specimens after curing. The wood plies were positioned in the mold between alignment pins to ensure accurate specimen width. For the hybrid configurations, the stacking sequence alternated between wood layers and adhesive film, following the designated material arrangement (O–P–O or P–O–P). Spacers were placed at the overlap region to guarantee a uniform overlap length across all specimens.

The adhesive was applied at nominally zero thickness, a condition that promotes penetration into the wood structure and minimizes the risk of insufficient adhesion. To achieve uniform consolidation, a hot press was used to apply constant pressure over the entire bonding area. Six SLJs were manufactured simultaneously under the same cycle. The curing conditions, in accordance with the manufacturer's recommendations for the Zeon film adhesive, consisted of 150 °C and 10 bar for 1 hour.

2.4 Testing conditions

In this study, five specimens were tested for each loading condition and temperature setting. Quasi-static single-lap joint (SLJ) tests were carried out using an Instron 8801 servo-hydraulic testing machine equipped with a 30 kN load cell, at a constant displacement rate of 1 mm/min in accordance with ASTM D5868-01 (2014) [22]

Impact tests were conducted on a custom-built drop-weight apparatus [23] capable of releasing a 56 kg mass from a height of up to 1.27 m (equivalent to an impact velocity of 5 m/s). For the present work, a 10 kg mass was dropped at 3 m/s, corresponding to an impact energy of 108 J.

Displacement was obtained by trapezoidal integration of the load–time data and validated through high-speed video recordings coupled with Digital Image Correlation (DIC). To enable accurate tracking, specimens were first coated with a white paint base layer and subsequently speckled with black paint, allowing the high-speed camera to capture the movement of the speckle pattern across successive frames and determine the corresponding displacements.

3 Numerical models

Alongside the experimental campaign, numerical simulations were developed to provide deeper insights into stress distributions in the different joint configurations. The numerical models were developed in ABAQUS, with the finite element (FE) analysis carried out to understand the improvements made when using the hybrid joints under impact conditions. Two distinct models were created: one for quasi-static conditions and one for impact.

Both models were constructed as 2D planar deformable shell parts, and the boundary conditions are illustrated in Figure B. 5. At one extremity, an encastre was applied to replicate the gripping system. For the opposite end of the single-lap joint (SLJ), in the case of quasi-static loading (tensile testing), a displacement of 3 mm was imposed, as for impact conditions, a mass (drop-weight) equivalent to the experimental impactor was

modelled and assigned the same initial velocity of 3 m/s. This velocity field was defined in the initial step and propagated throughout the subsequent analysis.



Figure B. 5: Modelled boundary conditions

For the quasi-static conditions, a static general analysis was used, when it comes to the step type, while for the impact condition, a dynamic explicit step was employed in the simulation.

The material properties reported in the experimental details section were used as input for the numerical model. For the simulations, only one reference configuration (oak) and one hybrid configuration (P–O–P) were analyzed to ensure that the substrate core remained consistent throughout the study.

No toughened configurations were taken into account in this study, because the exact properties of the toughened wood within the adhesive penetration zone, as well as the penetration depth itself, were unknown, therefore, it was not feasible to obtain reliable results for this case.

3.1 Elastic modelling

Selecting the optimal reinforcement strategy to mitigate delamination in wood joints is a complex task. In this study, different configurations were examined, namely reference joints and hybrid joints combining oak and pine layers. The primary goal was to redistribute stresses away from critical regions at the ends of the overlap, where delamination is most likely to initiate, and to spread them more evenly across the adhesive–wood interface and throughout the core ply of the substrate.

Since there is additional adhesive introduced between the different wood layers in the hybrid configurations, bonding relies solely on the resin of the hot-melt film and delamination may still occur at the wood plies. The substrate configuration, therefore, plays a crucial role in reducing stress concentrations. By placing stiffer oak plies in the core (P–O–P), for example, the weak region is shifted away from the overlap ends into the core of the substrate, under impact conditions, lowering the magnitude of peel stresses. At the same time, the stiffer inner layers minimize transverse deformation and transmit lower peel stresses due to the adhesive–wood transition.

While material selection can strongly influence this process, this study focused on pine and oak as representative species. Consequently, the design of the joints required a compromise between maintaining lightweight, renewable substrates and achieving sufficient stiffness to prevent premature delamination at the wood layers.

Finally, the mechanical properties of the adhesive film in the overlap are also critical to the behavior of SLJs and to the stress distribution across the transverse direction. To address this multi-variable problem and to better understand the influence of the substrate configuration, numerical models were developed under fully elastic assumptions, without cohesive damage laws. By applying a displacement-controlled boundary condition equivalent to the experimental loading, the peel stresses along the adhesive layer were

extracted using the path tool. Following the same method, the shear stress along the substrate thickness was also extracted utilizing once again the path tool

3.2 Numerical results

The results in Figure B. 6 show that, at the same displacement under quasi-static loading, the maximum peel stress in the adhesive layer is essentially unchanged between the reference oak joint and the P - O - P hybrid (15.75 vs 15.80 MPa). This indicates that, without stress-wave effects, which are present under impact conditions, the hybrid layup has limited influence on the substrate response.

Regarding the results under impact conditions, as Figure B. 7 demonstrates, the hybrid configurations shows much lower peak peel stresses when compared with the reference configuration. The maximum peel stress obtained with the hybrid joint simulation was 13.95 MPa and for the reference simulation was 22.60 MPa – showing a 38.27% decrease.

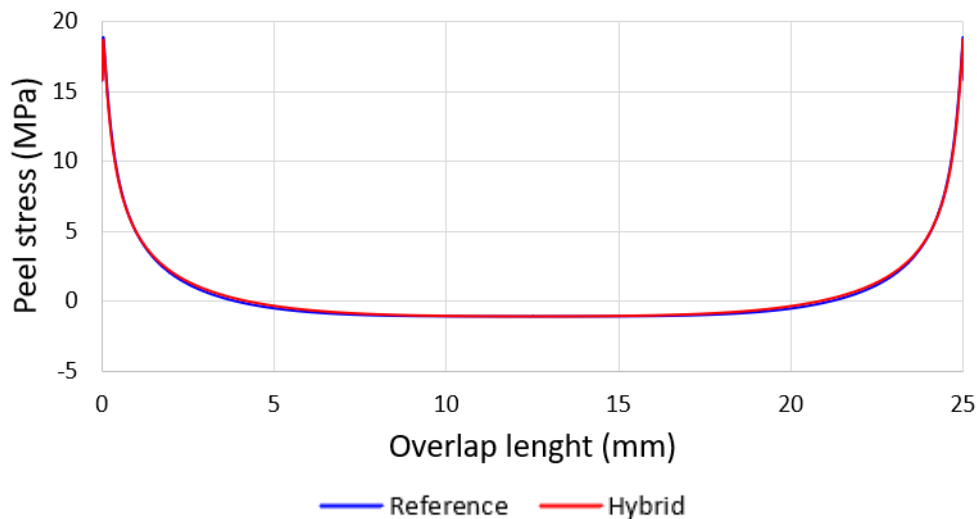


Figure B. 6: Peel stresses along the adhesive layer under quasi-static loading

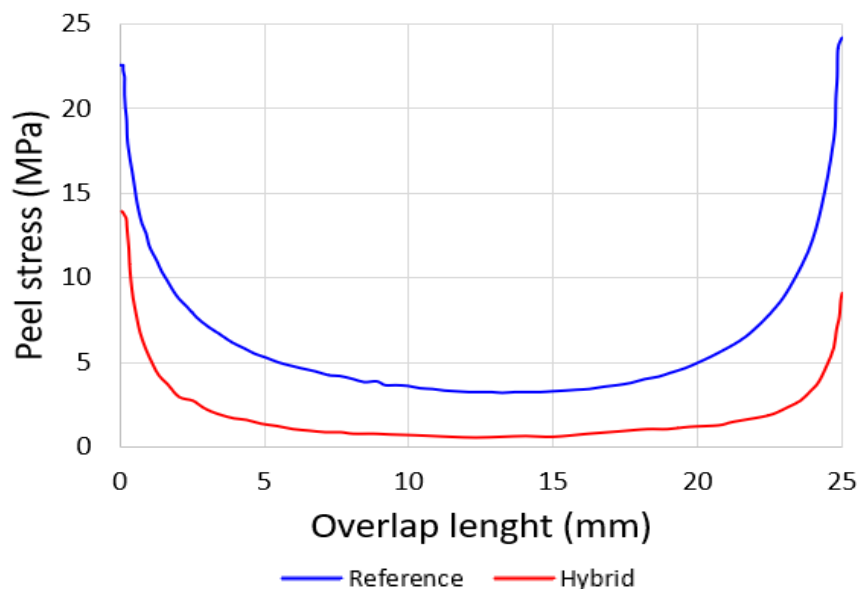


Figure B. 7: Peel stresses along the adhesive layer under impact loading

Similarly to the peel stress analysis, investigating the shear stress along the adhesive layer, for the same imposed displacement, under quasi-static loading, Figure B. 8 demonstrates that the peak shear stress in the adhesive layer remains virtually the same for the reference oak joint and the P–O–P hybrid, 2.69 MPa and 2.61 MPa respectively. This suggests that, in the absence of the stress-wave phenomena associated with impact, the hybrid stacking sequence has only a modest effect on the joint's response.

By contrast, the impact results in Figure B. 9 show that the hybrid configuration develops markedly lower peak shear stresses than the reference joint. In the simulations, the hybrid joint reached a maximum shear stress of 3.26 MPa, while the reference attained 2.10 MPa - amounting to a 35.58% reduction when it comes to the peak shear stress at the adhesive layer.

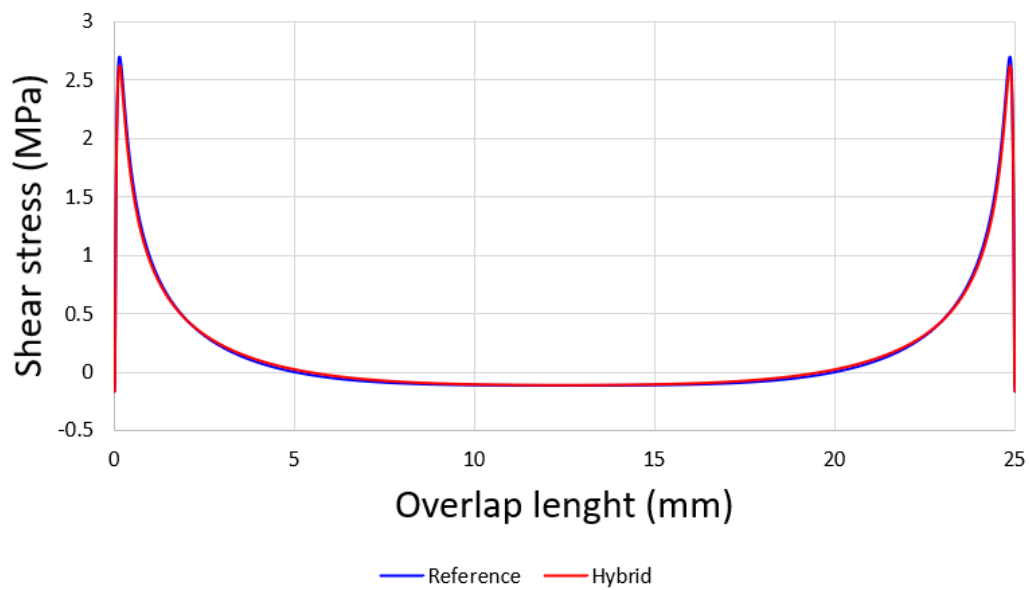


Figure B. 8: Shear stresses along the adhesive layer under quasi-static loading

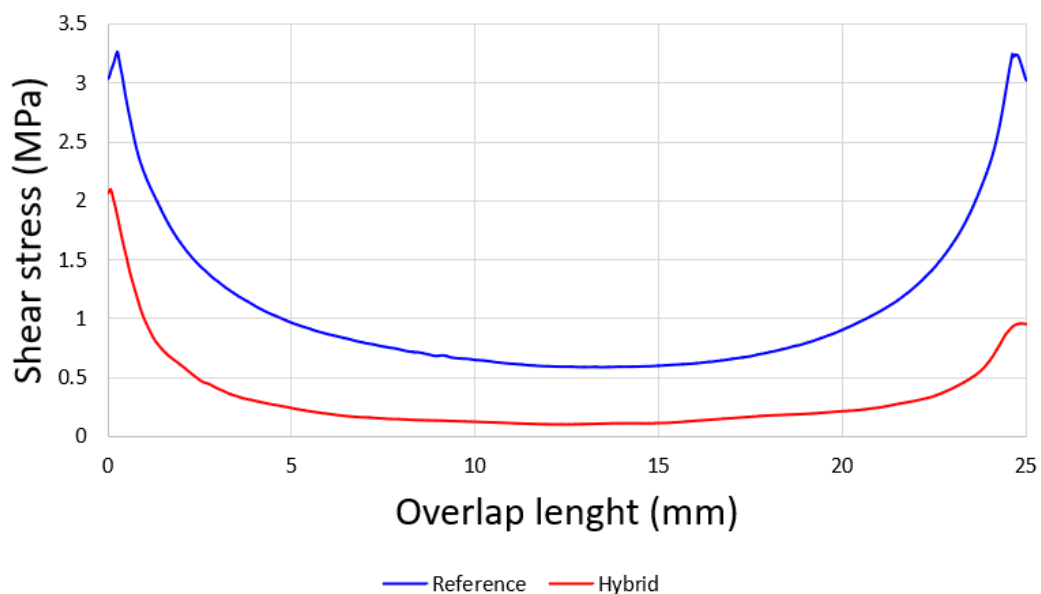


Figure B. 9: Shear stresses along the adhesive layer under impact loading

Since the peel stresses at the adhesive layer are a major driver of delamination, it is possible to conclude that, even though delamination was not prevented, there was a delay on the delamination and propagation of the stress in the hybrid joint, in consideration of the 38.27% decrease of the maximum peel stress from the reference to the hybrid configuration. Therefore, hybrid configurations can delay delamination by transmitting lower peel stresses, which reduces substrate rotation and bending and explains the improved impact performance.

Furthermore, Figure B. 10, shows a comparison of the shear stress, at quasi-static test conditions along the substrate thickness, between the reference (oak: at the top) and the hybrid (P – O – P: at the bottom) and configurations under numerical study.

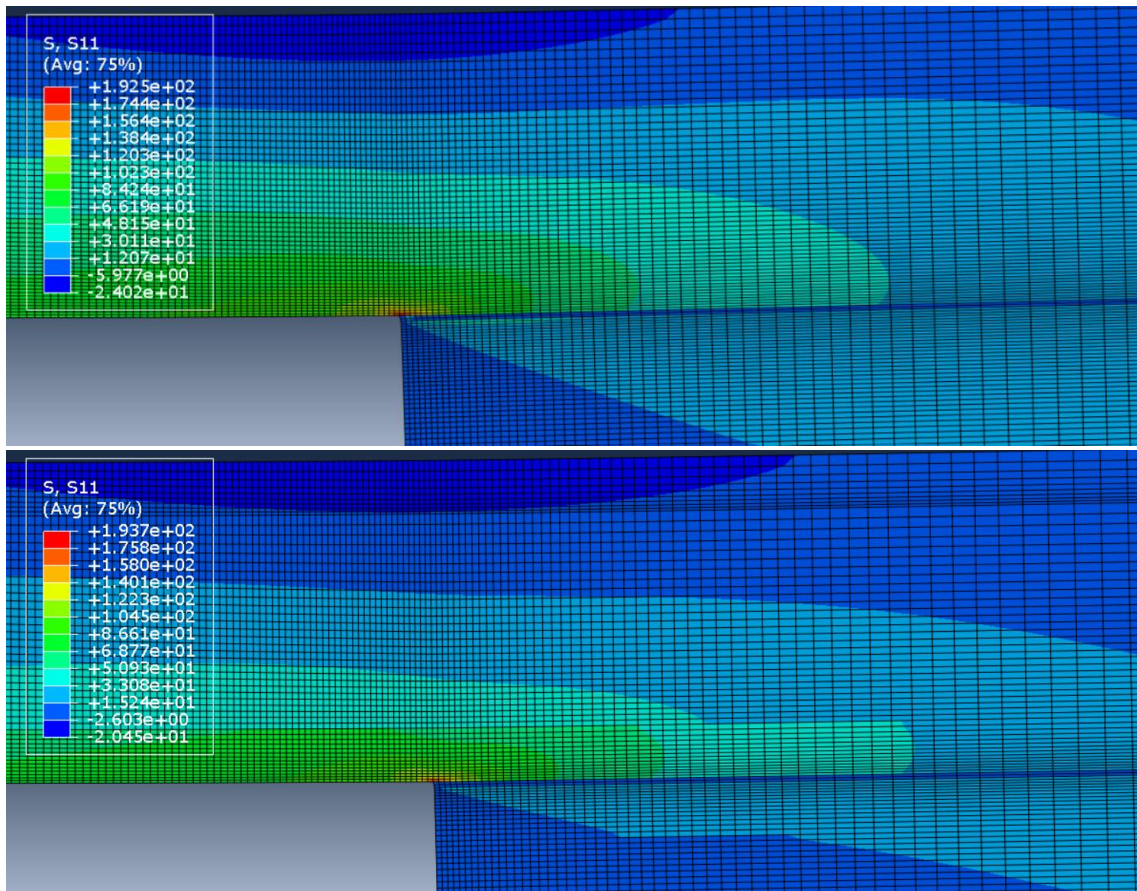


Figure B. 10: Tensile stress distribution at the substrate. Oak: top and P – O – P: bottom

Analyzing the shear stress through the thickness of the adhesive (Figure B. 10), under static conditions, it is noticeable that there are no significant improvements when using the hybrid configuration because the values of the stress are similar in both cases. However, it is also important to note the discontinuities of the stress distribution in the hybrid joint due to the interface between pine and oak wood.

In the impact testing of the hybrid configurations, a significant improvement in joint performance was observed compared to the reference specimens. Figure B. 11 and Figure B. 12, demonstrate the stress wave propagation, throughout the whole joint, for the reference and hybrid configurations, respectively.

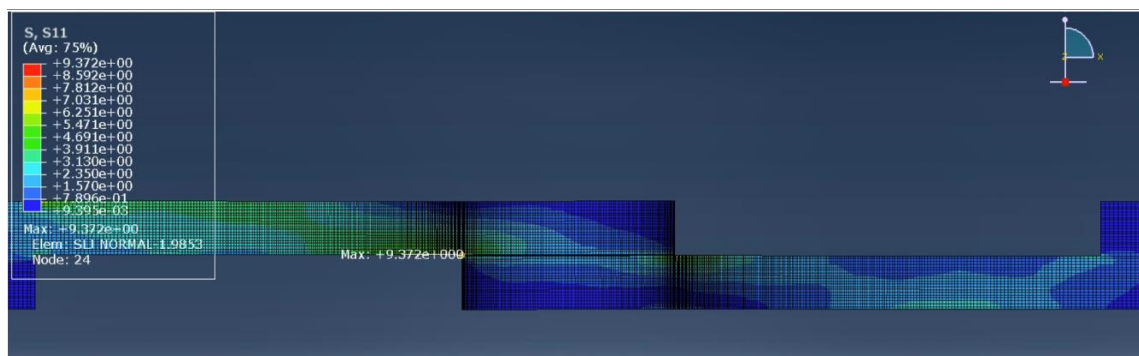
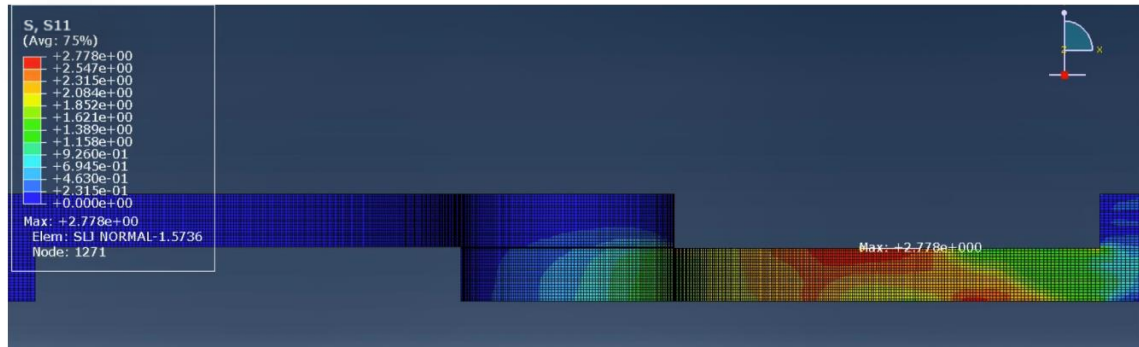
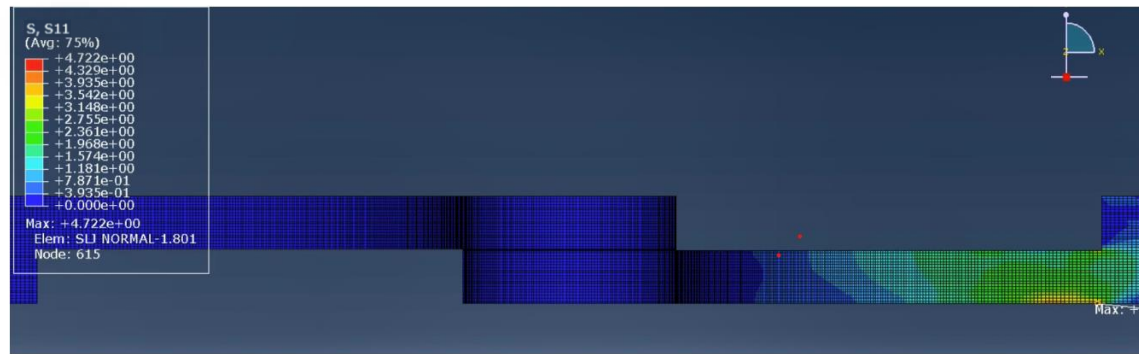
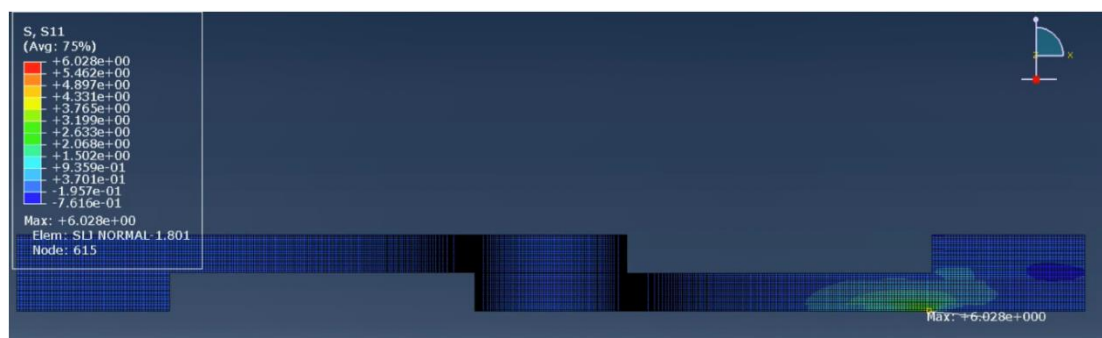


Figure B. 11: Sequence showing the stress wave propagation throughout the reference joint



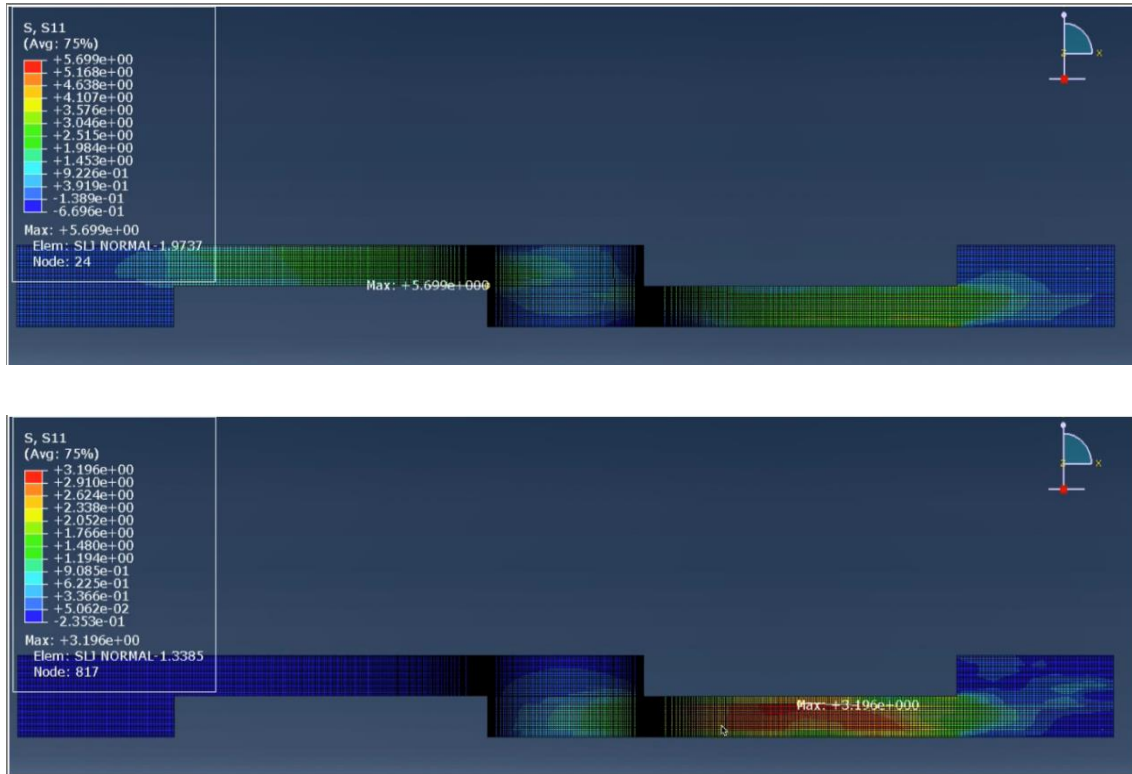


Figure B. 12: Sequence showing the stress wave propagation throughout the reference joint

When analyzing the stress wave propagation along the length of the joints for both modelled configurations, even though the maximum stress is roughly the same, it is notable that in the hybrid configuration the stress propagates along the inner layer of the substrate - along the core - while in the reference model the stress wave propagates in the edges of the wood. This will uniformize the energy absorption, concentrate the stress in stronger areas and allow the substrate to deform more evenly before failure.

Overall, as previously reported for the stresses at the adhesive layer, the numerical results, regarding the stress distribution, show no improvement of the hybrid joint when comparing with the reference joint, under quasi-static testing. Contrarily, when the joints are submitted to impact loading, the use of a hybrid configuration with both types of wood, highlights its ability to better distribute the stresses along the joint length showing great improvement when contrasting with the reference configuration.

4 Experimental results

This section presents the experimental findings obtained from the reference, toughened, and hybrid joint configurations under both quasi-static and impact loading conditions. The results are analyzed in terms of load–displacement response, failure load, and failure modes, enabling a direct comparison of the influence of substrate configuration and reinforcement strategy on joint performance, experimentally and numerically.

4.1 Reference joints

An average representative load-displacement curve from the quasi-static experiments for the reference configurations, using pine and oak woods, is shown in Figure B. 13. The failure load of both reference joints is very similar as well as their displacement since the stiffness of both woods are also comparable. Specifically, the average failure load of a reference oak joint is 2.41 ± 0.07 kN while the average failure load of the reference pine joint is 2.28 ± 0.31 kN.

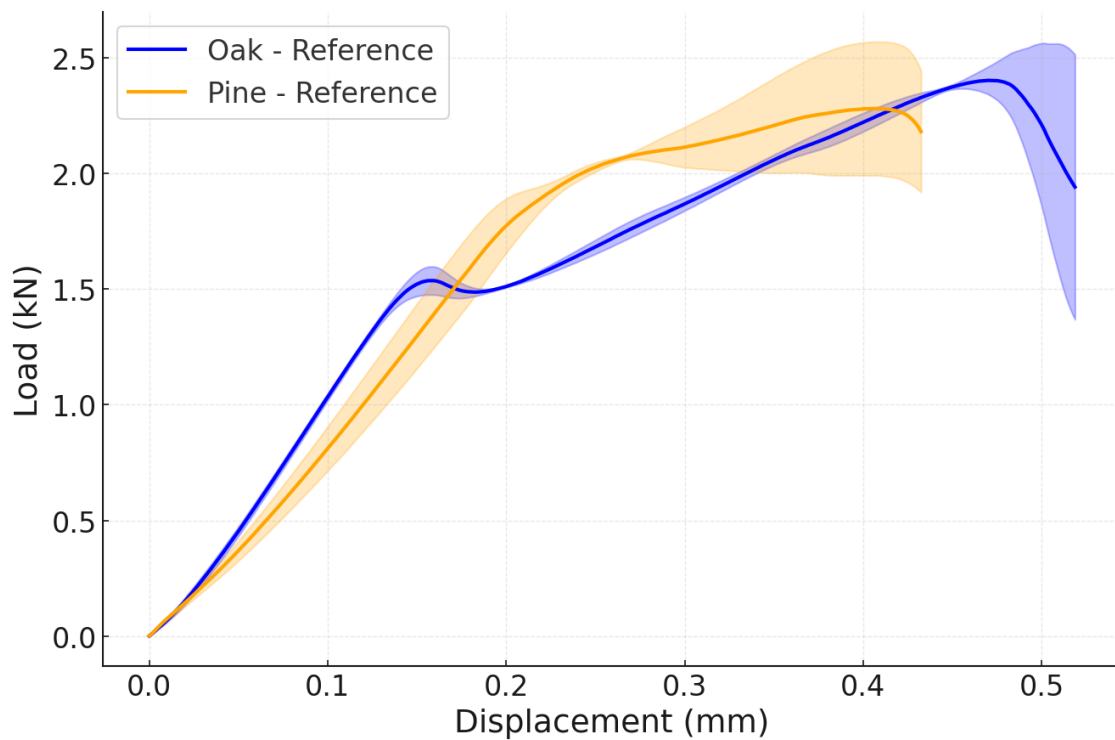


Figure B. 13: Experimental P- δ curves under quasi-static conditions for both reference configurations - oak and pine

Both wood reference joints failed adhesively, showing that the bond between the adhesive and the wood is weak. The failure modes of both joints are shown in Figure B. 14. Furthermore, Figure B. 15 illustrates the crack path that was obtained while testing the reference configurations under quasi-static loading.

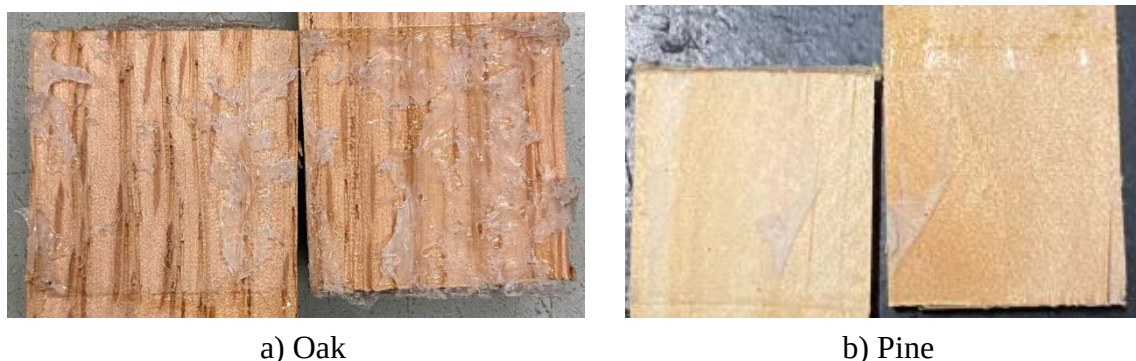


Figure B. 14: Failure modes obtained for reference joints under quasi-static conditions

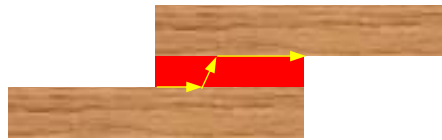


Figure B. 15: Crack path scheme for both reference configurations under quasi-static conditions

Regarding the impact performance of the reference joints, the average failure load was 13.58 ± 1.77 kN for the oak joints, just above the results obtained for the pine joints, which present a failure load of 10.23 ± 0.90 kN. Notably, the pine joint also exhibited a substantially greater displacement, which would result in a small increase of energy absorbed of approximately 16%, as shown in Figure B. 16.

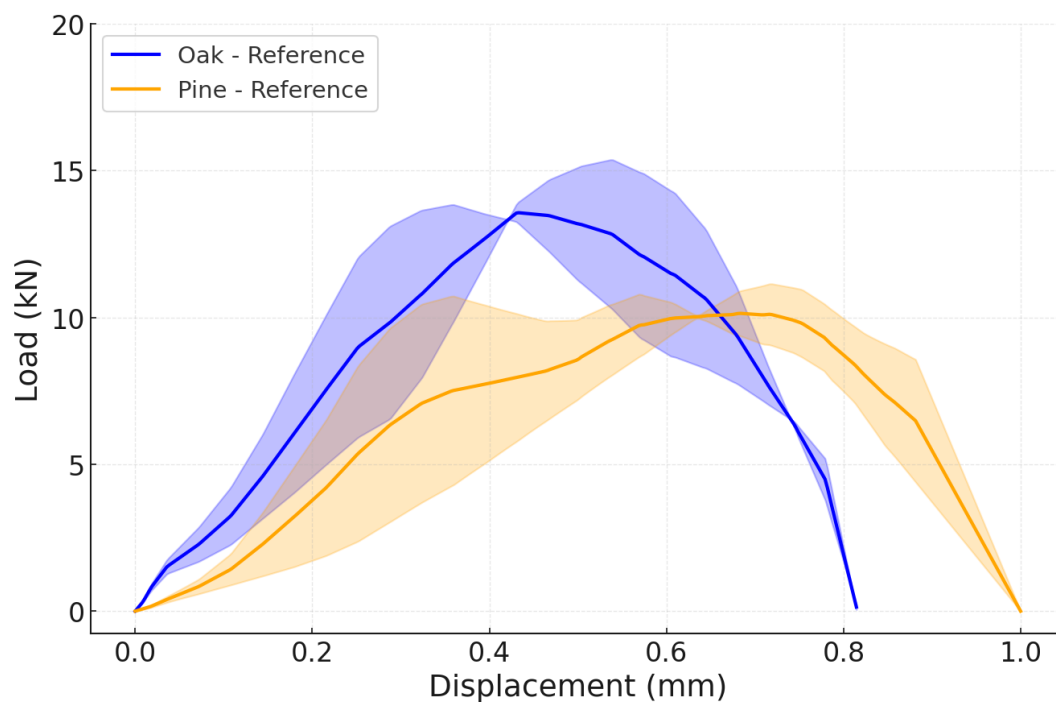


Figure B. 16: Experimental P-δ curves under impact conditions for both reference configurations - oak and pine

Under impact conditions both reference joints failed by delamination in the wood, shown in Figure B. 17. A scheme of the crack path is depicted in Figure B. 18.



a) Oak



b) Pine

Figure B. 17: Failure modes obtained for reference joints under impact conditions

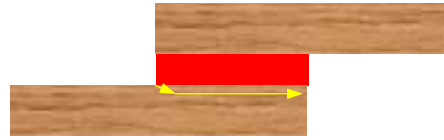


Figure B. 18: Crack path scheme for both reference configurations under impact conditions

Noticeably, the performance of both woods while using the reference configurations is very similar under quasi-static conditions, since the failure mode is adhesive. When submitted to impact conditions, pine wood has a lower failure load, due to its lower strength, but it shows higher ductility when compared with oak wood.

4.2 Toughened joints

A new joint configuration was tested, toughened with 15 mm of the HMA in each side of the overlap. The geometry was the same as the reference configuration previously tested. When compared to the previous configuration, the quasi-static behavior remained essentially unchanged, with the joint once again failing adhesively.

Nevertheless, the average failure load of the oak wood slightly increased to 2.70 ± 0.21 kN, representing a growth of about 12%. This increase is likely due to the effect of the extra adhesive that was added to the substrate. Regarding the pine wood, the average failure load of the toughened configuration decreased to 2.09 ± 0.07 kN, which represents a reduction of 8%. This smaller reduction shows that the additional adhesive as a higher impact in the oak substrates, which is due to the fact that oak wood is more porous and therefore the adhesive can penetrate more easily inside the oak wood.

Finally, Figure B. 19 presents a comparison of the experimental load–displacement curves between the new joint configuration and the reference, using both woods (pine and oak), presenting the aforementioned results.

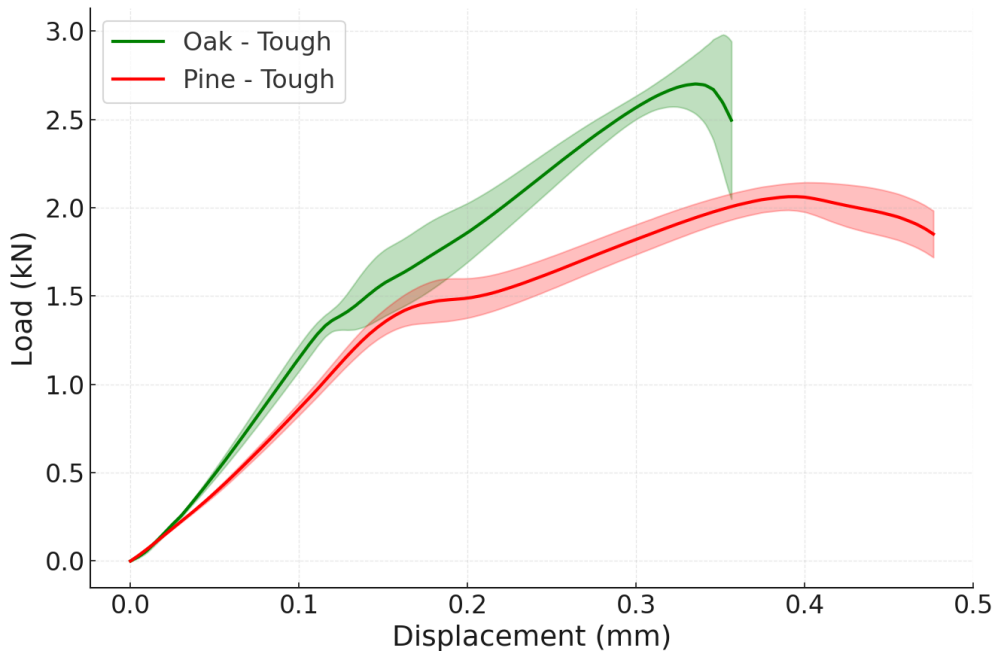


Figure B. 19: Experimental P- δ curves under quasi-static conditions for both reference and toughened configurations

As mentioned before, the failure mode for both toughened configurations were also adhesive failure (Figure B. 20) which once again shows that the interface is weakest link in the joint. Figure B. 21, shows the crack path obtained for the toughened configurations under quasi-static testing conditions.

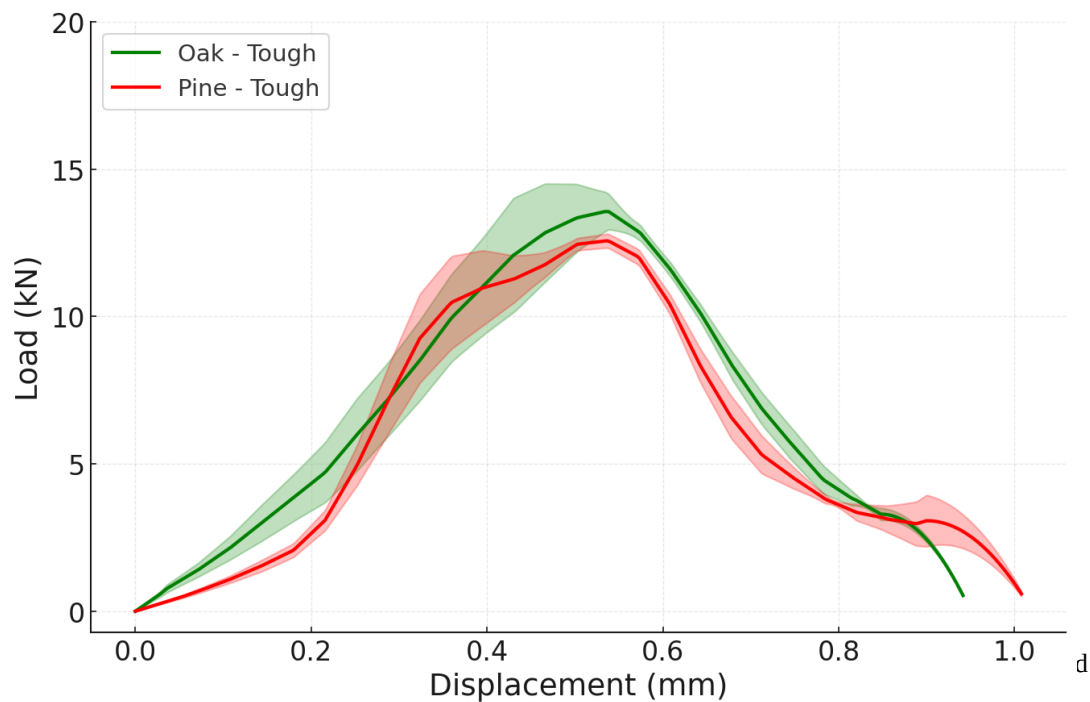


Figure B. 20: Failure modes obtained for toughened joints under quasi-static conditions



Figure B. 21: Crack path scheme for both toughened configurations under quasi-static conditions

When studying the impact performance of the toughened joints, a failure load of 13.59 ± 0.90 kN was obtained for the oak specimens, while for the pine specimens a failure load of 12.57 ± 0.29 kN was acquired. This represents, in the one hand, practically no improvement in the oak wood joints, but, in the other hand, an increase of around 23% in the pine wood joints, as it is depicted in Figure B. 22.



Concerning the failure mode of the toughened joints under impact testing, it is visible that the failure was, once more, delamination in the wood (Figure B. 23). The crack path was as Figure B. 24 suggests.



Figure B. 23: Failure modes obtained for reference joints under impact conditions.

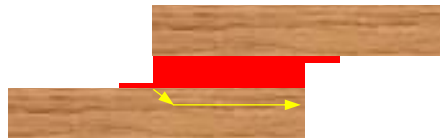


Figure B. 24: Crack path scheme for both toughened configurations under impact conditions

Under quasi-static loading, both wood species exhibited comparable performance in the reference configurations, since failure occurred adhesively. In contrast, under impact conditions, pine wood - despite the addition of extra adhesive in the toughened configuration - still showed a lower failure load than both oak configurations, due to its lower intrinsic strength, while simultaneously demonstrating greater ductility than the oak wood joints.

4.3 Hybrid joints

Lastly, the hybrid configurations were evaluated. These joints under static conditions showed very small improvements when compared to the reference configurations, and their load-displacement curves are shown in Figure B. 25.

The joints that used oak wood in the core of the substrate showed a slightly higher failure load, of 2.49 ± 0.12 kN, when compared to the O-P-O hybrid configuration which has a failure load of 2.43 ± 0.09 kN. This can be explained because the oak wood is stronger than the pine wood, and the P-O-P hybrid has a core layer composed of oak wood making it slightly stronger than the O-P-O hybrid joint.

These experimental results corroborate the numerical outcome, where the hybrid joints showed limited improvements at quasi-static conditions

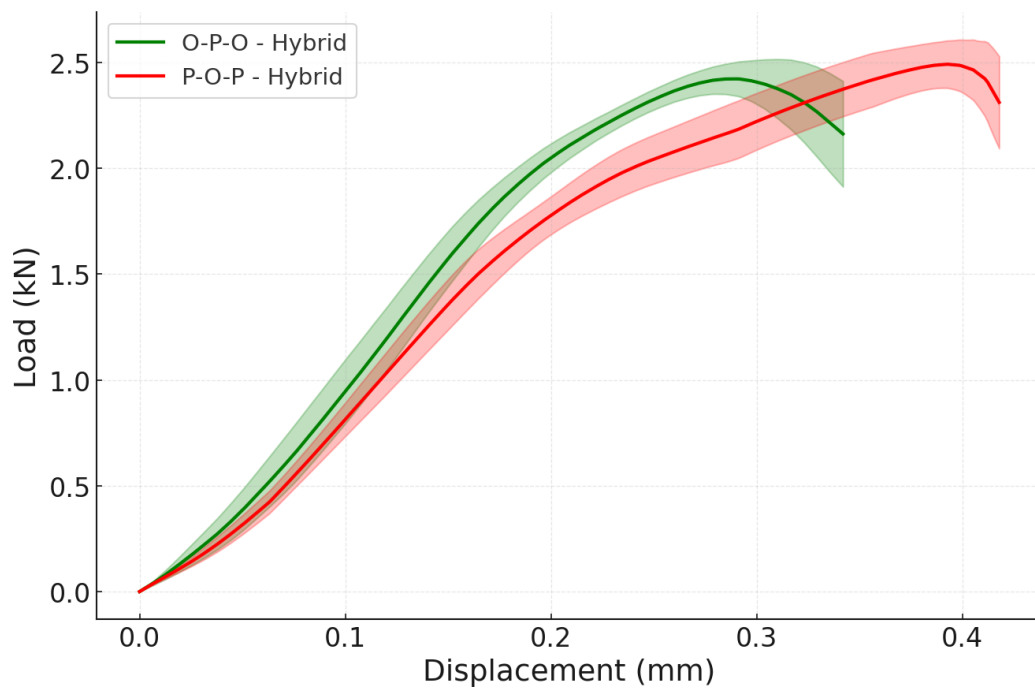


Figure B. 25: Experimental P- δ curves under quasi-static conditions for both reference and hybrid configurations

It should also be noted that the failure mode for both hybrid configurations under quasi-static conditions was, once more, adhesive. The failure surface of the pair is presented in Figure B. 26, while the crack path for both is shown in Figure B. 27.



Figure B. 26: Failure modes obtained for hybrid joints under quasi-static conditions.

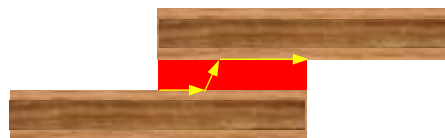


Figure B. 27: Crack path scheme for both hybrid configurations under quasi-static conditions

When it comes to the impact testing of the hybrid configurations, there is a considerable improvement in the joint behavior when confronted with the reference specimens. This was to be expected due to the numerical analysis previously done, that showed major improvements for the hybrid configurations under impact loading.

For instance, the O-P-O hybrid exhibited a failure load of 18.04 ± 1.81 kN and the P-O-P hybrid displays a failure load of 18.84 ± 2.32 kN, these results represent, for the O-P-O configuration, a 33% increase when compared with the reference oak and a 76% gain when compared with the reference pine, and for the P-O-P configuration, a 39% improvement while weighed against oak reference specimens and a 84% increase when contrasted against the pine reference. The results are shown in the load-displacement graph of Figure B. 28.

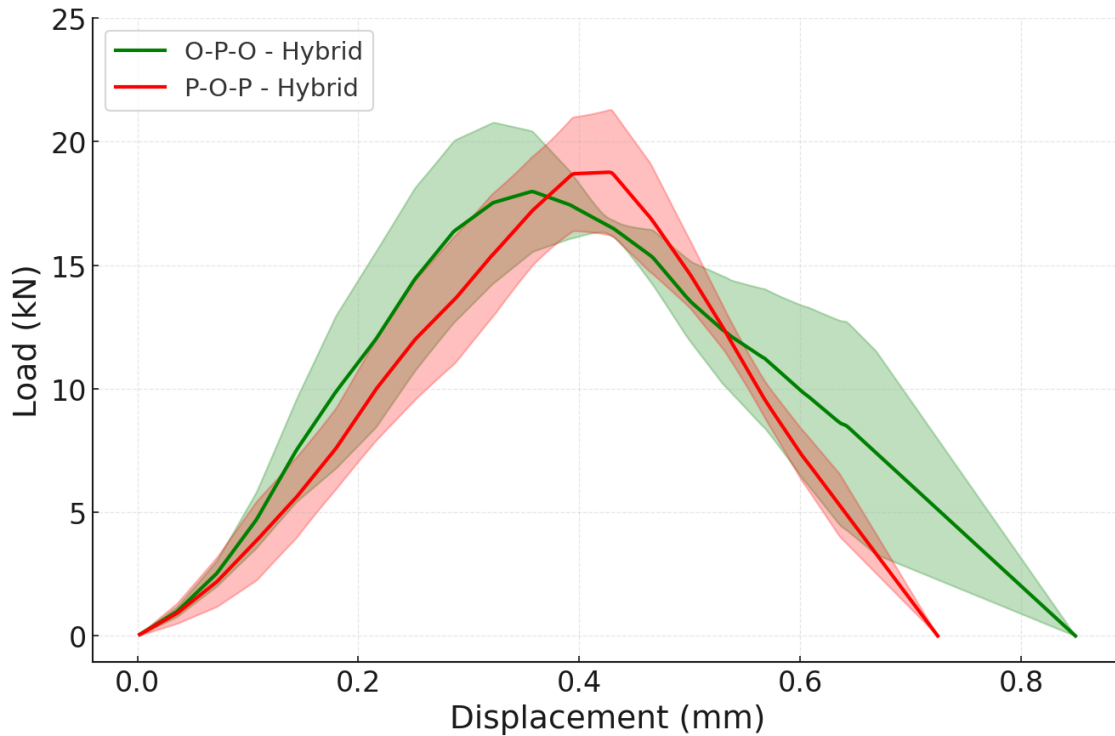


Figure B. 28: Experimental P- δ curves under impact conditions for both reference and hybrid configurations

While there is a big improvement regarding the joint behavior and specifically the failure load, the failure mode of the hybrid joints under impact was still delamination on the wood, as shown in Figure B. 29. It should be noted that in both hybrid configurations, the failure occurred in the pine layers of the substrate, as Figure B. 30 depicts, this is due to the fact that pine wood is slightly weaker than the oak wood, making the joint fail in its layers.

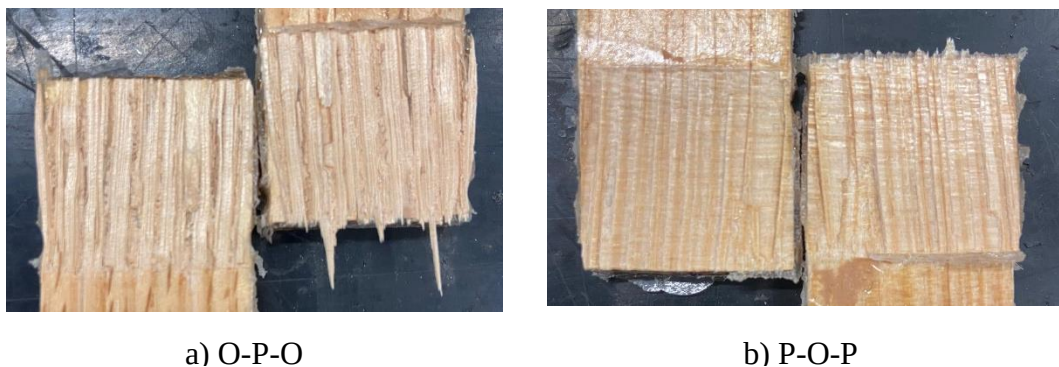


Figure B. 29: Failure modes obtained for hybrid joints under impact conditions



Figure B. 30: Crack path scheme for both hybrid configurations under impact conditions

Finally, although the hybrid configurations did not represent an upgrade when it comes to quasi-static conditions, when they are tested under impact conditions, the use of both types of wood and their ability to better distribute the stresses along the joint length proved to be very influential, showing great improvement in relation to the reference and also to the toughened. These experimental findings are consistent with the numerical simulations, which similarly highlighted the enhanced stress redistribution and delayed delamination in the hybrid layups, thereby validating the predictive capability of the developed models.

In order to make a summary of the entirety of the experimental results obtained in this study, Figure B. 31 provides a concise overview of the quasi-static performance of all tested configurations, with respect to failure load. It is worth noting that all joints tested under quasi-static loading failed adhesively, which helps explain the similarity of the results and the limited influence of the toughened and hybrid configurations, since the strength is mostly governed by the wood-adhesive interface rather than by the substrate reinforcement strategy.

Similarly, Figure B. 31 also summarizes the corresponding results under impact conditions. As expected, all configurations exhibited higher failure loads under impact compared to quasi-static loading, owing to the strain-rate sensitivity of the adhesives. Furthermore, it can be inferred that the hybrid configurations are much more strain-rate dependent showing a greater improvement. It should also be emphasized that, under impact loading, all joints failed by delamination within the wood. In this case, the reinforcement strategies became more relevant, with the hybrid configuration providing the most significant benefits, while the toughened configuration showed only marginal improvements.

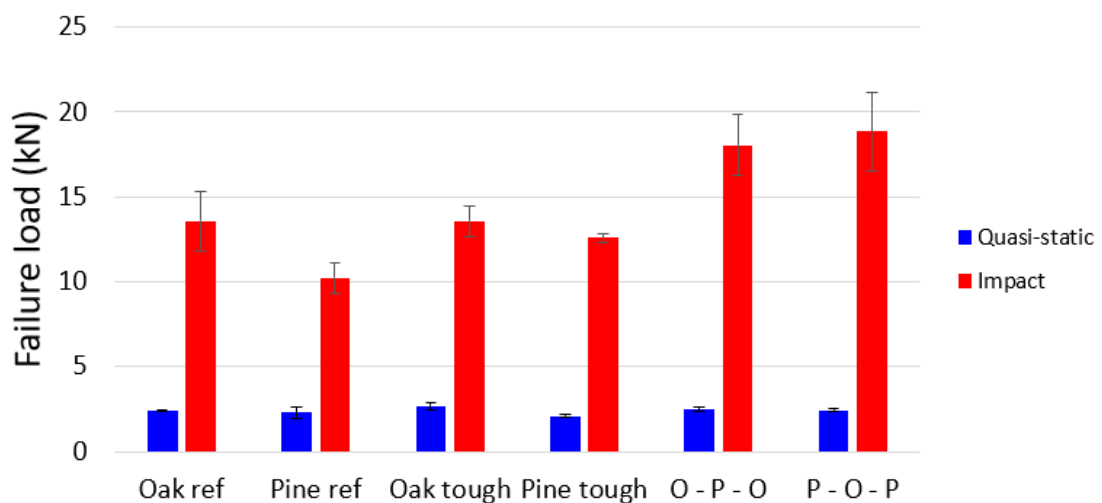


Figure B. 31: Summary chart of the experimental results

Ultimately, these experimental results are further supported by the numerical analyses previously performed, which likewise demonstrated improved joint behaviour in the hybrid configurations under impact loading, while not showing any improvement under quasi-static testing conditions, reinforcing the reliability of the predictive models developed.

5 Conclusions

This work investigated the performance of wood single-lap joints (SLJs) reinforced with a cyclic olefin-based hot-melt adhesive film. Three joint configurations—reference, toughened, and hybrid—were studied under quasi-static (1mm/min) and impact (3 m/s) loading conditions, supported by both experimental testing and finite element modeling.

- Overall, the results demonstrate that incorporating a thermoplastic film adhesive interlayer and hybridizing wood substrates can be an effective lightweight strategy to enhance the impact performance of wood SLJs. The experimental results were consistent with the numerical predictions, confirming both the accuracy of the modelling approach and the potential of these reinforcement strategies for reducing delamination in wood adhesive joints.
- The study shows that delamination, although not completely eliminated, can be significantly delayed by the introduction of a thermoplastic film adhesive as an interlayer. This approach improved the joints' ability to absorb energy, particularly under dynamic loading. The toughened configuration, which included additional adhesive at the overlap edges, provided limited benefits under quasi-static conditions but resulted in higher failure loads for pine under impact.
- Under quasi-static loading, all configurations failed adhesively, which limited the influence of reinforcement strategies. As a result, the failure loads were comparable across reference, toughened, and hybrid joints, showing that the adhesive–wood interface governed the response in these conditions.
- In contrast, under impact loading, all specimens failed by delamination within the wood, making the reinforcement strategies far more relevant. The toughened joints provided only marginal improvements, particularly in pine specimens. The hybrid joints, however, demonstrated a substantial enhancement in impact resistance, achieving failure loads up to 84% higher than the pine reference.
- This improvement is attributed to the redistribution of stresses through the substrate, as confirmed by the numerical simulations. The models showed that hybrid configurations reduced peel stresses at the overlap ends and shifted stress-wave propagation toward the inner plies, delaying delamination and allowing more uniform energy absorption.
- Although delamination was not completely prevented, the introduction of hybrid substrates significantly delayed its onset and increased the overall energy absorption capacity of the joints. These findings highlight the potential of combining oak and pine plies, bonded with a thermoplastic interlayer, as a

lightweight and effective strategy for improving the dynamic performance of wood adhesive joints.

Future research should focus on optimizing the interface between adhesive and wood, investigating different ply arrangements, and tailoring adhesive properties to further suppress delamination, as well as, developing a numerical model for the toughened joints. Such developments could extend the applicability of sustainable wood-based bonded structures in demanding structural applications.

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