

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

A Study on the Welding Viability of Recycled High-Performance Thermoplastic Composites

Helena Nadine Mendes Ferreira



Master in Mechanical Engineering

Supervisor: Prof. Abílio de Jesus

INEGI Supervisor: Eng. Alexandre Chícharo

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Approved in oral examination by the committee:

President: Prof. Jorge Lino Alves

Referee: Prof. Abílio de Jesus

External Referee: Prof. Raul Duarte Campilho

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Abstract

Ultrasonic welding has been adopted as a joining technology for carbon fibre-reinforced thermoplastic (CFRTP) composites, due to its short cycle times, high energy efficiency, and suitability for industrial automation. In the context of the transition to a circular economy, the application of this technology now extends to the joining of recycled materials. However, while the welding of continuous fibre composites is well-documented, its application to recycled CFRTP feedstock remains comparatively underexplored. This new approach introduces additional challenges, namely due to the morphological changes of the recycled material, such as discontinuous fibre length, which affect process stability, vibration transmission, and the consistency of the welded joints.

In this work, the influence of the main ultrasonic welding parameters on the mechanical performance of CFRTP joints is analysed, establishing a comparison between as-received and recycled material. The performance of the joints was evaluated through single lap shear tests, determining the maximum force and the shear strength. Additionally, metrics based on image processing were introduced, namely the analysis of material squeezing and the effectively welded area, allowing for a detailed interpretation of the bond formation mechanisms.

The experimental analysis was structured using the Taguchi method and supported by an analysis of variance (ANOVA). Overall, the recycled material exhibited an average reduction of approximately 30% in lap shear strength (LSS) compared to the as-received baseline. However, under optimal processing conditions, recycled joints reached peak strengths of up to 22.45 MPa, directly rivaling the maximum performance of virgin materials (22.57 MPa) and successfully achieving substrate failure. Furthermore, the study revealed that the inherent porosity and chopped-fibre architecture of the recycled feedstock lead to a 37% reduction in effective bonded area and a 17% increase in material squeezing. Crucially, due to the necessity of limiting cycle time to prevent premature matrix collapse, recycled joints achieved optimal consolidation with 42% less welding energy on average. This proves that simple energy-based control is inadequate, as the two materials exhibit fundamentally different thermal tolerance thresholds.

The obtained results demonstrate that, despite the greater morphological sensitivity and variability associated with the recycled material, optimising the interaction between time, pressure, and amplitude makes ultrasonic welding a technically viable solution for its reintegration into structural or semi-structural applications, thereby supporting the implementation of circular economy practices.

Keywords: CFRTP; Thermoplastic Composites; Ultrasonic Welding; Circular Economy; Mechanical Recycling; Design of Experiments; Lap Shear Strength.

Resumo

A soldadura por ultrassons tem sido adotada como uma tecnologia de união de compósitos termoplásticos reforçados com fibras de carbono (CFRTP), devido aos seus reduzidos tempos de ciclo, elevada eficiência energética e aptidão para automação industrial. No contexto da transição para uma economia circular, a aplicação desta tecnologia estende-se agora à união de materiais reciclados. No entanto, enquanto a soldadura de compósitos de fibra contínua está bem documentada, a sua aplicação a materiais CFRTP reciclados permanece comparativamente pouco explorada. Esta nova abordagem introduz desafios adicionais, nomeadamente devido às alterações morfológicas do material reciclado, tal como o comprimento descontínuo das fibras, que afetam a estabilidade do processo, a transmissão de vibrações e a consistência das juntas soldadas.

Neste trabalho, é analisada a influência dos principais parâmetros de soldadura por ultrassons no desempenho mecânico de juntas de CFRTP, estabelecendo uma comparação entre material virgem (*as-received*) e material reciclado. O desempenho das juntas foi avaliado através de ensaios de corte simples (*lap shear*), determinando-se a força máxima e a resistência ao corte. Adicionalmente, foram introduzidas métricas baseadas em processamento de imagem, nomeadamente a análise do extravasamento de material (*squeezing*) e da área efetivamente soldada, permitindo uma interpretação detalhada dos mecanismos de formação da união.

A análise experimental foi estruturada com recurso ao método de Taguchi e suportada por uma análise de variância (ANOVA). Globalmente, o material reciclado apresentou uma redução média de aproximadamente 30% na resistência ao corte (LSS) relativamente ao material virgem. Contudo, sob condições otimizadas, as juntas recicladas atingiram resistências de pico até 22.45 MPa, rivalizando diretamente com o desempenho máximo do material virgem (22.57 MPa) e alcançando a falha do substrato. O estudo revelou ainda que a porosidade inerente e a arquitetura de fibra cortada resultam numa redução de 37% da área soldada e num aumento de 17% do *squeezing*. Crucialmente, devido à necessidade de limitar o tempo de ciclo para evitar o colapso prematuro da matriz, as juntas recicladas atingiram a consolidação ótima com menos 42% de energia de soldadura, em média. Isto prova que um controlo baseado apenas no *input* energético é inadequado, dado que os dois materiais apresentam limites de tolerância térmica fundamentalmente distintos.

Os resultados obtidos demonstram que, apesar da maior sensibilidade morfológica e variabilidade associadas ao material reciclado, a otimização da interação entre tempo, pressão e amplitude torna a soldadura por ultrassons uma solução tecnicamente viável para a reintegração destes materiais em aplicações estruturais, contribuindo para a economia circular.

Palavras-chave: CFRTP; Compósitos Termoplásticos; Soldadura por Ultrassons; Economia Circular; Reciclagem Mecânica; Desenho de Experiências; Resistência ao Corte.

UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) provide a global framework for achieving a more sustainable and resilient future. They include 17 goals¹ addressing major global challenges, such as environmental sustainability, climate change, responsible resource management, and sustainable industrial development.

The most relevant SDGs addressed by this work are shown in Table 1.

Table 1: UN Sustainable Development Goals (SDGs) addressed in this work [1].

SDG	Relevance to this work
	SDG 9 – Industry, Innovation and Infrastructure. This work contributes to SDG 9 by investigating and optimising ultrasonic welding as an advanced, energy-efficient manufacturing technology for high-performance thermoplastic composites. The use of structured experimental design supports process innovation, facilitating the automation and industrial integration of cleaner joining technologies.
	SDG 12 – Responsible Consumption and Production. This study is strongly aligned with SDG 12, as it explicitly evaluates the reuse and recycling of carbon fibre reinforced thermoplastic composites. By validating the feasibility of welding recycled materials, this work supports Circular Economy strategies (Goal 12.5), promoting the reduction of waste generation and the efficient valorisation of high-value raw materials.
	SDG 13 – Climate Action. This work contributes to SDG 13 on two fronts: firstly, by enabling the effective recycling of composites, reducing the carbon footprint associated with producing virgin carbon fibre; secondly, by facilitating the integration of lightweight CF RTP materials in the transport sector (aerospace and automotive), which is critical for improving fuel efficiency and reducing global greenhouse gas emissions.

¹<https://sdgs.un.org/goals>

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Helena Ferreira

"It does not matter how slowly you go as long as you do not stop."

Confucius

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List of Acronyms

AFP	Automated Fibre Placement
ANOVA	Analysis of Variance
CF	Carbon Fibre
CV	Coefficient of Variation
CFRP	Carbon Fibre Reinforced Plastics
CFRTP	Carbon Fibre Reinforced Thermoplastic
DIC	Digital Image Correlation
DoE	Design of Experiments
ED	Energy Director
EoL	End-of-Life
FRC	Fibre Reinforced Composites
FRP	Fibre Reinforced Plastics
GLM	General Linear Model
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering
IW	Induction Welding
LMPAEK	Low Melt Poly-Aryl-Ether-Ketone
LCA	Life Cycle Assessment
LSS	Lap Shear Strength
PAEK	Poly-Aryl-Ether-Ketone
PEEK	Polyether-Ether-Ketone
PMC	Polymer Matrix Composites
PPS	Polyphenylene Sulfide
RW	Resistance Welding
SDG	Sustainable Development Goal
SEM	Scanning Electron Microscopy
TPC	Thermoplastic Composite Material
TSC	Thermoset Composite Material
UD	Unidirectional
UW	Ultrasonic Welding

List of Symbols

A_{eff}	Effective welded area	[mm ²]
D	Composite desirability	[-]
d_f	Nominal fibre size / dimension	[mm]
E_w	Welding energy	[J]
LSS	Lap Shear Strength	[MPa]
n	Number of repetitions/runs	[-]
P	Welding pressure	[bar]
P_0, P_1	Virtual tracking points (DIC)	[-]
T	Welding time	[s]
V	Full-field vertical displacement	[mm]
δ_{true}	True relative joint displacement	[mm]
ϵ_{xx}	Longitudinal strain	[-]
σ_{peel}	Peel stress	[MPa]
τ	Shear stress	[MPa]

1. Introduction

Carbon fibre reinforced polymer composites (CFRPs) have become increasingly critical in high-performance engineering applications due to their exceptional specific strength and stiffness, excellent fatigue resistance, and corrosion resilience. In particular, CFRTs have gained significant traction in the aerospace and automotive sectors. Unlike thermosetting materials, which form irreversible molecular cross-links during curing, thermoplastic matrices can be repeatedly melted and reprocessed. This characteristic opens multiple avenues for End-of-Life (EoL) strategies, ranging from simple reuse to advanced structural recycling, successfully combining the mechanical advantages of fibre reinforcement with the damage tolerance and rapid processing capabilities of thermoplastic polymers.

Among high-performance thermoplastics, Polyether-Ether-Ketone (PEEK) stands out due to its superior thermal stability, chemical resistance, and mechanical performance. Consequently, CFRTs based on PEEK are widely deployed in structural applications where lightweight design and extreme reliability are paramount. However, the expanding usage of these high-value materials has raised valid concerns regarding manufacturing costs and environmental impact, driving global research efforts toward recycling strategies and the re-integration of thermoplastic composite waste into the primary value chain.

Efficient and reliable joining techniques are essential for the structural assembly of these components. Ultrasonic welding (UW) has emerged as a highly promising joining process for CFRTs, enabling rapid, energy-efficient, and repeatable bonding without the need for external adhesives, surface pre-treatments, or mechanical fasteners. The process relies on high-frequency mechanical vibrations to generate localised viscoelastic and frictional heating at the joint interface, promoting rapid polymer melting and intermolecular diffusion under applied pressure. Consequently, machine parameters such as clamping pressure, vibration amplitude, and welding time play a critical role in dictating joint quality and structural integrity.

While the ultrasonic welding of continuous fibre (as-received) thermoplastic composites has been extensively investigated, its application to recycled CFRT feedstock remains comparatively underexplored. Recycled composites typically exhibit profound morphological differences, specifically regarding discontinuous fibre length, random distribution, and internal porosity. These differences drastically alter vibration transmission, polymer squeeze flow, and interfacial consolidation. As a result, energy windows and welding parameters optimised for continuous fibre materials cannot be directly transferred to recycled CFRTs, highlighting a critical need for systematic experimental studies to address this heterogeneous material behaviour.

In this context, the present work examines how the transition from as-received to recycled CFRT, combined with variations in ultrasonic welding parameters, influences the mechanical strength, consolidation kinematics, and overall robustness of the welded joints. A structured experimental design based on the Taguchi method is adopted to systematically evaluate the interaction between process variables, while an Analysis of Variance (ANOVA) is employed to quantify their statistical significance and relative contribution to the final joint performance.

1.1 Research Objectives and Questions

The primary objective of this dissertation is to evaluate the structural feasibility of joining recycled thermoplastic composites via ultrasonic welding, ultimately supporting their expansion in commercial applications. To achieve this, the research is framed around three fundamental questions:

1. **Process Feasibility and Energy Control (RQ1):** How do the energy absorption capacity and optimal processing windows of recycled thermoplastic composites compare to those of continuous-fibre baselines, and is simple energy-based control sufficient for heterogeneous materials?
2. **Consolidation and Morphological Influence (RQ2):** How does the morphology of the recycled feedstock (e.g., discontinuous fibre length and inherent porosity) alter the consolidation kinematics, material squeezing, and failure mechanisms of the welded joints?
3. **Performance and Industrial Robustness (RQ3):** Can recycled joints achieve peak structural performances comparable to virgin materials, and how is the overall repeatability (robustness) of the welding process affected by intrinsic material "noise"?

By addressing these questions, this study aims to provide a rigorous, data-driven assessment of whether recycled **CFRTPs** can be welded with sufficient reliability for structural or semi-structural applications, offering critical insights to support their broader industrial adoption.

1.2 Thesis Structure

The structure of this dissertation is designed to guide the reader logically from theoretical foundations to experimental validation and final conclusions. Following this Introduction, Chapter 2 establishes the theoretical framework, covering the fundamental concepts of thermoplastic composites, **PEEK** matrices, and the principles of the circular economy applied to composite recycling. This is complemented by Chapter 3, which reviews the state of the art of joining technologies, specifically detailing the ultrasonic welding process and identifying current technological gaps regarding recycled architectures.

The experimental methodology is described in Chapter 4, which details the material preparation, equipment setup, **DIC** monitoring, and testing procedures, alongside the statistical Design of Experiments (DoE) based on the Taguchi method. Subsequently, Chapter 5 presents the results and discussion, analysing mechanical performance, joint kinematics, and failure mechanisms, fully supported by the **ANOVA** and multi-response optimisation. Finally, Chapter 6 summarises the main conclusions of the study, directly addressing the formulated research questions and proposing strategic directions for future work.

2. Literature Review

This chapter reviews the theoretical foundations of this research, starting with the classification of composite materials and a focus on **CFRTP**. It then explores the main fusion-bonding techniques induction, resistance, and ultrasonic welding. Finally it concludes with an analysis of failure mechanisms and the industrial applications driving these technologies.

2.1 Composite Materials

A composite material consists of two primary phases: a matrix and a reinforcement (Figure 2.1). These phases can be arranged in various configurations, such as layered structures with specific fibre orientations, resulting in performance characteristics that surpass those of the individual constituents. Such enhancements typically include superior strength, stiffness, toughness, damage tolerance, wear and corrosion resistance, fatigue life, and thermal insulation [2]. Furthermore, specific properties, such as specific strength and modulus, often exceed those of conventional engineering metals, making composites highly attractive for weight-sensitive applications [2].

Due to these advantages, composite materials are extensively used in high-performance engineering sectors, including aerospace, automotive, naval, and construction [3]. Among these, the aerospace sector is of particular relevance to this work, motivating the specific focus on high-performance polymer matrix composites and their potential for advanced joining and recycling.



Figure 2.1: Schematic representation of a composite formation.

2.1.1 Matrix

The matrix phase may be polymeric, ceramic, or metallic (Figure 2.2). Its primary functions are to bind the reinforcement, transfer loads to the fibres, protect the reinforcement surface from environmental damage, and contribute to the overall toughness of the composite [3].

This work focuses on polymer matrix composites (**PMCs**), given their widespread adoption in lightweight structural applications. **PMCs** are generally classified according to the polymer type into thermosets and thermoplastics (Figure 2.2):

- **Thermosets** undergo an irreversible chemical reaction (curing) when heated. Consequently, they degrade or burn rather than melt at high temperatures [2]. Epoxies are the most common example, favoured for their low initial viscosity which facilitates fibre impregnation [2].

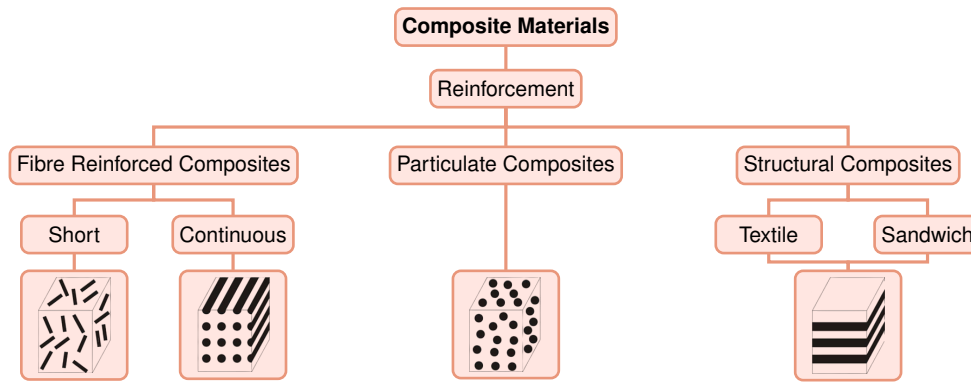


Figure 2.3: Classification of composite reinforcement geometries. *Adapted from [4, 6].*

- **Thermoplastics** soften and melt when heated and re-solidify upon cooling, a process that can be repeated indefinitely [2]. This characteristic enables rapid manufacturing routes (e.g., injection moulding, extrusion) and is fundamental for recycling and fusion bonding (joining by localised melting) [2].

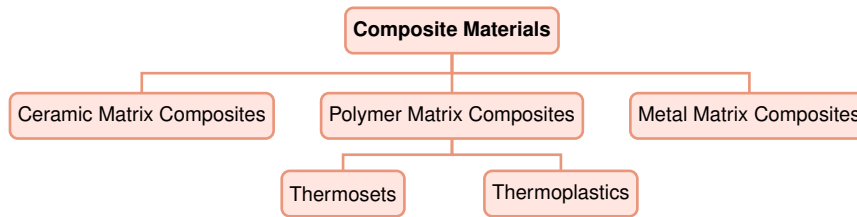


Figure 2.2: Composite materials matrix classification. *Adapted from [4].*

Historically, thermoset matrix composites have been dominant due to their high stiffness and strength, which enable the design of lightweight structural components [5]. They also offer excellent adhesion and chemical resistance. However, the cross-linked nature of thermosets makes them difficult to repair and recycle, leading to significant end-of-life (EoL) waste. This challenge has driven the development of thermoplastic composite alternatives, which offer a pathway to circularity [5].

2.1.2 Reinforcement

Composite materials can be reinforced by fibres (short or continuous), particles, or laminar structures (e.g., textiles and sandwich architectures), as illustrated in Figure 2.3 [6]. Fibre-reinforced composites (FRC) represent the most common category, particularly for polymer matrices [6].

Typical fibre reinforcements include glass, carbon, organic fibres (e.g., aramids), and natural fibres [6]. In the present work, the focus is placed on carbon fibres (CF) due to their high specific stiffness and strength, which are essential for aerospace and high-performance applications [6]. Consequently, the material system studied corresponds to a carbon fibre reinforced thermoplastic (CFRTP), specifically using a PEEK matrix.

2.2 Materials used in PMCs

Table 2.1 summarises common thermoplastic and thermosetting polymers used in polymer matrix composites, distinguishing between general engineering plastics and high-performance grades relevant to aerospace.

Table 2.1: Common thermosetting and thermoplastic matrices used in structural composite materials. *Adapted from [3, 7].*

Type	Thermoplastic Matrices	Thermosetting Matrices
Engineering	Polyamide (PA)	Epoxy (EP)
	Polycarbonate (PC)	Polyester (UP)
	Polypropylene (PP)	Vinyl Ester (VE)
High-Performance	Polyether-ether-ketone (PEEK)	Phenolic (PF)
	Polyetherimide (PEI)	Bismaleimide (BMI)
	Polyphenylene Sulfide (PPS)	Thermoset Polyimide (PI)
	Thermoplastic Polyimide (TPI)	Cyanate Ester (CE)

While engineering plastics such as Polyamide (PA) and Polypropylene (PP) are widely used in general applications, high-performance thermoplastics like PEEK, PEI, and PPS are preferred for aerospace structures due to their superior thermal and mechanical properties.

Figure 2.4 illustrates the distribution of these thermoplastic matrices in terms of morphology (amorphous vs. semi-crystalline) and thermal resistance. As this work targets aerospace-relevant applications, the focus falls on the high-performance semi-crystalline category, namely PEEK.

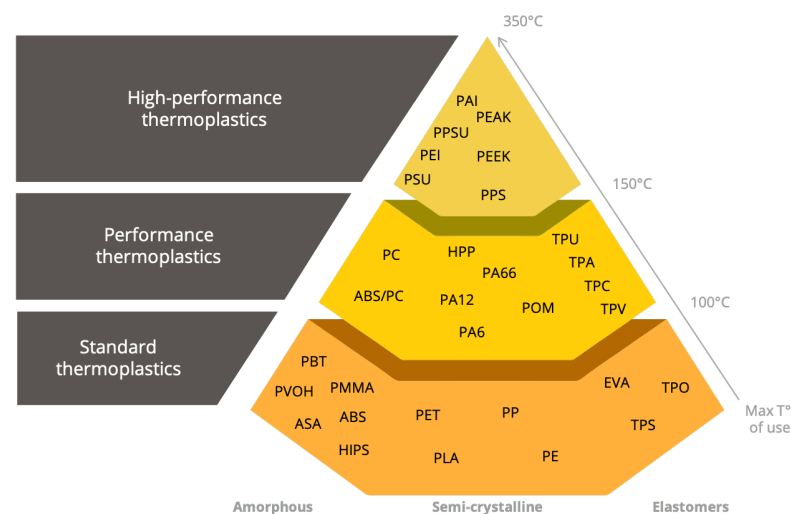


Figure 2.4: Thermoplastic composites classification by morphology and thermal resistance. [8].

2.2.1 PEEK properties

Tables 2.2 – 2.4 summarise the representative properties of unreinforced PEEK, PEEK reinforced with 30% carbon fibre, and the unidirectional (UD) Low Melt Poly-Aryl-Ether-Ketone (LMPAEK) composite used in this study. While PEEK systems are established benchmarks for high-performance applications, the adoption of LMPAEK is particularly relevant for the samples produced in this work. This material retains the exceptional thermal and mechanical performance characteristic of the PAEK family, but its lower melting point (305°C) and reduced melt viscosity (150 Pa.s) significantly enhance its suitability for fusion bonding and the reprocessing cycles required for recycling [9].

Table 2.2: PEEK and UD LMPAEK mechanical properties [9, 10].

Mechanical properties	PEEK (Unfilled)	PEEK (30% Carbon Fibre)	UD LMPAEK (0°)
Density [g/cm ³]	1.30 – 1.32	1.42 – 1.44	1.58
Young's modulus [GPa]	3.76 – 3.95	20.7 – 25	130
Yield strength [MPa]	90 – 110	190 – 228	–
Tensile strength [MPa]	97 – 117	190 – 228	2320
Elongation at break [%]	30 – 150	1 – 4	–
Shear modulus [GPa]	1.36 – 1.43	7.3 – 8.8	4.5

Table 2.3: PEEK thermal and electrical properties [10].

Thermal and electrical properties	PEEK (Unfilled)	PEEK (30% Carbon Fibre)
Melting point [°C]	322 – 346	322 – 346
Maximum service temperature [°C]	239 – 260	260 – 280
Thermal conductivity [W/m°C]	0.24 – 0.26	0.87 – 0.97
Electrical conductivity [% IACS]	5.71×10^{-21} – 5.22×10^{-21}	1.72×10^{-5} – 1.72×10^{-4}

Table 2.4: PEEK processing properties [10].

Processing properties	PEEK (Unfilled)	PEEK (30% Carbon Fibre)
Polymer injection moulding	Limited use	Limited use
Polymer extrusion	Acceptable	Limited use
Polymer thermoforming	Limited use	Limited use
Melt temperature [°C]	349 – 399	309 – 427
Mould temperature [°C]	120 – 160	120 – 160
Moulding pressure range [MPa]	68.8 – 138	68.8 – 138

2.3 Sustainability and Life Cycle Assessment (LCA)

The global demand for CFRP continues to rise. According to recent market analysis, the global CF market size was estimated at USD 5.75 billion in 2024 and is projected to reach USD 10.68 billion by 2030, registering a Compound Annual Growth Rate (CAGR) of 10.9% [11]. This growth is driven primarily by demand in the aerospace, automotive, and wind energy sectors [11].

To contextualise production volumes, Table 2.5 presents the distribution of global plastics production. While China dominates the market, Europe maintains a significant share, emphasising the regional importance of sustainable practices and circular economy regulations [12].

Table 2.5: Share of global plastics production by region in 2023 [12].

Region	Share of Global Production (%)
China	33.3
North America	17.1
Rest of Asia	19.7
EU27+3	12.3
Middle East & Africa	8.5
Japan	3.8
Central & South America	2.5
CIS (Commonwealth of Independent States)	2.8

Despite this growth, End-of-Life (EoL) management remains a critical challenge. While the general plastics industry in Europe has recently reached a milestone where recycling rates have surpassed landfilling, the scenario for composite materials is more complex [12, 13]. It is estimated that a significant portion of thermoset composite waste is still disposed of in landfills or incinerated for energy recovery, as effective recycling routes remain limited by technical and economic barriers.

In contrast, TPCs present a compelling solution as they offer a direct pathway to mechanical recycling and circularity [13, 14]. Their application in aerospace is not entirely new; historically, they have been used in commercial applications such as the glass/PPS wing leading edges of the Airbus A340, manufactured since the 1990s [15] (Figure 2.5).

Despite this early adoption, widespread implementation was initially slower than that of thermosets due to challenges in processing with technologies like Automated Fibre Placement (AFP) [14, 15]. Nevertheless, thermoplastics remained attractive due to their superior toughness, indefinite shelf-life, and inherent reprocessing ability [14, 15].

TPCs offer the potential for reduced production costs, particularly when paired with high-throughput manufacturing methods like injection moulding, which allow for rapid cycle times compared to thermoset curing cycles [14]. Regarding geometric complexity, whilst the high melt viscosity of thermoplastic matrices makes liquid moulding processes (e.g., RTM) difficult, TPCs enable significant design freedom through techniques like injection and overmoulding, allowing for the production of intricate net-shape components [17].



Figure 2.5: Application of PPS in the Airbus A340 [16].

Crucially, the ability of thermoplastic matrices to undergo localised melting enables structural joining through fusion bonding techniques and supports circular-economy approaches [5]. Unlike the irreversible chemical cross-linking of thermosets, thermoplastics can be re-heated and reprocessed. This property opens avenues for various recycling methodologies, generally categorised into mechanical, thermal, and chemical recycling [14].

2.4 Recycling and reuse methods for composites

End-of-life (EoL) composite materials are frequently disposed of in landfills due to the complexity of separating their constituents and the limited recycling routes available, particularly for cross-linked thermoset systems [18]. Nevertheless, several recycling strategies have been developed, broadly classified as mechanical, thermal, and chemical routes, enabling the recovery of materials for secondary applications [14].

In this work, the emphasis is placed on the mechanical recycling and reuse of TPCs, which is considered a suitable and industrially feasible route for CFRTTP systems [14].

This specific focus on mechanical recycling is supported by several practical considerations. As reported by Zhang *et al.* [14], mechanical recycling is a non-toxic process that can be performed at room temperature, thereby avoiding the hazardous chemicals typically involved in chemical recycling as well as the high-temperature treatments required in thermal recovery routes. In addition, its relatively simple processing chain contributes to its economic attractiveness [14]. Some studies further suggest that mechanical recycling may entail lower overall energy requirements compared to certain thermal and chemical processes, particularly those operating at elevated temperatures and under pressurised conditions [19]. Despite these advantages, mechanical recycling is not without limitations. Contamination risks and the production of recyclates with a broad fibre length distribution are commonly reported challenges [14]. Furthermore, practical aspects related to industrial implementation must also be considered. The generation of airborne dust during shredding necessitates appropriate mitigation measures, such as advanced ventilation and extraction systems, while the highly abrasive nature of CF may accelerate equipment wear [18].

For **TPCs**, the initial reinforcement architecture is often continuous, enabling optimal mechanical performance. However, when targeting the reuse of **EoL** material through mechanical recycling, a fundamental change in morphology occurs. The severe size-reduction processes (e.g., shredding) lead to significant fibre breakage, yielding a discontinuous morphology and a complete loss of the original fibre alignment [14]. This transition results in a reduction of the superior structural performance typically associated with continuous fibre-reinforced systems [14].

Nevertheless, this morphological shift also creates new opportunities. Discontinuous fibre composites provide enhanced design flexibility and allow the manufacturing of components with complex geometries that are difficult to achieve using continuous reinforcement architectures. These materials are commonly processed using high-volume manufacturing technologies such as injection moulding and compression moulding [17, 20].

Although both processing routes are compatible with recyclates, their requirements differ significantly. Injection moulding generally requires smaller particle sizes to ensure adequate material flow and prevent nozzle clogging, which often necessitates additional shredding and compounding of the recyclates into pellets [17]. In contrast, compression moulding is a more direct process capable of accommodating larger fragments (chips) and longer-fibre recyclates, which is advantageous for maximising mechanical properties [20].

This study adopts a direct recycling approach: mechanical size reduction followed by compression moulding of the resulting chips. This avoids intermediate melt-compounding steps that further degrade the fibres. To assess how discontinuous fibre length affects material flow and the structural integrity of the final welded joint, the chips were sorted and processed at specific lengths.

These methods represent only a subset of a much wider range of composite manufacturing techniques. Figure 2.6 summarises representative fabrication processes for both **TPC** and **TSC** systems.

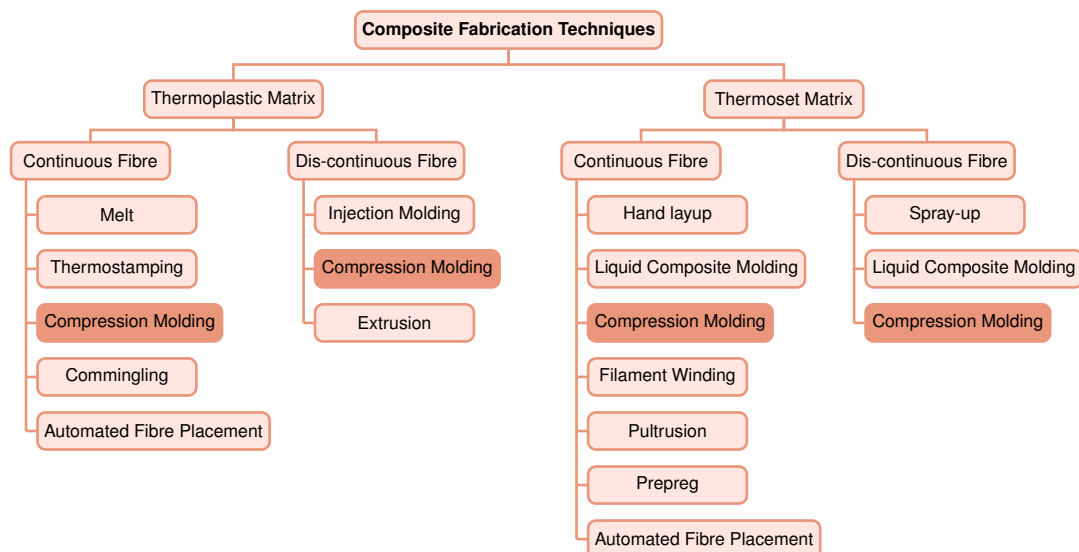


Figure 2.6: Composite materials fabrication techniques. Adapted from [4].

2.5 Welding techniques applied to composites

Figure 2.7 summarises bonding and joining methods categorised by heating mechanism. Within the realm of fusion bonding approaches, Induction Welding (IW), Resistance Welding (RW), and Ultrasonic Welding (UW) stand out as the most developed technologies for thermoplastic composites [21]. The following sections provide a review of these techniques, with particular emphasis on Ultrasonic Welding, which constitutes the primary focus of the present dissertation.

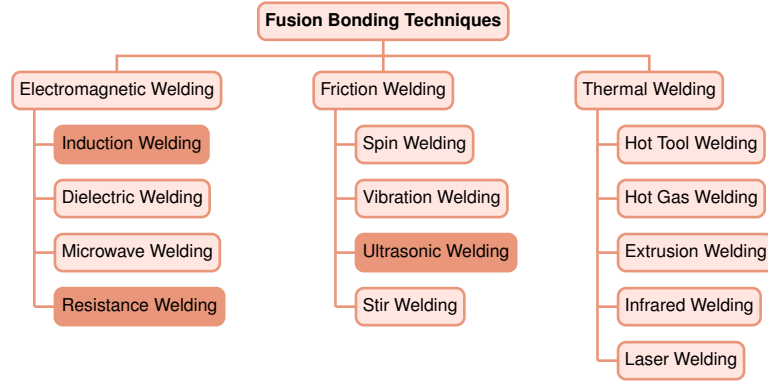


Figure 2.7: Classification of fusion bonding techniques. *Adapted from [21].*

2.5.1 Induction welding (IW)

Induction welding (IW) generates heat through the application of an alternating magnetic field, which induces Eddy currents in electrically conductive materials and/or magnetic hysteresis losses in magnetic susceptors [22, 23]. This localised heat generation enables the melting or softening of the thermoplastic matrix at the bonding interface. For entirely non-conductive composite systems, the addition of a susceptor at the interface is strictly required [22, 23].

In the case of CFRTP, the inherent electrical conductivity of the carbon fibres allows for the generation of Eddy currents directly within the laminate. Consequently, the carbon fibres act as internal heating sources, often reducing or eliminating the need for external susceptors [22, 23]. The heating efficiency depends heavily on factors such as fibre conductivity, the distance between the coil and the workpiece, and the fibre orientation relative to the magnetic field [23]. The main heating mechanisms involved in induction welding are schematically illustrated in Figure 2.8.

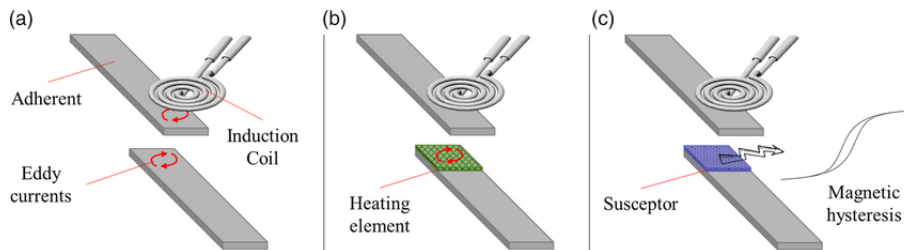


Figure 2.8: Heat dissipation in IW: (a) adherend Eddy currents; (b) susceptor Eddy currents; (c) susceptor hysteresis losses [24].

Equipment used

A standard **IW** system (Figure 2.9) consists of an induction generator that supplies high-frequency alternating current to a work coil, creating the required magnetic field [25]. The setup also includes a cooling system, fixtures to ensure component alignment, and a mechanical press or roller to apply consolidation pressure during the heating and cooling phases [25].

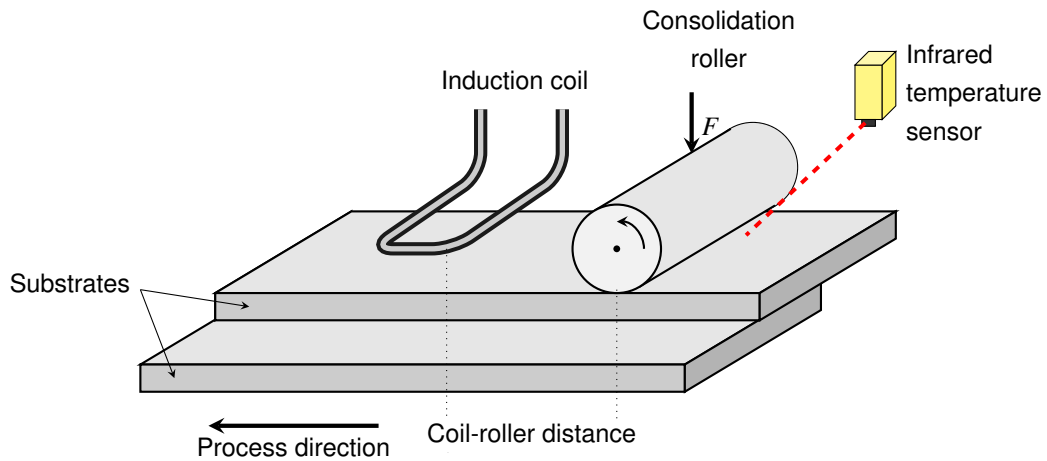


Figure 2.9: Schematic of the **IW** process: induction coil for localised heating, consolidation roller applying force (F), and infrared sensor for temperature monitoring. *Adapted from [26].*

Control parameters

Key process parameters include frequency, input power (current), applied pressure, and weld-time (Table 2.6) [5, 23]. Increasing the input current intensifies the magnetic field and thus the heat generation rate. Longer cycle times may improve temperature uniformity through thermal conduction, though excessive heating can lead to polymer degradation [23]. The material architecture, such as fibre arrangement and consolidation quality, also significantly affects heat generation efficiency and joint quality [5].

Table 2.6: Typical control parameters for Induction Welding (**IW**). *Adapted from [5, 27].*

Process parameters	Typical values	Influence
Heating time [s]	10 – 360	Determines the duration of heat exposure and the uniformity of the melt pool.
Power input [kW/m^2]	–	Controls the rate of energy delivery to the interface.
Pressure [MPa]	≈ 0.8	Ensures intimate contact and suppresses deconsolidation in heated regions.
Frequency [kHz]	60 – 100	Affects the depth of penetration and heat generation efficiency.

Materials and applications

Induction welding is applicable to a wide range of thermoplastic materials, including both amorphous and semi-crystalline polymers, as well as fibre-reinforced systems [25].

This technique has been successfully applied to high-performance thermoplastic composites, such as **CF/PEEK** and **CF/PPS**, particularly in aerospace structures involving large components and stiffened assemblies [23, 25]. Notable applications include the welding of clips and brackets to fuselage skins, benefiting from the non-contact nature of the heating source which facilitates automation.

Advantages and limitations

The most significant advantage of **IW** is its non-contact nature, which facilitates the production of continuous welds [22, 23, 28]. However, the process is limited by specific electromagnetic requirements, as the generation of Eddy currents in **CFRP** typically requires multi-directional fibre orientations (e.g., cross-ply) to establish closed electrical loops [23, 28]. Otherwise, the use of susceptors becomes necessary, which may compromise the joint's structural integrity [23, 28]. Furthermore, joining thick substrates is challenged by the "skin effect", where magnetic field attenuation prevents efficient heating at the weld interface without risking surface degradation [22, 28]. These thermal challenges are often compounded by the "edge effect" (Figure 2.10), where magnetic field distortion leads to localised overheating at the boundaries [22]. From a mechanical perspective, these inconsistencies at the extremities are particularly critical because the eccentric loading in lap shear tests generates out-of-plane "peel stresses", which often act as the primary sites for failure initiation [22, 29].

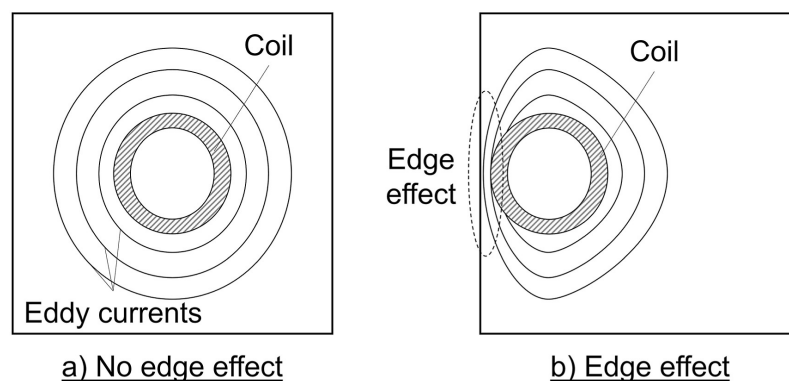


Figure 2.10: Eddy current distribution in an electrically conductive material: (a) uniform distribution without edge effects; and (b) concentration of currents due to edge effects [22].

2.5.2 Resistance welding (RW)

Resistance welding (RW) relies on Joule heating generated by passing an electric current through a conductive implant placed at the interface between the adherends [5]. As current flows through the resistive element, the temperature at the interface rises, melting the surrounding thermoplastic matrix. Subsequent application of pressure ensures consolidation of the joint (Figure 2.11) [5].

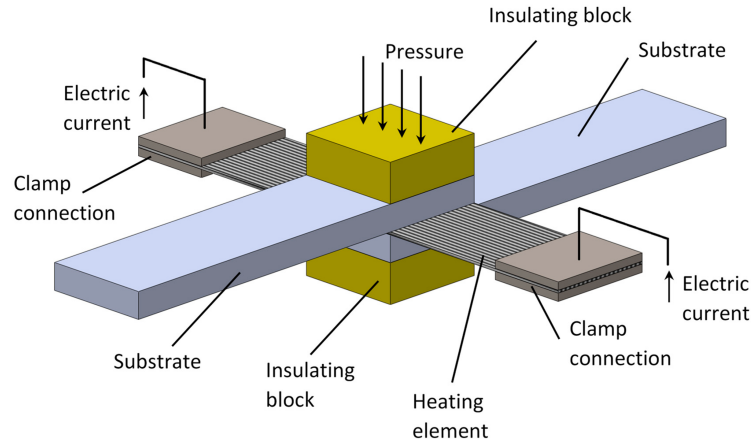


Figure 2.11: Schematic representation of Resistance Welding (RW) [5].

Equipment used

RW systems are relatively simple, typically consisting of a DC power supply, a clamping or pressing system, and the heating implant itself [30]. Power sources may operate in constant current, constant voltage, or constant power modes, with constant current often preferred to maintain stable heating as the resistance of the implant changes with temperature [30].

Control parameters

The primary control parameters are welding current, welding time, and clamping pressure, in addition to the electrical resistance of the heating element [30].

Table 2.7: Typical control parameters for Resistance Welding (RW). Adapted from [5, 27].

Process parameters	Typical values	Influence
Heating time [s]	30 – 300	Affects total energy input and heat distribution.
Power input [kW/m ²]	30 – 160	Determines the heating rate.
Welding pressure [MPa]	0.4 – 1.4	Promotes flow and consolidation.
Clamping pressure [MPa]	4 – 20	Ensures electrical contact at the electrodes.
Heating element resistance [Ω]	$R = \gamma \frac{L}{W}$	Determines heat generation capacity ($Q = I^2 R t$).

where L and W are the length and width of the heating element, γ is the electrical resistivity, I is the electric current, and t is the welding time.

Materials and applications

Resistance welding is versatile and can join a broad range of thermoplastic polymers and composites [30]. The technique is widely used in the aerospace industry for joining secondary and tertiary structures, such as ribs and stringers, where reliable bonding is critical [23]. It has also found applications in the marine and energy sectors, notably for pipeline systems [30].

Advantages and limitations

RW offers high joint strength and simple equipment requirements compared to other fusion bonding methods [30]. However, the heating element remains embedded in the joint, which constitutes a foreign object that adds weight and may act as a stress concentrator or initiation site for failure [5].

2.5.3 Ultrasonic welding (**UW**)

In Ultrasonic Welding (**UW**), components are clamped under pressure while high-frequency mechanical vibrations (typically 20 – 50 kHz) are applied perpendicular to the contact interface [5]. These vibrations are generated by a piezoelectric transducer and amplified by a booster and sonotrode. The mechanical energy is converted into heat at the joint interface through surface friction and viscoelastic dissipation, causing localised melting and subsequent fusion of the thermoplastic matrix [5].

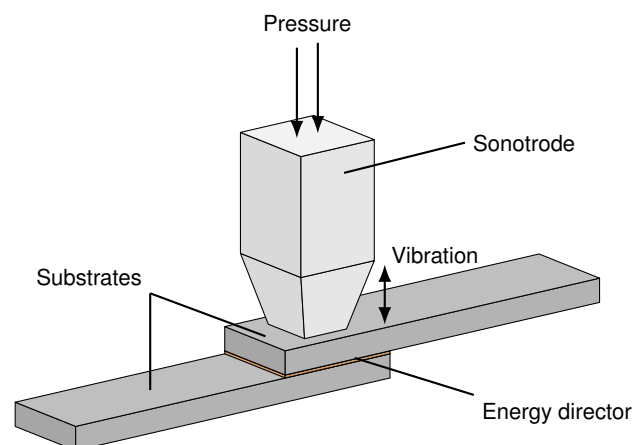


Figure 2.12: Schematic representation of the Ultrasonic Welding (**UW**) process. *Adapted from [5].*

Equipment used

A typical **UW** system consists of a generator, a piezoelectric converter (transducer), a booster, a sonotrode (horn), and a pneumatic or servo-electric press [5, 31]. Modern equipment allows for precise monitoring of power, energy, and collapse (displacement) curves, which is essential for process control and quality assurance [5, 31].

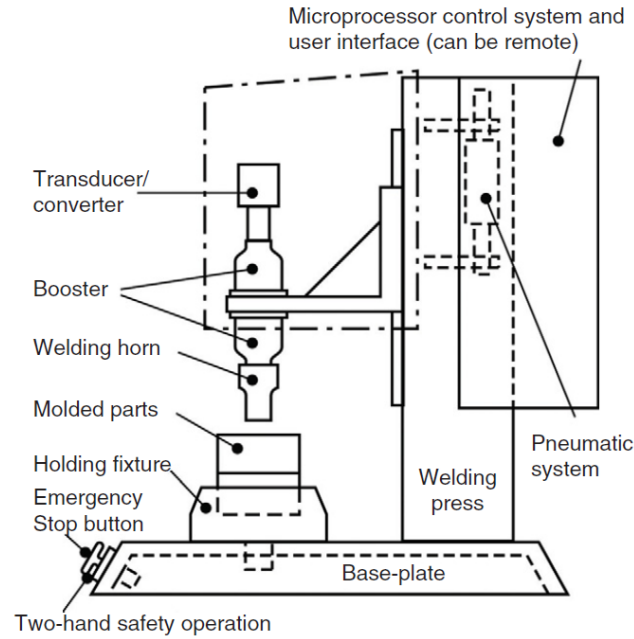


Figure 2.13: Standard Ultrasonic Welding (UW) machine configuration [31].

Control parameters

The most influential parameters in UW are vibration amplitude, welding pressure (force), and welding time [5]. Additionally, the use of Energy Directors (EDs), small resin protrusions at the interface, is common to concentrate energy and initiate melting at specific locations.

Table 2.8: Typical control parameters for Ultrasonic Welding (UW). Adapted from [5, 27].

Process parameters	Typical values	Influence
Welding time [s]	0.5 – 4.0	Short cycles are characteristic of UW.
Power input [kW/m ²]	≈ 80	Depends on amplitude and impedance.
Welding pressure [MPa]	1 – 5	Critical for coupling and consolidation.
Frequency [kHz]	20 – 50	Affects the heating generation.
Vibration amplitude [μm]	50 – 85	Primary driver of heat generation rate.

Materials and applications

UW is highly effective for joining small to medium-sized thermoplastic components and is increasingly applied to CFRTP systems [31]. While amorphous polymers are easier to weld, semi-crystalline matrices like PEEK require higher energy input to melt the crystalline phase [31].

For CF/PEEK laminates, UW can produce high-quality joints with strengths comparable to the base material, provided that process parameters are optimised to prevent matrix degradation or fibre damage [23, 31].

Advantages and disadvantages

UW is characterised by very short cycle times (often under 2 seconds), energy efficiency, and suitability for automation [31]. It does not require foreign materials (like resistive implants) at the interface. However, the process is limited by the size of the sonotrode (making it difficult to weld large continuous areas in a single shot) and is sensitive to surface irregularities [23, 31].

2.6 Failure mechanisms in fusion-bonded **CFRTP** joints

Although ultrasonic welding creates a continuous polymer matrix between the adherends, the mechanical behaviour and failure mechanisms of the joint can be effectively modelled using the principles of structural adhesive joints [32]. In this context, the Energy Director (**ED**) acts analogously to a thermoplastic hot-melt adhesive layer [32]. Because the **ED** is composed of the same unreinforced polymer as the substrate's matrix, its melting and subsequent consolidation create a polymer-rich interfacial zone [33]. This localised increase in resin volume promotes optimal macromolecular diffusion, but it also establishes a distinct physical layer with its own mechanical properties [33].

Consequently, the failure of these fusion-bonded **CFRTP** joints can be classified according to classical adhesive failure theory, manifesting in four primary modes [34, 35]:

- **Adhesive (Interfacial) failure:** The rupture occurs precisely at the boundary between the consolidated **ED** layer and the composite substrate [34, 35]. This failure mode typically indicates poor wetting or insufficient energy input during the welding process, which prevents adequate macromolecular inter-diffusion across the interface [34, 35].
- **Cohesive failure:** The fracture propagates entirely within the polymer-rich weld line (the melted **ED** layer) [34, 35]. While this mode is theoretically well-defined and indicates a strong interfacial bond, pure cohesive failure is practically rare when the initial **ED** film is extremely thin (e.g., 60 μm), as the propagating crack tends to interact with the stiffer adherend boundaries [34, 35].
- **Substrate failure:** The strength of both the interface and the cohesive layer exceeds the local strength of the base material [36]. The crack is forced to initiate and propagate exclusively within the **CFRTP** adherends, tearing the composite plies without disrupting the weld line [36]. This represents the maximum achievable joint efficiency [36].
- **Mixed-mode failure:** A combination of two or more of the aforementioned mechanisms [34, 35]. Due to the geometric constraints of a micro-metric weld line, the crack path frequently deflects and alternates between tearing the substrate, shearing through the cohesive polymer matrix (splitting the **ED**), and peeling at the adhesive interface along the overlap length [34, 35].

A schematic representation of these four fundamental failure mechanisms, adapted to the context of ultrasonic fusion-bonded joints, is provided in Figure 2.14.

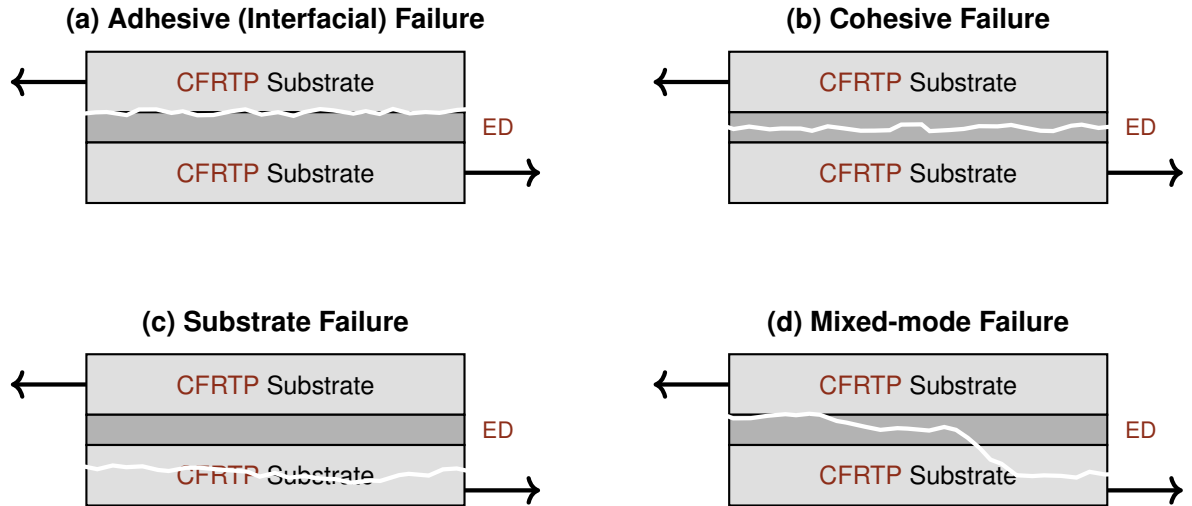


Figure 2.14: Schematic representation of classical adhesive failure modes in fusion-bonded joints: (a) adhesive failure, (b) cohesive failure, (c) substrate failure, and (d) mixed-mode failure.

2.7 Statistical Analysis in Experimental Design

The ultrasonic welding of CFRTP composites is a highly dynamic process governed by multiple interdependent parameters, such as welding time, clamping pressure, and vibration amplitude. Historically, traditional experimental approaches relied on the one-factor-at-a-time (OFAT) method. However, this approach is not only time-consuming but also fails to capture the complex interactions between different variables [37]. Consequently, modern engineering literature heavily favours the Design of Experiments (DoE) methodology to systematically investigate process parameters.

Among DoE techniques, the Taguchi method is widely adopted in manufacturing research due to its use of orthogonal arrays, which significantly reduces the number of required experimental runs while ensuring a comprehensive exploration of the parameter space [38, 39]. While the Taguchi method is effective for identifying optimal parameter combinations via the Signal-to-Noise (S/N) ratio, it does not inherently quantify the statistical significance of each individual parameter [38, 39].

To address this limitation, the Analysis of Variance (ANOVA) is universally employed as a complementary statistical tool [40]. In the context of this study, ANOVA was selected for three fundamental reasons:

- **Quantification of influence:** ANOVA calculates the percentage contribution of each welding parameter, objectively identifying which factors dominate the joint's mechanical performance, typically evaluated through lap-shear testing, and which are negligible [41].

- **Separation of signal from noise:** Recycled composites inherently exhibit higher morphological variability (e.g., internal porosity and irregular fibre distribution) than virgin materials [40, 41]. **ANOVA** isolates the variance caused by changes in machine parameters from the variance caused by experimental error or material inconsistency, using the p -value to determine statistical significance [40, 41].
- **Literature validation:** Combining Taguchi with **ANOVA** is an established gold standard for complex multi-objective optimisation in thermal and manufacturing processes, ensuring that the results obtained for recycled **CFRTPs** can be directly, fairly, and rigorously compared with existing baseline studies [40].

By coupling the Taguchi experimental design with **ANOVA**, researchers can move beyond empirical observation, establishing robust and statistically validated process windows even for heterogeneous materials like recycled **CFRTPs**.

2.8 Applications in primary and secondary composites

Joining technologies are a key enabler for the widespread adoption of thermoplastic composites in aerospace. Unlike thermosets, thermoplastics allow for "dust-free" assembly via welding, eliminating thousands of mechanical fasteners and reducing weight [21].

Thermoplastic composites have been used in secondary structures (e.g., clips, brackets, floor panels) since the 1980s and are now moving towards primary structures like fuselage shells and wing components (Figure 2.15) [42, 43].

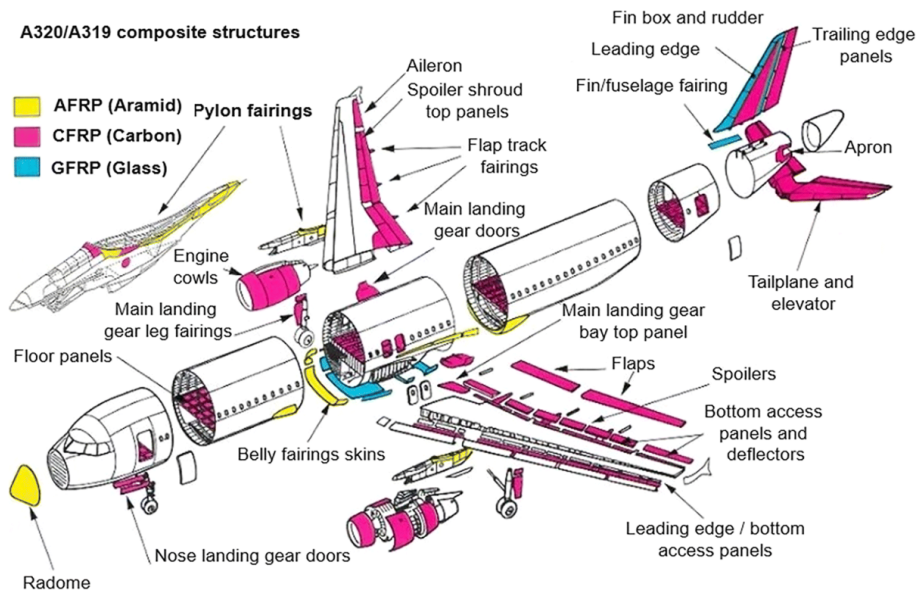


Figure 2.15: Representative applications of composite structures in commercial aircraft (e.g., Airbus A320 family) [42].

A landmark achievement in this transition is the STUNNING project (Clean Sky 2, led by NLR ¹), which developed the Multi-Functional Fuselage Demonstrator (MFFD) [44–46]. As the world’s largest known thermoplastic aircraft structure, this 8.5-meter-long fuselage section demonstrated the industrial viability of joining large-scale components without mechanical fasteners [44, 45]. Specifically, the project showcased the automated induction and conduction welding of the external fuselage skin (Figure 2.16a) and the subsequent integration of internal frames and stringers (Figure 2.16b), achieving a significant reduction in both weight and assembly time [44–46].



(a) Full 8-meter MFFD fuselage shell.



(b) Detail of the welded frames and stringers.

Figure 2.16: The MFFD demonstrator from the STUNNING project: (a) external view of the 8-meter fuselage section; and (b) internal structure assembled via automated thermoplastic welding [45, 46].

Recent initiatives have also focused on recycled materials. For instance, the ECO-CLIP project (GKN Fokker ²) demonstrated the feasibility of manufacturing structural brackets using recycled CF/LMPAEK joined by ultrasonic welding [43, 47]. Similarly, the Airbus A350 programme has explored recycling production waste into structural rods [48].

These examples confirm that welding technologies are not only critical for as-received materials but are also essential for enabling the structural reuse of recycled composites. This industrial context underpins the research presented in this dissertation. To provide a broader perspective on the academic landscape, Chapter 3 presents a quantitative analysis of publication trends in CFRTTP welding.

¹<https://www.nlr.org/>

²<https://www.gknaerospace.com/>

3. State of the Art

High-performance thermoplastic composites, particularly **CFRTPs** such as **CF/PEEK**, have gained increasing relevance in aerospace, automotive, and medical applications due to their favourable strength-to-weight ratio, damage tolerance, and potential for recyclability. In this context, welding technologies have emerged as a competitive alternative to conventional mechanical fastening and adhesive bonding, enabling the formation of continuous, uniform joints highly suitable for structural applications.

Alongside the increasing industrial adoption of **CFRTPs**, recent research has begun to address both primary (as-received) and secondary (recycled or reprocessed) materials, reflecting a growing imperative for sustainability and material efficiency. However, studies explicitly addressing the welding of recycled **CFRTPs** remain comparatively limited, particularly when analysed at the level of specific joining processes.

To investigate how these developments are reflected in the scientific literature, a bibliometric analysis was performed using the Scopus¹ database. Structured searches based on titles, abstracts, and keywords were employed to identify publications related to **CFRTP** welding in general, the welding of recycled **CFRTPs**, and the application of specific welding processes. No additional filters were applied beyond those explicitly defined in the search queries. For each query, annual publication data were extracted and represented as cumulative publication counts. This cumulative approach facilitates the identification of long-term research trends and provides insight into the relative maturity of different topics and processes. The complete set of search queries is provided in Appendix A. The bibliometric search was initially conducted in *January 2026* and updated in *March 2026*, encompassing all available records up to that date.

3.1 Overall trends: General vs. recycled **CFRTPs**

The cumulative publication trends reveal a sustained and accelerating growth in general **CFRTP** welding research over the last two decades. While early studies can be traced back to the 1980s and 1990s, a marked increase in publication volume is observed from approximately 2005 onwards, coinciding with the broader industrial uptake of thermoplastic composite technologies. By the most recent year analysed, the total number of publications addressing **CFRTP** welding exceeded one thousand, highlighting the maturity and continued expansion of this research field.

In stark contrast to this extensive body of work, publications explicitly focusing on the welding of recycled **CFRTPs** appeared considerably later and remain limited in number. The first studies emerged in the early-to-mid 2000s, followed by a gradual but consistent increase from around 2010 onwards. Despite this growing trend, the cumulative number of publications on recycled **CFRTP** welding remains an order of magnitude lower than that of general **CFRTP** welding.

¹<https://www.scopus.com/>

This delayed development and the significant disparity in research volume are clearly captured in Figure 3.1, which contrasts the massive growth of overall **CFRTP** welding studies with the emerging, yet nascent, field of recycled material welding.

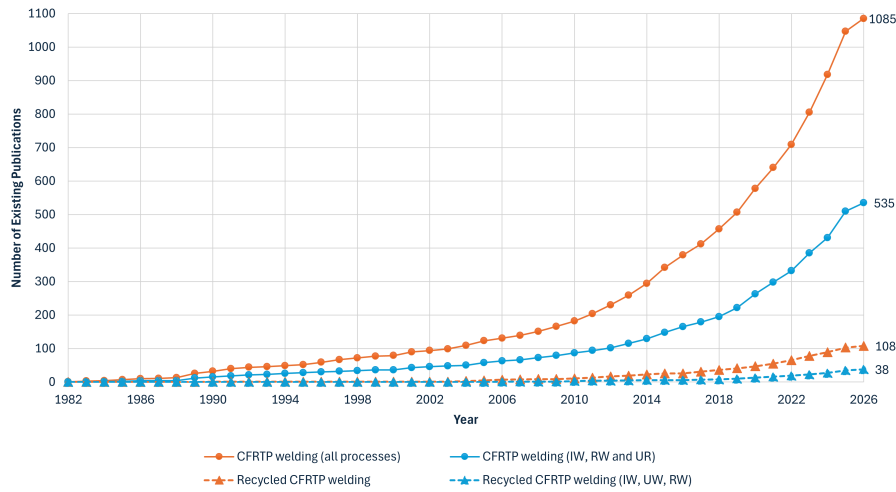


Figure 3.1: Cumulative publication trends comparing the overall **CFRTP** welding literature with studies explicitly focusing on recycled materials.

3.2 Process-specific trends: General vs. recycled **CFRTPs**

An examination of individual welding processes highlights clear disparities in research emphasis, both within the overall literature and in the specific context of recycled materials. For general **CFRTP** welding, ultrasonic welding consistently appears as the most extensively investigated technique, followed by resistance and induction welding. The prominence of ultrasonic welding can be largely attributed to the relative simplicity and flexibility of its experimental setups, which facilitate systematic parametric studies and process optimisation under controlled laboratory conditions [23, 27].

Conversely, resistance and induction welding are frequently associated with large-scale or continuous industrial applications. In these contexts, equipment complexity and component size impose practical constraints, leading studies to prioritise application-driven developments rather than extensive parametric exploration [25, 30].

When the analysis is restricted to recycled **CFRTPs**, a similar hierarchy among the processes is maintained, but the evolutionary timeline is drastically different. All three welding processes exhibit a delayed but persistent increase in research interest concerning recycled materials, primarily from the mid-2010s onwards. However, the absolute number of publications remains at an incipient stage compared to the mature body of work on as-received materials.

This stark contrast between the mature general landscape and the emerging recycling-focused research is directly compared in Figure 3.2, which presents the cumulative publication trends for the three main processes applied to general (left) and recycled (right) **CFRTPs**.

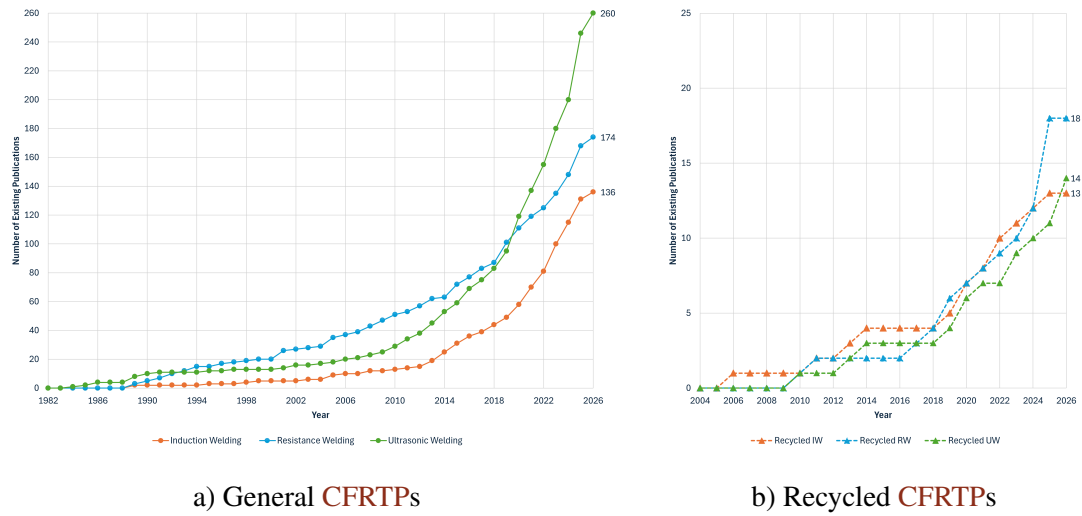


Figure 3.2: Comparison of cumulative publication trends for induction (IW), resistance (RW), and ultrasonic welding (UW) applied to (a) overall CFRTPs and (b) exclusively recycled CFRTPs.

3.3 Comparative studies: Primary vs. secondary CFRTPs

Crucially, publications explicitly comparing welding behaviour between primary and secondary CFRTPs remain particularly scarce. As shown in Figure 3.3, the cumulative number of comparative studies is negligible even in recent years, evidencing a significant gap in systematic assessments addressing the influence of material origin on welding performance. This scarcity underscores the lack of direct benchmarking required to confidently transition from primary (as-received) to circular composite structures.

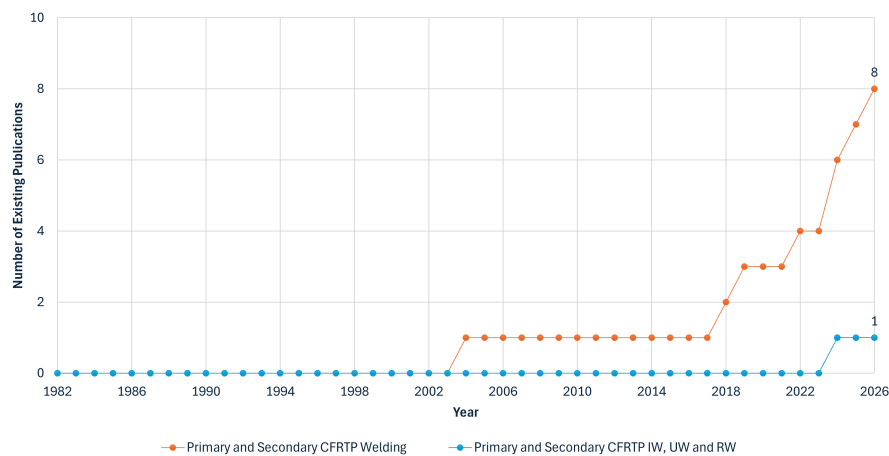


Figure 3.3: Cumulative publication trends comparing welding studies on primary (as-received) and secondary (recycled or reprocessed) CFRTPs.

3.4 Overview of recent ultrasonic welding studies

To contextualise the experimental methodology adopted in this thesis, Table 3.1 presents a summary of recent literature specifically focused on the ultrasonic welding of high-performance thermoplastic composites. The studies presented were primarily identified through the recycling-focused bibliometric searches, complemented by foundational baseline studies on as-received (primary) materials.

This compilation highlights the investigated material combinations, recycling routes, Energy Director (ED) designs, and the resulting weld strengths. By including both advanced primary configurations, such as mesh or 3D-printed energy directors, and emerging recycling approaches, the table establishes a comprehensive reference baseline for the experimental and analytical methods employed in the following chapters.

3.5 Synthesis and knowledge gaps

The bibliometric analysis highlights a stark contrast between the maturity of CFRTP welding research and the emerging nature of studies addressing recycled CFRTPs. While welding technologies for thermoplastic composites are well established, their application to recycled materials remains limited and methodologically fragmented. Specifically, there is a distinct absence of systematic and comparative studies addressing how recycled material streams affect welding performance compared to as-received counterparts.

These observations directly motivate the experimental work presented in the following chapters, which aims to bridge this knowledge gap by focusing on the ultrasonic welding of primary and mechanically recycled CFRTP materials under strictly controlled and comparable conditions.

Table 3.1: Summary of recent studies on ultrasonic welding of general and recycled thermoplastic composites.

Material	State	Energy Director	Parameters	Standard	Evaluation & Key Results	Ref.
CF/PEEK	Primary	PEEK woven mesh	Weld time/speed	ASTM D3164	LSS (40.3 MPa spot, 33.9 MPa cont.); Uniform interfacial heating.	[49]
CF/PEEK	Primary	3D-printed net	Weld time, Pressure	ASTM D3165 / D3166	LSS increased by 206%; Mitigated secondary bending in thin joints.	[50]
CF/LMPAEK	Shredded	Flat	Energy, Pressure	N/A	LSS (25–32 MPa); Squeezing flow and heating analysis.	[51]
GF+Flax/PE	Upcycled	N/A (Skin-core)	Amp., Energy	ASTM D5868 / D790	Impact & flexural tests; Specific energy absorption increased 23%.	[52]
CF/PPS	Recycled	Triangular	Time, Force	N/A	LSS (28 MPa); Fracture surface SEM characterisation.	[5]
GF/PP	Reproc.	Nanocomp. film	Temp., Voltage	ASTM D1002	Disassembly evaluation for recycling/reuse via resistance heating.	[53]

Abbreviations: CF: Carbon fibre; GF: Glass fibre; PEEK: Polyetheretherketone; LMPAEK: Low-melt polyaryletherketone; PE: Polyethylene; PPS: Polyphenylene sulfide; PP: Polypropylene; LSS: Lap shear strength; SEM: Scanning electron microscopy.

4. Experimental Methodology

This chapter describes the experimental methodology adopted in this work, including the materials used, the manufacturing and preparation of test specimens, the ultrasonic welding procedure, and the mechanical and post-weld characterisation techniques. The experimental plan was designed to evaluate the influence of material condition and welding parameters on joint performance, assessed through lap shear strength and complementary image-based metrics.

Two material conditions were investigated: as-received **CFRTP** laminates (primary material) and mechanically recycled **CFRTP** laminates. The as-received material was used as a baseline reference, while the recycled material enabled the assessment of the influence of mechanical recycling on the ultrasonic welding response. Owing to the complexity of the process and the variability introduced by recycling, the experimental strategy was supported by a Design of Experiments (**DoE**) approach based on the Taguchi method.

4.1 Materials and Welding Setup Description

The primary material investigated was VICTREX **LMPAEK**[™] UDT AS4-143-34, a unidirectional high-performance thermoplastic prepreg. This system comprises a **LMPAEK** matrix reinforced with continuous Hexcel HexTow[®] AS4 12K carbon fibres, whose mechanical and thermal properties were detailed in section 2.2.1. The selection of this material was motivated by its industrial relevance in aerospace primary structures and its specific design for thermoplastic joining processes [9].

The welding process was performed using an industrial ultrasonic welding (**UW**) machine from Emerson Branson, equipped with a digital generator and an integrated load cell. To ensure repeatable positioning and rigorous alignment of the individual adherends, a custom-designed clamping fixture was employed. The equipment setup and the details of the adherend fixation system are illustrated in Figure 4.1.

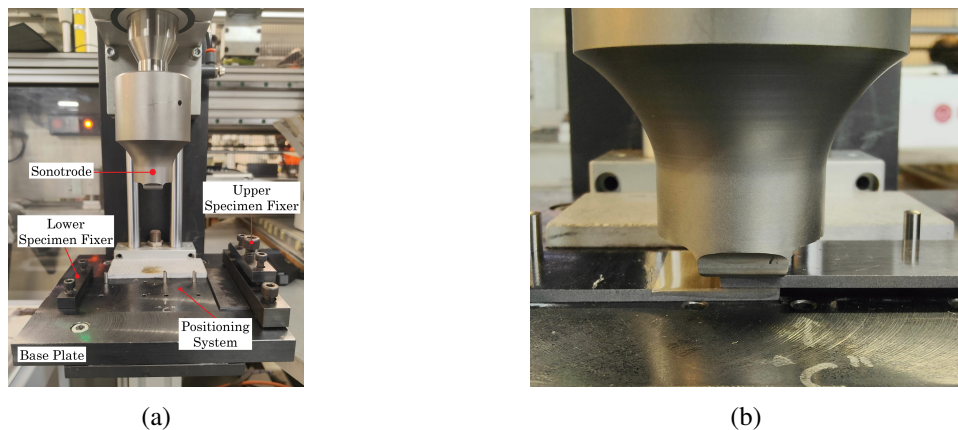


Figure 4.1: Experimental setup used for the ultrasonic welding process: (a) overview showing the sonotrode and fixture; (b) detail of the adherend alignment and clamping system.

The Branson **UW** system operates through a pneumatic pressure regulating valve. Due to the specificities of the equipment interface, two key conversions were necessary to define the process parameters in physically meaningful terms:

Welding Pressure The selection of nominal pneumatic pressures: 2.0, 4.0, and 6.0 bar, was initially guided by reference values found in the literature for the ultrasonic welding of high-performance thermoplastic composites [5]. To ensure these parameters were suitable for the specific recycled **CFRTP** used in this study, preliminary trial welds were conducted. These preliminary tests confirmed that this pressure range provided a robust processing window for the Taguchi orthogonal array, successfully capturing the material's response from insufficient consolidation at the lowest pressure to potential excessive squeeze flow at the highest.

While the operator interface dictates this nominal valve pressure (in bar), the actual mechanical consolidation depends on the specific force transferred by the sonotrode. Therefore, to determine the true equivalent pressure (p_{eq}) exerted at the joint interface, the force (F) measured by the equipment's load cell was divided by the nominal contact area of the lap joint ($A_c \approx 322.6 \text{ mm}^2$), as defined in Equation 4.1:

$$p_{eq} = \frac{F}{A_c} \quad (4.1)$$

Table 4.1 summarises the relationship between the nominal valve settings used during the experiments and the resulting equivalent pressure applied to the adherends.

Table 4.1: Relationship between nominal valve pressure, measured load cell force, and equivalent welding pressure at the joint interface.

Nominal Pressure (bar)	Load Cell Force (N)	Equivalent Pressure (MPa)
2.0	300	0.93
4.0	500	1.55
6.0	700	2.17

Vibration Amplitude Regarding the vibration amplitude, the absolute peak-to-peak displacement (in μm) was not explicitly provided by the equipment manufacturer. Consequently, the amplitude was set and monitored as a percentage of the equipment's maximum output power (80%, 90%, and 100%). Consistent with established practices for high-temperature thermoplastics [5], preliminary trials demonstrated that amplitude levels below 80% failed to generate sufficient interfacial friction to reliably reach the melting point of the **LMPAEK** matrix. Conversely, the selected 80–100% range ensured rapid, stable viscoelastic heating and proper polymer diffusion at the interface.

Energy Input In ultrasonic welding, the total energy delivered to the joint interface is a primary driver for matrix melting and consolidation. To quantitatively relate the selected process parameters, a theoretical energy index (E) can be defined based on the physical principles of ultrasonic technology. This index integrates the equivalent welding pressure (p_{eq}), welding time (t), vibration amplitude (A), and the constant ultrasonic frequency (ω), as expressed in Equation 4.2:

$$E \propto p_{eq} \cdot t \cdot A \cdot \omega \quad (4.2)$$

where ω is the constant operating frequency of the sonotrode (30 kHz). Because the exact peak-to-peak displacement for the amplitude (A) is monitored as a percentage of the machine's maximum output rather than an absolute distance, Equation 4.2 provides a proportional representation of the input energy density rather than an absolute thermodynamic value in Joules. Nevertheless, this metric is highly valuable for comparing the relative thermal energy input across the different experimental runs of the Taguchi orthogonal arrays.

4.2 Experimental Design Definition

Ultrasonic welding of carbon fibre reinforced thermoplastic composites involves several processing parameters that can significantly influence joint formation and mechanical performance. Parameters such as welding pressure, welding time, vibration amplitude, and, in the case of recycled materials, fibre size, may interact in a complex manner [5].

To address these constraints without requiring a prohibitively large number of trials, the Taguchi method was adopted as a structured Design of Experiments (DoE) approach. This methodology employs orthogonal arrays to systematically investigate the influence of multiple control factors while significantly reducing the number of experimental runs [39].

In this study, the primary objective was to evaluate the relative contribution of the main process parameters to joint performance and quality. For each experimental run defined in the Taguchi arrays, a sample size of $n = 3$ specimens was tested to ensure statistical significance. Three main response variables (outputs) were defined:

- **Lap Shear Strength (LSS):** The primary mechanical indicator of joint performance, determined through destructive tensile testing according to ASTM D5868.
- **Material Squeezing:** An image-based metric used to quantify the amount of polymer expelled from the overlap. High squeezing levels often serve as an indicator of "overwelding", where excessive energy input leads to significant flashes and potential fibre deconsolidation.
- **Effective Welded Area:** A post-failure metric obtained through microscopy and digital image processing to identify the actual bonded region, providing a more accurate assessment of the weld quality than the nominal overlap area.

These responses were analysed using a Taguchi-based DoE complemented by Analysis of Variance (ANOVA). The statistical evaluation of the experimental data was performed using Minitab® Statistical Software. A detailed breakdown of the statistical workflow, including data organisation, General Linear Model (GLM) setup, and model validation through residual analysis, is provided in Appendix B. Two distinct experimental designs were defined for the as-received and recycled material conditions.

4.2.1 As-received Material Design (L₄)

For the as-received material, three welding parameters were investigated at two levels each. Unlike the recycled composites, fibre length was excluded as a control factor since this baseline material features a continuous fibre architecture.

The selection of the parameter levels was guided by literature [5] and preliminary experimental trials. Initially, the trials aimed to replicate the exact same parameter window established for the recycled material. However, it was observed that applying these parameters to the as-received material resulted in insufficient matrix melting and poor interfacial consolidation. Because the continuous fibre structure presents different thermal dissipation and rheological behaviours compared to the recycled feedstock, higher energy inputs were required to achieve a sound weld. Consequently, the parameter levels, most notably the welding time, had to be significantly increased (from the 3.0–4.0 s range used for recycled up to 4.5–5.0 s). The final definition of these levels is presented in Table 4.2, and the resulting L₄ orthogonal array is detailed in Table 4.3.

Table 4.2: Welding parameters and corresponding levels for as-received CF RTP materials.

Parameter	Level 1	Level 2
Welding pressure (bar)	4	6
Welding time (s)	4.5	5.0
Vibration amplitude (%)	90	100

Table 4.3: L₄ Taguchi orthogonal array for as-received CF RTP welding trials ($n = 3$ per run).

Run	Pressure (bar)	Time (s)	Amplitude (%)	LSS (MPa)	Squeezing (%)	Eff. Area (%)
J	4	4.5	90	—	—	—
K	4	5.0	100	—	—	—
L	6	4.5	100	—	—	—
M	6	5.0	90	—	—	—

4.2.2 Recycled Material Design (L₉)

For the recycled material, the discontinuous fibre length (d_f) was explicitly included as a control factor to evaluate its influence on the material's weldability. Four parameters were analysed at three levels each, requiring an L₉ orthogonal array. The definition of the levels is summarised in Table 4.4, while the resulting experimental matrix is presented in Table 4.5.

Table 4.4: Welding parameters and corresponding levels for recycled CF RTP materials.

Parameter	Level 1	Level 2	Level 3
Fibre length (mm)	4	17	25
Welding pressure (bar)	2	4	6
Welding time (s)	3.0	3.5	4.0
Vibration amplitude (%)	80	90	100

Table 4.5: L₉ Taguchi orthogonal array for recycled CF RTP welding trials ($n = 3$ per run).

Run	Fibre length (mm)	Pressure (bar)	Time (s)	Amplitude (%)	LSS (MPa)	Squeezing (%)	Eff. Area (%)
A	4	2	3.0	80	—	—	—
B	4	4	3.5	90	—	—	—
C	4	6	4.0	100	—	—	—
D	17	2	3.5	100	—	—	—
E	17	4	4.0	80	—	—	—
F	17	6	3.0	90	—	—	—
G	25	2	4.0	90	—	—	—
H	25	4	3.0	100	—	—	—
I	25	6	3.5	80	—	—	—

4.3 Specimen Manufacturing

4.3.1 Plates Manufacturing

The as-received CF RTP plates used in this research as reference material were produced at INEGI within the scope of the ReCAP project [51]. These plates were manufactured using a laboratory-scale variant of the AFP technology.

AFP, illustrated in Figure 4.2, is an advanced additive manufacturing process in which thin, unidirectional composite tapes are precisely placed by a robotic system onto a lamination tool to build up the laminate ply by ply [54, 55]. Adhesion between the incoming tows and the underlying substrate is ensured through the synchronised action of localised heating, compaction pressure,

and controlled tensioning. Driven by the demand for sustainable and weldable structures, AFP is increasingly adopted for thermoplastic composite manufacturing. Its ability to accurately steer narrow composite tows over complex tooling, combined with out-of-autoclave consolidation, makes it a highly efficient process for advanced composite structures.

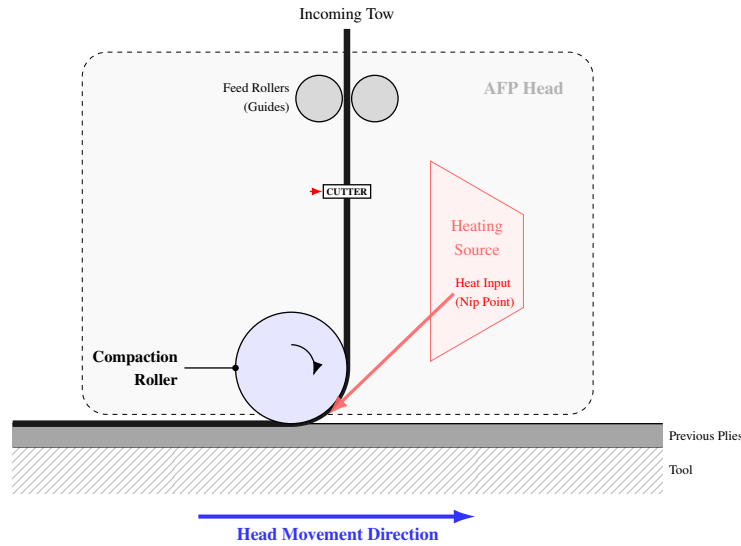


Figure 4.2: Schematic of the AFP process showing vertical tow feeding, compaction roller, and heating source. Adapted from [54].

In the present work, the AFP system was employed to produce reference laminates with a cross-ply stacking sequence ($[0/90]_{ns}$). To ensure full consolidation and eliminate any process-induced porosity, the panels were subsequently placed in a hydraulic hot press. The application of heat and pressure promoted macromolecular diffusion across the interfaces, resulting in high-quality baseline plates.

The recycled plates were manufactured from mechanically processed material in the form of chips, with nominal fibre lengths of 4, 17, and 25 mm (Figure 4.3). This second manufacturing route, detailed in the following sections, aims to evaluate the potential of property retention in discontinuous-fibre systems compared to the high-performance reference material.

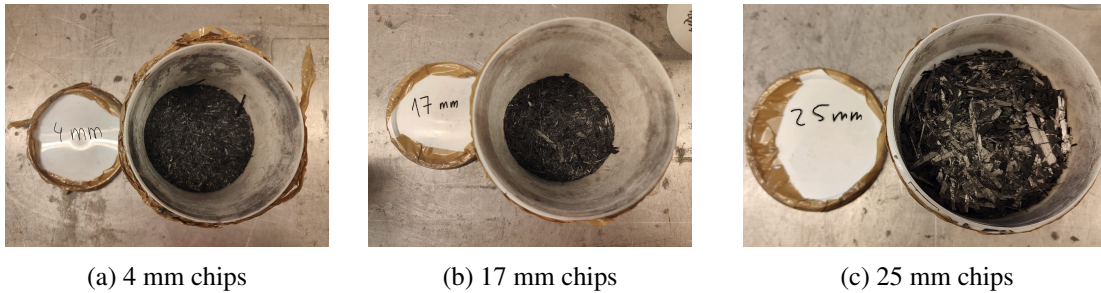
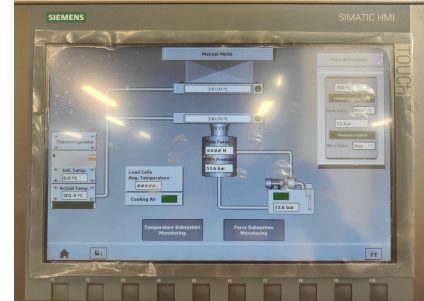


Figure 4.3: Recycled CFRTP chips with different nominal fibre sizes used for the manufacturing of the flat panels.

For each plate, 300 g of recycled material was weighed and placed into a metallic frame ($300 \times 300 \times 2$ mm), as shown in Figure 4.4. The material was then consolidated using a hot-pressing process at 390°C .



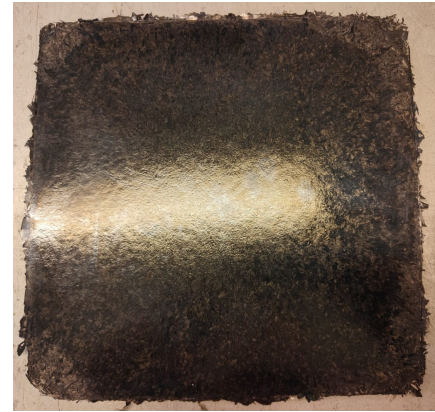
(a) Hot-press used for consolidation.



(b) Hot-press control panel.



(c) Metallic frame used for moulding.



(d) Recycled **CF RTP** plate.

Figure 4.4: Recycled **CF RTP** plate manufacturing process: (a) hot-press equipment, (b) process control, (c) mould frame, and (d) final recycled plate.

A consolidation pressure of 6 bar was applied for 20 minutes once the target temperature was reached. Cooling was performed under pressure to achieve a crystallinity level of $25\% \pm 5\%$ [9]. The applied temperature–pressure cycle is illustrated in Figure 4.5.

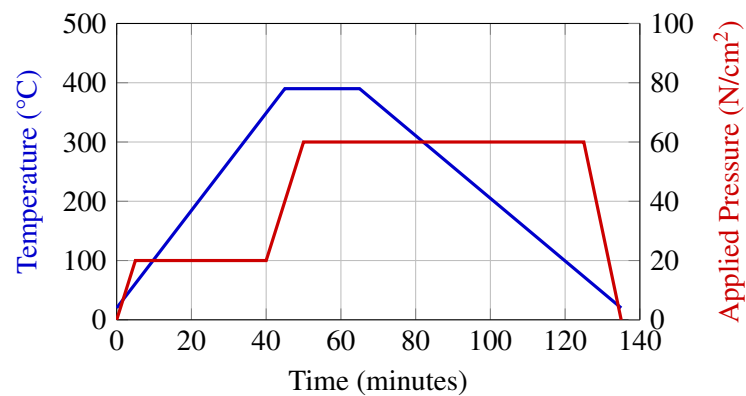


Figure 4.5: Typical press consolidation cycle for VICTREX **LMPAEK™** UDT [9].

Prior to the welding experimental campaign, it is critical to establish a baseline for the structural performance of the base materials, both the as-received and the recycled **CFRTP**. This initial characterisation allows for the subsequent calculation of joint efficiency and provides context for the maximum theoretical load-bearing capacity of the welded joints.

Regarding the mechanical performance of the manufactured recycled plates, Figure 4.6 and Table 4.6 summarise the ultimate tensile strength and Young's modulus, alongside their respective Coefficients of Variation (CV), as a function of fibre length. This experimental data was provided by the **INEGI** ReCAP project [51], forming the basis for the comparative analysis in this study.

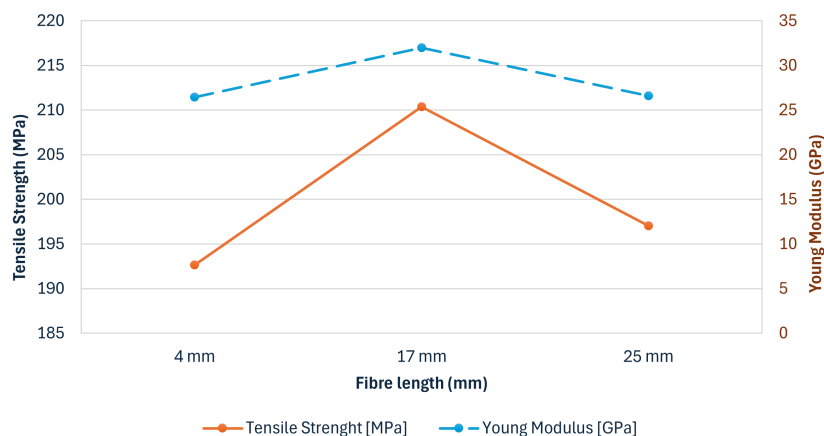


Figure 4.6: Effect of fibre length on tensile strength and Young's modulus of recycled **CFRTP** plates ($n = 5$) [51].

Table 4.6: Tensile properties and Coefficients of Variation (CV) of recycled **CFRTP** plates as a function of fibre length ($n = 5$) [51].

Fibre length (mm)	Tensile Strength (MPa)	Strength CV (%)	Young's Modulus (GPa)	Modulus CV (%)
4	192.65 ± 25.56	13	26.43 ± 1.39	5
17	210.35 ± 12.74	6	31.98 ± 6.39	20
25	197.04 ± 14.15	7	26.59 ± 3.97	15

A distinct correlation between performance, chip length, and data scatter is observed. The 17 mm chips exhibited the highest average strength (210.35 MPa) and the greatest consistency in this parameter, evidenced by the lowest CV of just 6%. The 4 mm chips presented a lower average strength and higher data scatter (CV of 13%), which is attributed to a reduced fibre aspect ratio and potential edge effects during testing. Conversely, while the 25 mm condition maintained acceptable strength variability (CV of 7%), it demonstrated a significant scatter in stiffness (Young's

Modulus CV of 15%), with the 17 mm chips even reaching a Modulus CV of 20%. This high variability in the elastic response of longer chips is a known phenomenon in discontinuous composites, driven by processing heterogeneities, uneven fibre distribution, and random in-plane orientation.

When comparing these recycled laminates to the continuous architecture of the as-received material, a degradation in mechanical properties is inherent. The transition from continuous to discontinuous fibres, coupled with potential matrix degradation during the shredding and consolidation phases, results in a noticeable reduction in both ultimate tensile strength and stiffness. The lower Young's modulus of the recycled composite is particularly relevant, as it directly affects the material's acoustic impedance and vibration transmission during ultrasonic welding, potentially influencing the heating rates at the interface.

Furthermore, a representative assessment of the recycled material's viability requires a comparison with a morphologically similar commercial grade, such as 30% short carbon fibre-reinforced PEEK (30% CF/PEEK), whose reference properties were previously detailed in Table 2.2.

Ultimately, these baseline values are crucial for the forthcoming analysis in Chapter 5, as they confirm that "substrate failure" (or laminate tearing) in recycled specimens will naturally occur at lower absolute loads than in the as-received specimens. This discrepancy is not indicative of poor weld quality, but rather a reflection of the recycled material's intrinsic structural limits.

4.3.2 Preparation of Adherends

Before welding, the manufactured plates were sectioned into individual adherends with nominal dimensions of 25.0×100 mm using a diamond abrasive circular disk. According to the ASTM D5868 standard, the nominal thickness for FRP adherends should be 2.5 mm (0.1 in.). In this study, the average thickness of the adherends (denoted as t in Figure 4.7) varied according to the material state, measuring approximately 2.45 mm for the as-received laminates and 2.30 mm for the recycled plates. This dimensional variability in the recycled material, which also included minor out-of-plane distortion (warping), is a direct consequence of the manufacturing process. The inherent difficulty in achieving a perfectly uniform volumetric distribution of the discontinuous chips within the forming frame hindered strict control over the final consolidated thickness. Furthermore, although the standard prescribes a specimen width of 25.4 mm (1 in.), this dimension was slightly adjusted to 25.0 mm to accommodate the physical constraints of the ultrasonic welding setup and ensure proper alignment within the fixtures.

Consequently, the bonded overlap region was established as 25.0×12.7 mm², reflecting the adjusted width and the standard 12.7 mm (0.5 in.) overlap length. To guarantee accurate stress evaluation, this actual overlap area was systematically used to compute the nominal lap shear strength (LSS) for all tested specimens.

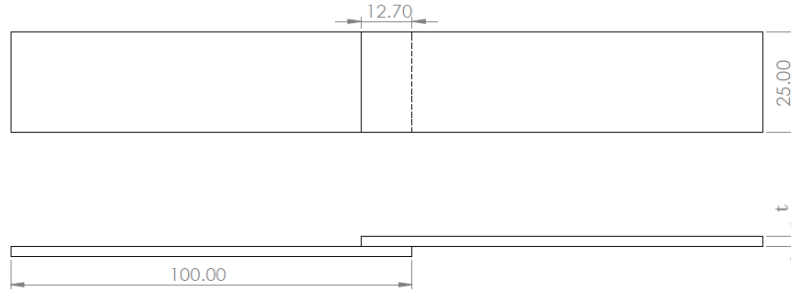
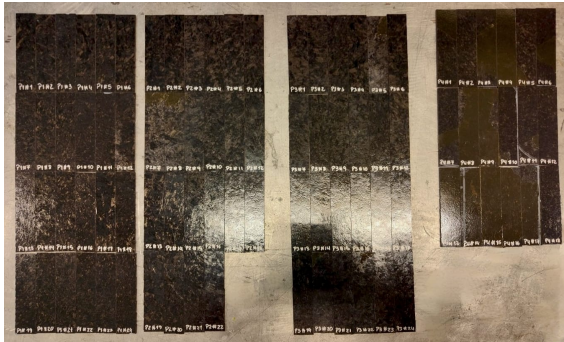
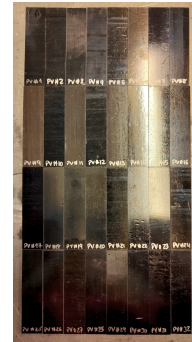


Figure 4.7: Geometry and dimensions of the single-lap shear specimen used in this study. The width was adapted to 25.0 mm to properly fit the ultrasonic welding apparatus, and the thickness t varies between 2.30 and 2.45 mm depending on the material state.

After sectioning, the adherends were catalogued to ensure traceability throughout the experimental campaign (Figure 4.8). Burrs resulting from the cutting process were carefully removed, and the bonding surfaces were cleaned with acetone to eliminate any contaminants.



(a) Recycled **CFRTF** adherends.



(b) As-received **CFRTF** adherends.

Figure 4.8: Individual adherends prepared for the welding process.

For the welded configurations, a flat Energy Director (**ED**) was introduced at the interface of the lower adherend. To ensure absolute material compatibility and prevent secondary interfacial effects, the **ED** consisted of a 60 μm thick neat film sharing the exact chemical composition of the composite's matrix (**LMPAEK**). The implementation of flat **EDs** is well established in the ultrasonic welding of thermoplastic composites, as they promote preferential and localised heating [56]. This phenomenon is driven by the lower compressive stiffness of the neat film relative to the rigid composite adherends, which induces localised strain and enhanced viscoelastic dissipation at the interface during the cyclic mechanical vibration [56]. Furthermore, a flat geometry was deliberately selected to isolate the influence of the welding parameters under investigation, enabling the formation of a fully welded interface without the need for complex optimisation of the **ED**'s shape or placement.

4.4 Ultrasonic Welding Procedure

The lower adherend was first positioned on the rigid fixture using alignment pins to guarantee a consistent overlap length and accurate lateral alignment. Once correctly positioned, it was mechanically secured using two fastening screws. The upper adherend was then placed on top, aligned using the same reference pins, and clamped in position. Particular care was taken to verify the alignment of both components before welding, as misalignment can lead to non-uniform stress distribution and inconsistent weld formation [56, 57].

After assembly, the welding stack was visually inspected to confirm proper contact between the adherends and the energy director. The system was then ready to initiate the UW cycle.

Despite the controlled setup, several sources of experimental variability were identified. These include variations in clamping force, potential non-uniform tightening of the fastening screws, and small displacements during the welding process. Such effects may influence the propagation of ultrasonic vibrations, the effective energy input at the joint interface, and the resulting weld quality [56]. These factors were carefully considered during the interpretation of the experimental results.

4.4.1 Experimental challenges and setup adjustments

During the welding stage, several experimental challenges were identified regarding setup stability and the geometric quality of the specimens. These challenges were significantly more pronounced in the recycled CF RTP samples compared to the as-received laminates. The latter exhibited superior planarity and a more predictable response due to their continuous fibre architecture and standardised AFP manufacturing.

Firstly, slight geometric irregularities, such as warpage, were observed in the recycled CF RTP plates. This lack of perfect planarity affected the initial contact between the samples and the sonotrode, necessitating a more robust clamping strategy to ensure a uniform pressure distribution. As demonstrated by Brito *et al.* [57], the thermomechanical properties of LMPA EK and the alignment of the adherends significantly affect heating rates and through-thickness energy dissipation.

Secondly, the high-frequency vibration inherent to the UW process posed difficulties in maintaining accurate alignment. In early trials, particularly with the recycled material, the vibration caused the adherends to shift out of the positioning jig. The transmission of ultrasonic vibration from the sonotrode to the welding interface is highly sensitive to local contact pressure and clamping conditions [56, 57].

To mitigate these effects and standardise the contact conditions, a supplementary clamping system was introduced. As shown in Figure 4.9, two manual clamps were used to secure auxiliary hold-down plates against the specimens. These auxiliary plates served the primary purpose of preventing lateral movement and misalignment caused by the high-frequency vibrations. While this manual clamping procedure was necessary to ensure the specimens remained against the alignment stops, it is acknowledged as an inherent source of experimental variability. Although efforts

were made to maintain a consistent clamping pressure, the manual nature of this adjustment introduces uncertainties regarding its precise influence on energy propagation and process variance [56]. This factor was therefore considered as a potential source of scatter during the subsequent analysis of the results.

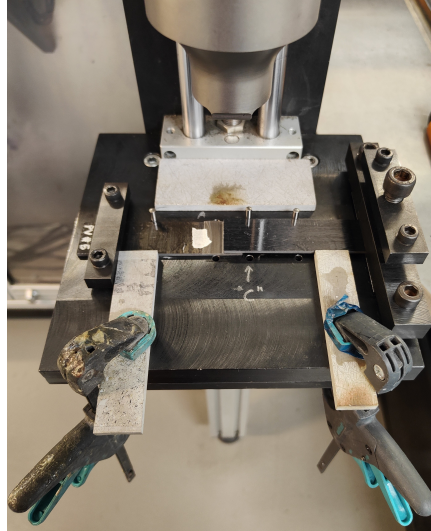


Figure 4.9: Experimental setup for UW specimens, highlighting the supplementary clamping system. Manual clamps and auxiliary hold-down plates are used to prevent vibration-induced misalignment and ensure contact stability during welding.

These auxiliary plates served the primary purpose of preventing lateral movement and misalignment caused by the high-frequency vibrations. While this manual clamping procedure was necessary to ensure the specimens remained against the alignment stops, it is acknowledged as an inherent source of experimental variability. Although efforts were made to maintain a consistent clamping pressure, aiming to prevent shifting without excessively damping the ultrasonic energy, the manual nature of this adjustment introduces uncertainties regarding its precise influence on energy propagation and the resulting heating rates [56, 57]. Consequently, the transmission of ultrasonic vibration to the welding interface remains highly sensitive to these local contact conditions [56]. This factor was therefore considered as a potential source of scatter during the subsequent analysis of the results.

4.5 Data Acquisition and Methods

This section details the experimental protocols used to evaluate the welded joints, ranging from mechanical testing and image-based quantification to the statistical methods employed for data validation.

4.5.1 Lap shear test (LSS)

The mechanical performance of the joints was assessed through single-lap shear testing following the methodology in ASTM D5868. Tests were carried out in an Instron 5900R universal testing machine, equipped with a 200 kN capacity load cell. The standard testing configuration, used for the majority of the specimens, is shown in Figure 4.10a. Specifically for the third group of specimens, an extended setup was employed (Figure 4.10b). In this configuration, a high-resolution camera system was synchronised with the Instron machine to continuously capture the deformation of the joint's lateral edge. These acquired images were stored for subsequent post-processing using Digital Image Correlation (DIC) software. This extended imaging setup included a dedicated lighting system to ensure uniform illumination and high contrast, which is essential for accurate DIC tracking.



(a) Standard testing setup.



(b) Extended setup for DIC.

Figure 4.10: Experimental setups for the lap shear tests using the Instron 5900R: (a) standard configuration, and (b) extended configuration with a synchronised camera and dedicated lighting system for DIC analysis.

A critical challenge in single-lap joints is the inherent eccentricity (e) of the load path, which introduces bending moments (M). To mitigate this effect at the beginning of the test, packing plates (tabs) of the same thickness as the adherends (t) were placed in the grips (Figure 4.11a). This offset gripping configuration ensures that the load line is initially collinear with the shear plane, minimising early joint rotation. However, as the tensile load increases, the joint inevitably undergoes significant rotation (angle α) in an attempt to align the adherends with the loading axis. This geometric non-linearity generates macroscopic bending moments and, consequently, severe peel stresses (σ_{peel}) concentrated at the edges of the overlap (Figure 4.11b). These normal tensile stresses are typically responsible for crack initiation, meaning the stress state is never purely shear.

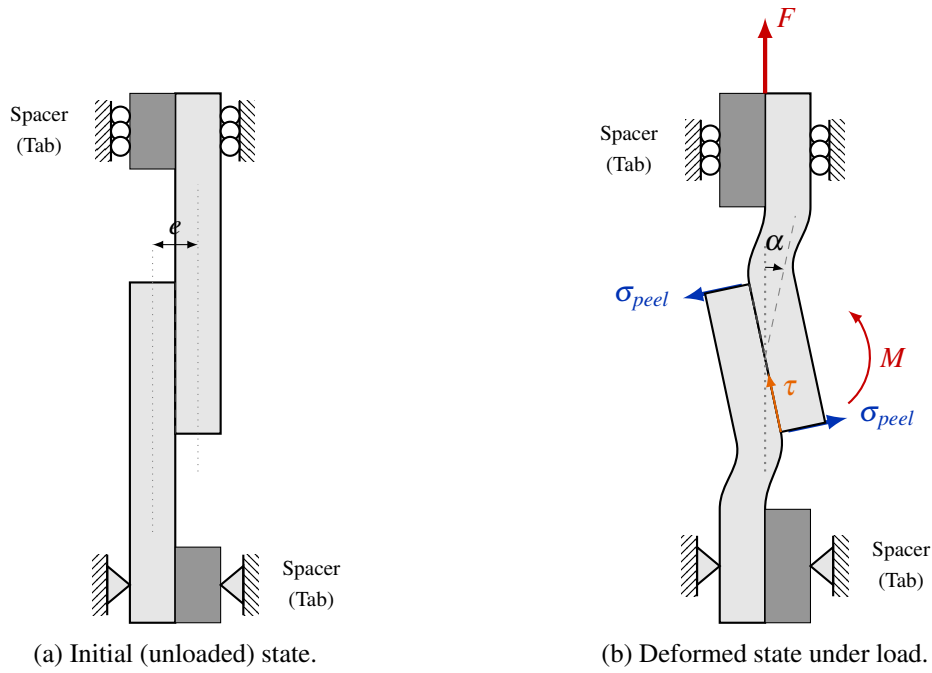


Figure 4.11: Schematic representation of the single-lap shear test setup. **(a)** The initial unloaded state, highlighting the geometric joint eccentricity (e). The lower grips are fully constrained (pinned), and the upper grips allow vertical displacement (rollers). **(b)** The deformed state, where the applied force (F) and eccentricity induce a macroscopic bending moment (M). This moment forces the joint to rotate by an angle α , causing severe transverse peel stresses (σ_{peel}) at the overlap edges alongside the shear stress (τ).

Each specimen was clamped with a constant grip separation and loaded under displacement control at a constant crosshead speed of 1.3 mm/min until failure. For each welding condition, three replicates ($n = 3$) were tested. From each test, the maximum load $F_{\max}$ was extracted to compute two distinct response variables. The nominal lap shear strength (LSS_{nom}) was calculated as the ratio between the maximum load and the nominal overlap area A_{nom} ($25.0 \times 12.7 \text{ mm}^2$):

$$LSS_{\text{nom}} = \frac{F_{\max}}{A_{\text{nom}}} \quad (4.3)$$

Additionally, an effective lap shear strength (LSS_{eff}) was defined to account for partial bonding within the overlap, using the effective welded area (A_{eff}) obtained via image processing (Section 4.5.2):

$$LSS_{\text{eff}} = \frac{F_{\max}}{A_{\text{eff}}} \quad (4.4)$$

4.5.2 Squeezing quantification

Material squeezing identifies polymer expelled beyond the nominal overlap due to excessive energy input. The analysis focused on quantifying this material using static images acquired immediately prior to the destructive testing. Once the specimens were securely clamped in the testing machine, the pre-installed high-resolution camera and dedicated lighting system, from the DIC setup analysis (Figure 4.10b, Section 4.5.1), were used to capture the initial state of the joints. The

complete visual matrix comprising these initial pre-test images for all specimens is presented in Appendix C. This procedure ensured a consistent focal length and high-contrast imaging of the expelled polymer across all specimens.

The digital image processing was conducted via custom scripts developed in GNU Octave (detailed in Appendix D). Before numerical processing, all images were pre-treated to isolate the regions of interest. This procedure, which includes background removal and binarisation to isolate the expelled polymer, is illustrated in Figure 4.12. In the resulting binary masks, the white pixels (foreground) strictly isolate the displaced material (squeezed polymer), while the black pixels (background) represent the uncompromised boundaries of the specimen and the surrounding environment. The complete set of processed binary images used for these calculations across all tested conditions is compiled in Appendix E. The squeezing metric was defined as the expelled area expressed as a percentage of the nominal overlap area (A_{nom}). It is important to acknowledge an inherent limitation of this 2D optical approach: because the measurements are restricted to a frontal perspective, the thickness of the expelled material is unknown. Consequently, determining the true volume of the squeezed polymer, which would represent the most accurate metric for material loss, is not possible. This reliance on a 2D projected area introduces a potential bias, as two specimens exhibiting identical squeezing percentages could theoretically possess significantly different volumes of expelled material. Nevertheless, this procedure was applied consistently to all recycled and as-received specimens to provide a reliable comparative baseline.

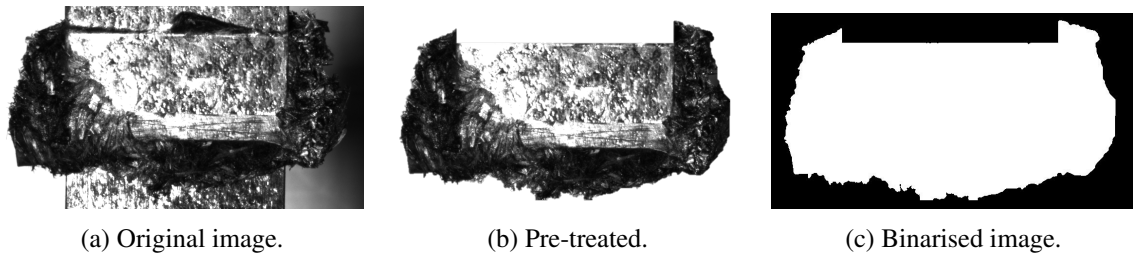


Figure 4.12: Representative example of the squeezing quantification procedure using specimen B3: (a) raw image acquired after welding, (b) pre-processed image with background removal, and (c) binarised result used for pixel-based area calculation, where white pixels represent the expelled material and black pixels denote the background.

4.5.3 Effective welded area quantification

The effective welded area was determined using fracture surface images captured after the lap shear tests with a digital microscope (RS PRO). The complete visual matrix of these initial fracture surfaces for all tested specimens is provided in Appendix F. As detailed in the scripts provided in Appendix D, the non-welded regions were isolated and binarised to compute A_{eff} , as shown in Figure 4.13. In the generated binary masks, the white pixels strictly isolate the non-welded regions (unaffected substrate or voids), whereas the black pixels represent the effectively welded area (fused polymer). The full visual compilation of these processed binary masks for all specimens is also provided in Appendix E.

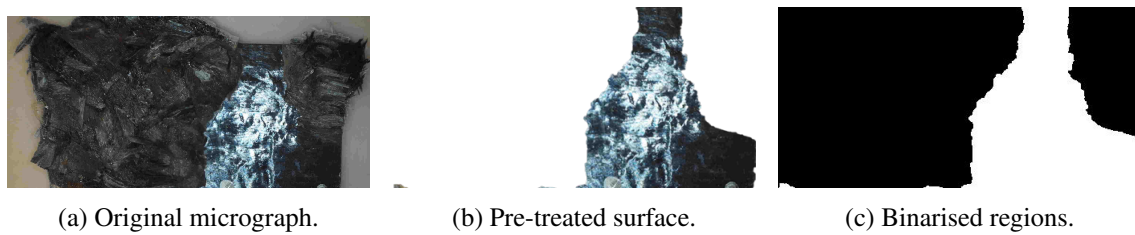


Figure 4.13: Representative example of the effective welded area quantification procedure using specimen E3: (a) raw micrograph, (b) pre-processed fracture surface, and (c) binarised image used for area calculation, where the white regions represent the non-welded area and the black regions correspond to the effectively welded area.

4.5.4 Failure mode classification procedure

Following the lap shear tests, the fracture surfaces of all specimens were visually inspected to categorise their macroscopic crack propagation path. As established in Section 2.6, pure cohesive failure within the polymer was not considered as an isolated category due to the microscopic thickness of the ED film and the identical polymeric nature of the adherends.

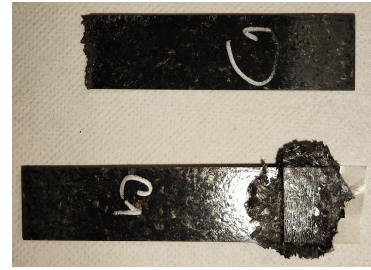
Therefore, to systematically evaluate and catalogue the structural integrity of the joints, the following practical macroscopic criteria were applied:

- **Adhesive (interfacial) failure:** The ED film remains entirely attached to one adherend, while the opposite adherend presents a clean, intact surface. This indicates apparent interfacial debonding without macroscopically damaging the composite structure.
- **Substrate failure:** The ED film remains attached to one adherend but carries with it a visible layer of torn carbon fibres and polymer matrix extracted from the opposite adherend. This demonstrates that the interfacial bond strength successfully exceeded the interlaminar shear strength of the Carbon Fibre Reinforced Thermoplastic (CFRTP).
- **Mixed-mode failure:** The crack path alternates dynamically between the adhesive interface and the composite substrate. This often results in the ED layer being visibly torn or sheared, leaving polymer and fibre residues scattered on both adherend surfaces.

Representative macrographs illustrating the application of these criteria to the tested CFRTP joints are presented in Figure 4.14.



(a) Adhesive failure: clean debonding.



(b) Substrate failure: torn carbon fibres.



(c) Mixed-mode failure: torn ED film.

Figure 4.14: Representative macrographs illustrating the primary failure mode criteria used for the visual inspection of the CFRTTP joints.

4.5.4.1 Digital Image Correlation (DIC)

To accurately evaluate the joint kinematics and exclude inherent machine compliance, Digital Image Correlation (DIC) was employed during the mechanical testing. Through a non-contact optical setup, a virtual extensometer was defined using tracking points (P_0 and P_1) to monitor the relative motion of the adherends. This technique allowed for the extraction of the longitudinal strain maps (ϵ_{xx}) and the vertical displacement fields (V), which are fundamental to isolating the true relative displacement (δ_{true}) at the weld interface.

5. Experimental results and statistical assessment

5.1 Overview of experimental results

This chapter presents the mechanical performance of the ultrasonic lap joints produced under the experimental matrices described in Chapter 4. Joint performance was primarily assessed through the maximum force recorded during lap shear testing and the corresponding lap shear strength (LSS), calculated using the nominal overlap area. In addition, complementary response metrics obtained from image-based post-processing (squeezing and effective welded area) were used to support the interpretation of the welding behaviour, as described in Section 4.5.

To provide a clear context for the subsequent data analysis, it is pertinent to recall the core research questions driving this investigation, as initially established in Chapter 1. The experimental results, visual inspections, and statistical assessments detailed in this chapter are systematically structured to answer the following:

1. Are the energy input and process parameters window required to achieve high-quality welds with recycled thermoplastic composites comparable to those of as-received materials?
2. What is the influence of recycled material morphology (e.g., fibre length and distribution) on the mechanical strength and failure behaviour of welded joints, when compared to welds made from as-received materials?
3. Are the weld quality metrics (e.g., Lap Shear Strength (LSS) and preferred failure mode) obtained with recycled thermoplastic composites comparable to those of welds made from as-received materials, or is the robustness and repeatability of the welding process affected?

Following this rationale, the results are presented separately for the recycled CF RTP specimens (Taguchi L9 orthogonal array with four factors: fibre size d_f , pressure p , welding time t , and amplitude A) and the as-received CF RTP specimens (Taguchi L4 orthogonal array with three factors: p , t , and A). Unless otherwise stated, the error bars shown in the subsequent bar charts represent the standard dispersion of the repeated tests performed for each experimental group.

5.2 Lap shear performance of the welded joints

To comprehensively evaluate the mechanical performance of the ultrasonic welds, the lap shear response of both the recycled (group A–I) and as-received (J–M) **CFRTP** joints was analysed.

Crucially, the **LSS** presented in this section was calculated using the effective welded area (obtained via the image post-processing detailed in Chapter 4), rather than the theoretical nominal overlap area ($12.7 \times 25 \text{ mm}^2$). Given that ultrasonic energy tends to concentrate centrally, leaving unwelded edges, dividing the maximum force by the true bonded area provides a much more accurate and physically representative measure of the interface's structural integrity. A comprehensive summary of the experimental data, detailing the individual specimen results, energy inputs, and statistical metrics for both the effective **LSS** and the welded area, is provided in Appendix G.

5.2.1 Mechanical Response and Failure Kinematics

The fundamental differences in mechanical response and failure behaviour are further corroborated by the mechanical curves obtained during the lap shear tests. Figure 5.1 presents a direct comparison of the **LSS**-displacement behaviour between a highly consolidated as-received joint and an optimally welded recycled joint.

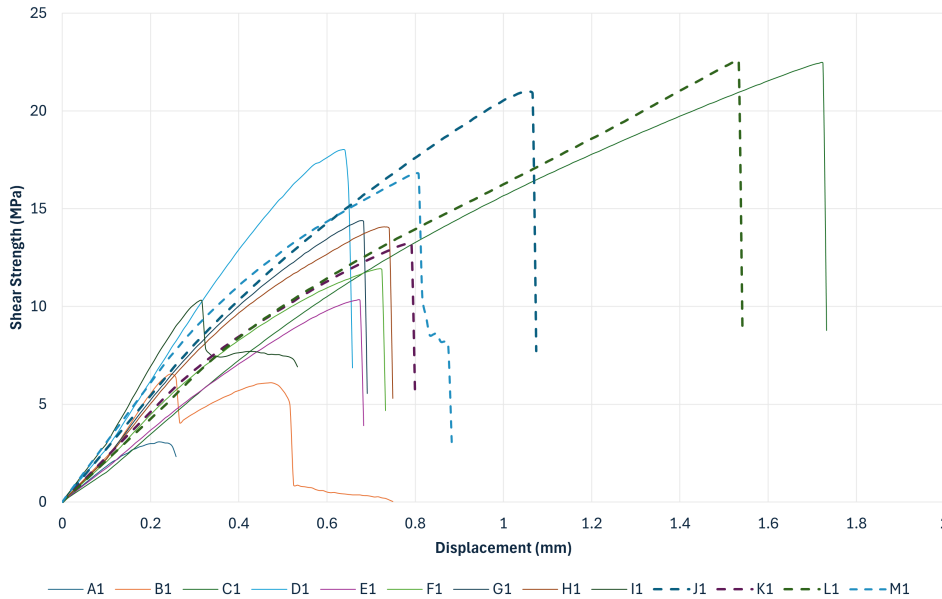


Figure 5.1: Representative **LSS**-displacement curves contrasting the typical structural response of as-received (continuous fibre) and recycled (chopped fibre) **CFRTP** joints.

The curves demonstrate that while the as-received material sustains higher peak stresses with a sharp load drop, the recycled joints exhibit a lower initial stiffness and a progressive, stepwise failure sequence. This is consistent with the discontinuous fibre architecture, where localised matrix yielding and fibre pull-out occur before catastrophic fracture. A complete compilation of these curves is provided in Appendix H.

5.2.2 Performance of Recycled CFRTJ Joints

Figure 5.2 correlates the effective **LSS** and the average effective welded area with the nominal energy input for the recycled experimental groups.

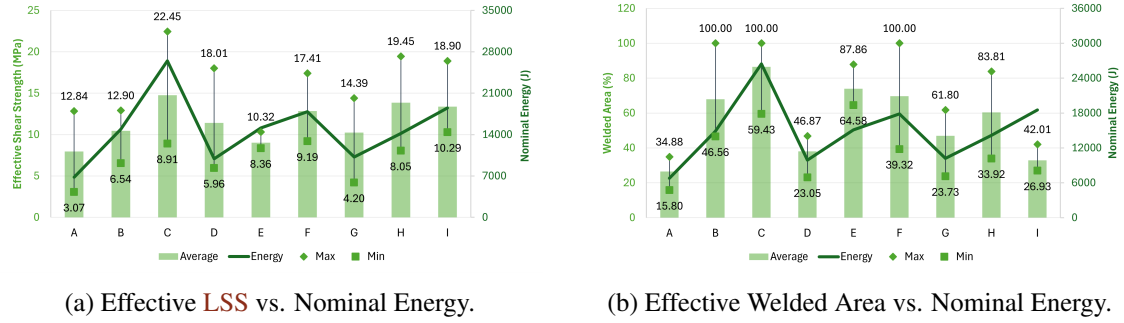


Figure 5.2: Lap shear performance of recycled CFRTJ joints (groups A–I), analysed in terms of effective strength and bonded area as a function of the energy input.

A considerable variability is evident in both metrics. Cross-referencing Figure 5.2a with Figure 5.2b reveals that joint resistance is not solely dependent on the extent of the bonded interface. In several instances (e.g., comparing the high peak strength of Group H against the fully bonded but weaker specimens of Group F), groups with smaller welded areas achieved higher **LSS** values, demonstrating that optimal parameters govern the weld quality rather than just its macroscopic footprint.

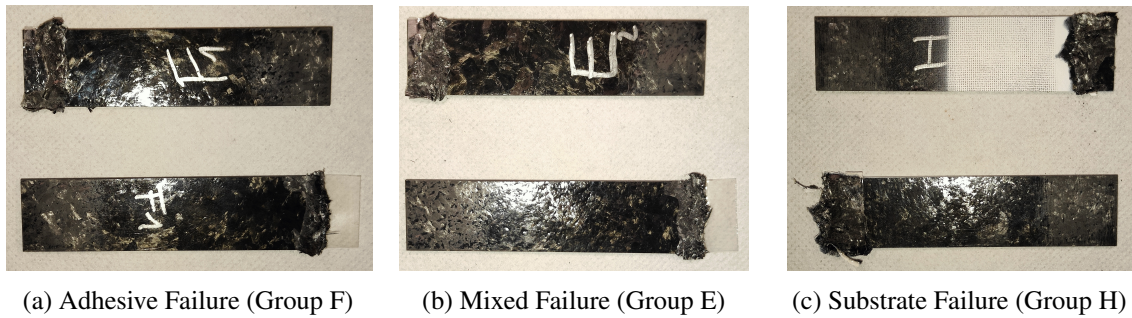


Figure 5.3: Representative macroscopic fracture surfaces showcasing the transition between the three identified failure modes: adhesive, mixed, and substrate failure. A detailed matrix of all tested specimens is provided in Appendix I.

The macroscopic inspection of the fracture surfaces (Figure 5.3) provides a physical explanation for the **LSS** variations. Lower energy inputs, such as in Group F, typically resulted in Adhesive failure, where the polymer failed to fully penetrate the substrate's fibre network. In contrast, optimal parameter combinations (e.g., Group H) promoted a Substrate failure mode, indicating that the weld interface became stronger than the bulk material itself. The prevalence of Mixed failure modes in the recycled specimens further reinforces the impact of material heterogeneity, as the crack path often deviated according to local fibre orientations. A comprehensive photographic record of all experimental repetitions is compiled in Appendix I.

5.2.3 Comparative Analysis: Recycled vs. As-received

The performance of as-received joints (groups J–M) is juxtaposed with the recycled material in Figure 5.4.

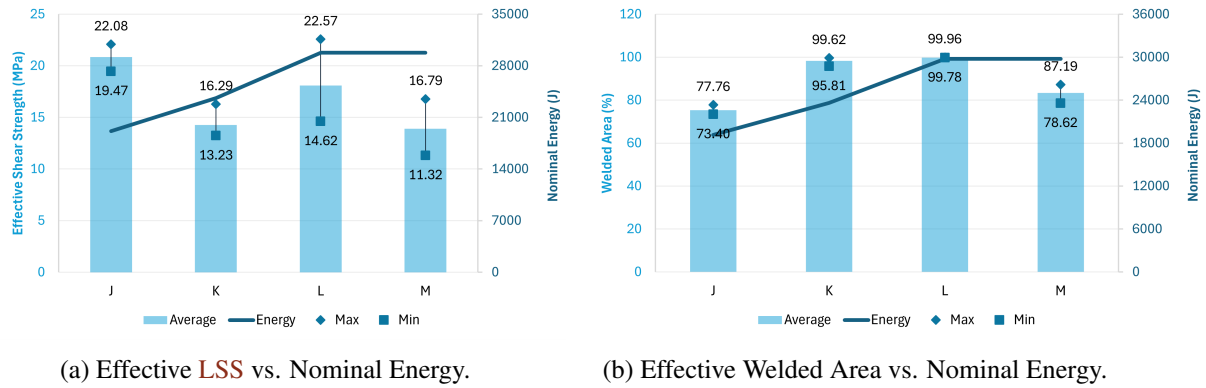


Figure 5.4: Lap shear performance of as-received CF RTP joints (groups J–M).

As-received joints demonstrate significantly higher average stress limits (16.78 MPa) and improved process stability. The predefined sequence of continuous fibres ensures stable acoustic transmission, leading to a consistent bonded area (average Coefficient of Variation (CV) of 2%), which sharply contrasts with the erratic behaviour of the chopped fibre joints.

A direct quantitative comparison between the two material conditions reveals the significant impact of the recycling process on joint morphology. On average, the recycled CF RTP joints exhibited a 37% reduction in the effective welded area and a corresponding 30% drop in Lap Shear Strength (LSS) when compared to the as-received specimens.

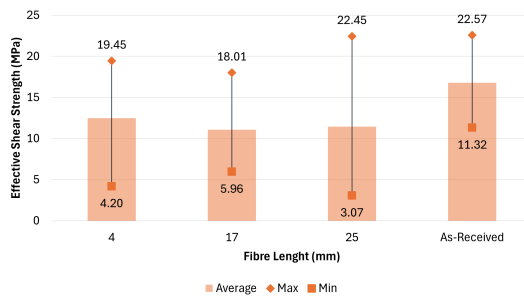
Interestingly, this drop in area was accompanied by an average 17% increase in squeezing (vertical indentation). This inverse relationship is mechanically sound: due to the high surface roughness and internal porosity of the recycled laminates, the ultrasonic energy and clamping pressure are primarily consumed in vertical consolidation, compressing the voids and flattening surface peaks, rather than promoting the lateral spread of the molten ED. Consequently, the restricted polymer flow results in a smaller bonded area, which, combined with the inherently lower strength of discontinuous fibres, directly limits the final load-bearing capacity of the joint.

5.2.4 Influence of Fibre Length on Joint Strength

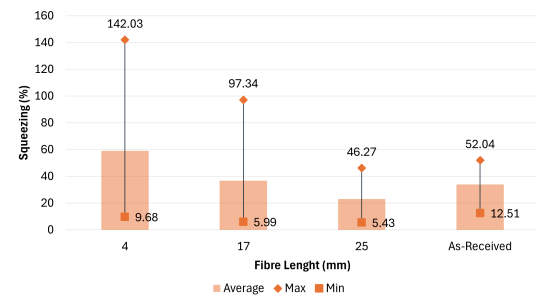
To isolate the material's morphological impact, data was grouped by fibre size (d_f), as detailed in Table 5.1 and Figure 5.5a.

Table 5.1: Statistical overview of the LSS grouped by fibre size condition.

Condition	Min (MPa)	Max (MPa)	Average (MPa)	Std. Dev.	CV (%)
Recycled - 4 mm	3.07	22.45	11.44	5.34	47%
Recycled - 17 mm	5.96	18.01	11.09	3.87	35%
Recycled - 25 mm	4.20	19.45	12.49	4.61	37%
As-Received (Cont.)	11.32	22.57	16.78	3.61	22%



(a) Dispersion of LSS as a function of the internal fibre architecture.



(b) Dispersion of squeezing as a function of the internal fibre architecture.

Figure 5.5: Comparison of fibre architecture metrics.

The 25 mm configuration yielded slightly higher average strengths, while the 17 mm condition showed the lowest variability among the recycled materials. In contrast, although the 4 mm condition reached high maximum values, it also exhibited the largest data dispersion and the lowest minimum strength, indicating poor process consistency.

When analysed together with the squeeze flow data (Figure 5.5b), a clearer trend emerges. The 4 mm configuration shows significantly higher material expulsion, suggesting excessive melt flow during welding. This behaviour is detrimental, as it reduces the effective material available at the joint interface and compromises structural integrity. In contrast, longer fibres (17 mm and especially 25 mm) exhibit reduced squeeze flow, indicating a more stable material response under ultrasonic vibration and clamping pressure.

Therefore, although shorter fibres may locally achieve high strength values, their tendency for excessive flow and expulsion makes them less reliable overall. Larger discontinuous fibres appear to better resist this flow, helping to maintain material at the weld interface and improving load transfer consistency.

From a physical standpoint, it is plausible that the macroscopic squeeze flow induced by ultrasonic vibration promotes reorientation and displacement of smaller fibres more easily, whereas

longer fibres provide mechanical resistance to this movement, effectively bridging the weld line. This results in a more stable joint formation and improved repeatability.

5.2.5 Process Window and Parametric Interactions

3D surface plots were generated (Figure 5.6) to evaluate the interactions between machine variables. These surfaces indicate that Amplitude is the dominant driver of interfacial heating. However, pairing maximum amplitude with extended welding times (Figure 5.6b) leads to polymer degradation and excessive squeeze-out, reducing joint strength.

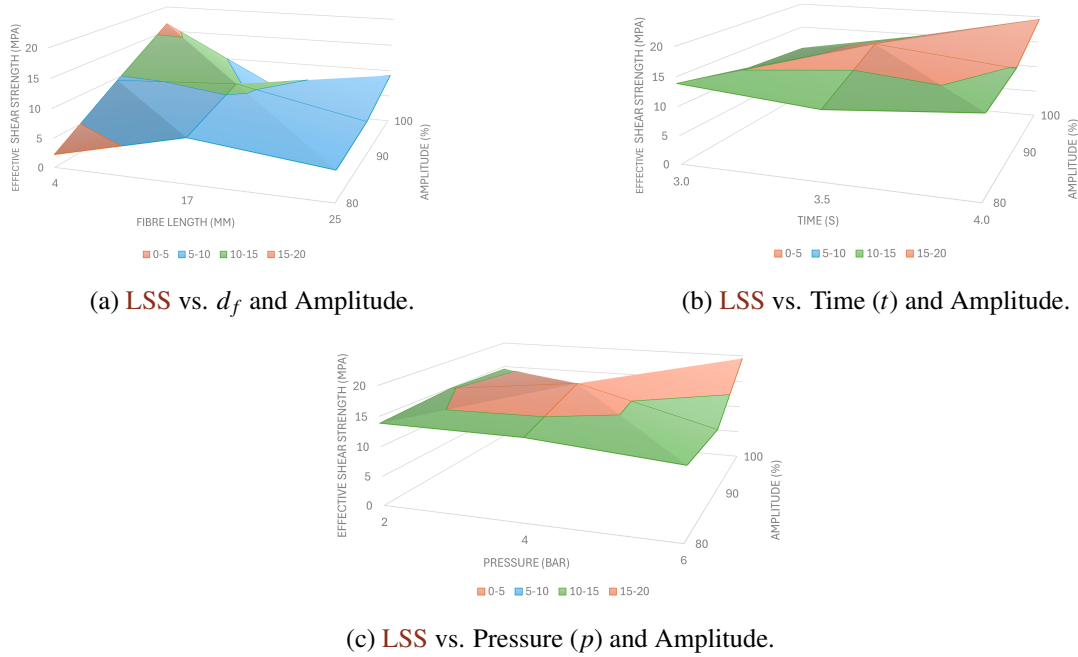


Figure 5.6: 3D response surface plots for the recycled CFRTP joints.

In contrast, the response surfaces for the as-received laminates (Figure 5.7) form a stable plateau, corroborating that the continuous-fibre process is remarkably robust and insensitive to minor parameter variations.

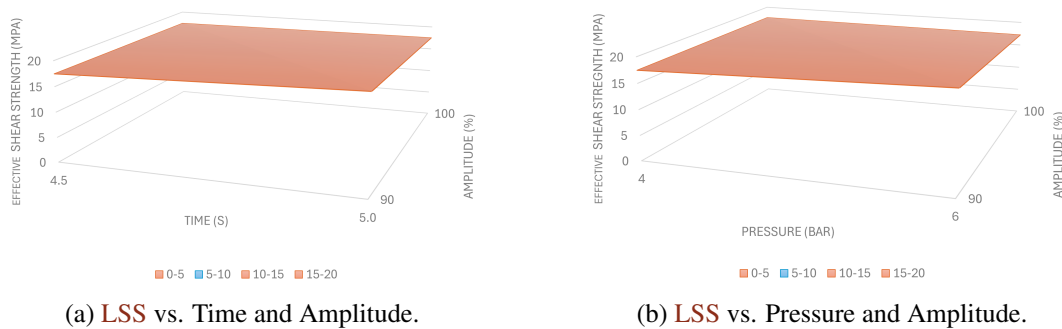


Figure 5.7: 3D response surfaces for the as-received laminates.

5.3 Statistical Analysis of Process Parameters

In this section, the influence of welding parameters on joint performance is analysed using Taguchi main effects plots and Analysis of Variance (ANOVA). The analysis focuses on three response variables: LSS, Material Squeezing, and Welded Area. A confidence level of 95% was selected ($p \leq 0.05$). The validity of the General Linear Models (GLM) presented herein was confirmed through residual analysis, with the complete statistical diagnostics, main effects plots, and interaction contour plots detailed in Appendix B.

5.3.1 Lap Shear Strength (LSS)

The influence of welding parameters on mechanical strength reveals distinct behaviours. For the as-received material (Table 5.2), Welding Time is the only significant factor ($p = 0.008$). In contrast, the recycled material (Table 5.3) is dominated by noise, with no parameter reaching statistical significance.

Table 5.2: ANOVA results for LSS: As-received material.

Factor	DF	Adj SS	Adj MS	F-Value	P-Value
Pressure (p)	1	7.251	7.251	1.00	0.346
Welding Time (t)	1	86.945	86.945	12.03	0.008
Amplitude (A)	1	4.329	4.329	0.60	0.461
Error	8	57.799	7.225		

Table 5.3: ANOVA results for LSS: Recycled material.

Factor	DF	Adj SS	Adj MS	F-Value	P-Value
Fibre Size (d_f)	2	11.722	5.8612	0.22	0.803
Pressure (p)	2	63.319	31.6593	1.20	0.326
Welding Time (t)	2	0.743	0.3716	0.01	0.986
Amplitude (A)	2	45.835	22.9176	0.87	0.437
Error	17	448.589	26.3876		

5.3.2 Material Squeezing

Squeezing is driven by viscous flow. In as-received specimens (Table 5.4), Amplitude is highly significant ($p = 0.002$). For recycled specimens (Table 5.5), no factor is strictly significant, although Pressure shows a statistical tendency ($p = 0.083$).

Table 5.4: ANOVA results for Squeezing: As-received material.

Factor	DF	Adj SS	Adj MS	F-Value	P-Value
Pressure (p)	1	75.15	75.15	1.37	0.276
Welding Time (t)	1	0.02	0.02	0.00	0.985
Amplitude (A)	1	1066.81	1066.81	19.43	0.002
Error	8	439.22	54.90		

Table 5.5: ANOVA results for Squeezing: Recycled material.

Factor	DF	Adj SS	Adj MS	F-Value	P-Value
Fibre Size (d_f)	2	4004	2002.2	2.57	0.106
Pressure (p)	2	4498	2248.9	2.89	0.083
Welding Time (t)	2	2012	1006.0	1.29	0.300
Amplitude (A)	2	3062	1531.2	1.97	0.171
Error	17	13241	778.9		

5.3.3 Welded Area

Welded area analysis (Tables 5.6 and 5.7) highlights the importance of Pressure ($p = 0.029$) for recycled joints to overcome surface irregularities, while Amplitude remains the dominant factor ($p < 0.001$) for as-received joints.

Table 5.6: ANOVA results for Welded Area: As-received material.

Factor	DF	Adj SS	Adj MS	F-Value	P-Value
Pressure (p)	1	70.02	70.02	9.78	0.014
Welding Time (t)	1	31.94	31.94	4.46	0.068
Amplitude (A)	1	1168.33	1168.33	163.12	0.000
Error	8	57.30	7.16		

Table 5.7: ANOVA results for Welded Area: Recycled material.

Factor	DF	Adj SS	Adj MS	F-Value	P-Value
Fibre Size (d_f)	2	1242	621.0	1.42	0.268
Pressure (p)	2	3822	1910.9	4.38	0.029
Welding Time (t)	2	2422	1210.9	2.78	0.090
Amplitude (A)	2	1265	632.7	1.45	0.262
Error	17	7409	435.9		

5.3.4 Correlation between Effective Welded Area and Squeezing

The relationship between the effective welded area (A_{eff}) and squeezing was analysed to verify the consistency of the image-based metrics (Figure 5.8).

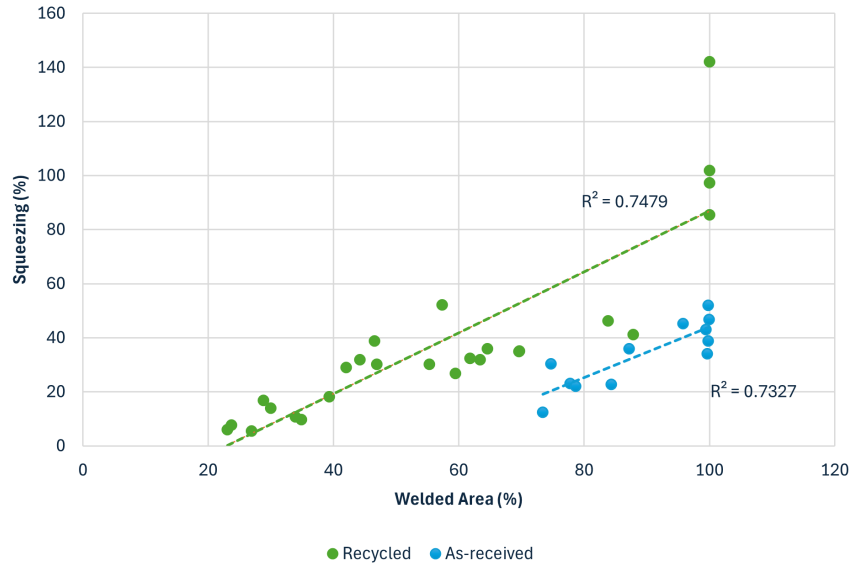


Figure 5.8: Correlation between effective welded area and squeezing. Both materials exhibit a positive linear trend ($R^2 \approx 0.74$), indicating that bonded area growth is inherently linked to lateral material displacement.

The strong coefficients of determination validate the physical coupling between consolidation and flow. Reaching larger welded areas inevitably increases the volume of molten polymer, which is then expelled as flash under the clamping pressure. This consistent relationship suggests that squeezing could potentially serve as a non-destructive visual indicator of internal weld development in an industrial environment.

5.3.5 Summary of Statistical Trends

The comparative analysis demonstrates that material homogeneity dictates process predictability. While the as-received material follows clear parametric trends (governed by Time and Amplitude), the recycled material's mechanical strength is largely decoupled from machine settings due to high internal noise. However, the significance of Pressure ($p = 0.029$) in governing the welded area of recycled specimens confirms its role in overcoming the material's complex surface topology. These findings reinforce the need for the energy-based discussion presented in the following section (Section 5.7), which seeks to unify these erratic responses into a more holistic performance metric. To support this transition, a detailed linear regression analysis quantifying the lack of correlation between total energy and joint strength is provided in Appendix B.

5.4 Analysis of Failure Mechanisms and Mechanical Correlation

To comprehensively evaluate the quality of the ultrasonic welding process, the fracture surfaces of all tested specimens were visually examined. Given the nature of thermoplastic welding, where both the **ED** film and the composite matrix consist of the same polymer, true interfacial boundaries are largely eliminated due to molecular diffusion and co-crystallisation during the melt phase.

Consequently, characterising the exact fracture path is complex. As the final consolidated **ED** layer is extremely thin (often reduced to a few micrometres after squeeze-out), pure cohesive failure within the **ED** itself is highly unlikely unless a significantly thicker **ED** volume is utilised. Therefore, failures were categorised into three primary macroscopic modes: apparent adhesive failure, substrate failure, and mixed-mode failure.

Table 5.8 integrates the ultimate **LSS** results with the corresponding macroscopic failure modes for all tested repetitions. A complete photographic record of the fracture surfaces is provided in Appendix I.

Table 5.8: Experimental results detailing the Lap Shear Strength (**LSS**) in MPa and the associated macroscopic failure mode for all tested **CFRTP** joints.

Group	Repetition 1		Repetition 2		Repetition 3	
	LSS (MPa)	Mode	LSS (MPa)	Mode	LSS (MPa)	Mode
A	3.07	Adhesive	12.84	Mixed	N/A	N/A
B	6.54	Mixed/Adhesive	11.92	Mixed	12.90	Substrate
C	22.45	Substrate	8.91	Adhesive	12.90	Substrate
D	18.01	Mixed	5.96	Mixed/Adhesive	10.26	Mixed/Adhesive
E	10.32	Substrate	8.40	Mixed	8.36	Mixed
F	11.92	Adhesive	9.19	Mixed/Adhesive	17.41	Substrate
G	14.39	Mixed	4.20	Adhesive	12.12	Mixed/Adhesive
H	14.07	Mixed	8.05	Adhesive	19.45	Substrate
I	10.29	Mixed/Adhesive	10.92	Adhesive	18.90	Mixed/Adhesive
J	21.00	Mixed/Adhesive	19.47	Mixed	22.08	Mixed/Adhesive
K	13.23	Adhesive	16.29	Adhesive	13.28	Substrate
L	22.57	Adhesive	17.09	Adhesive	14.62	Substrate
M	16.79	Mixed/Adhesive	13.62	Mixed/Adhesive	11.32	Substrate

Note: N/A indicates the specimen was not tested or the data was excluded.

5.4.1 Correlation between Failure Mode and Joint Strength

Analysing the data in Table 5.8, a correlation emerges between the surface condition, the apparent failure mode, and mechanical performance:

- **Recycled groups (A to I):** For specimens with rougher textures, macroscopic failure modes are a direct indicator of consolidation quality. Under-welded joints exhibiting apparent adhesive failure (e.g., A1, G2) consistently yielded the lowest **LSS** values, indicating insufficient energy to melt the **ED** and establish molecular entanglement. Conversely, optimal parameters induced Substrate failure (e.g., C1, H3), yielding high peak strengths (up to 22.45 MPa). This proves that the welded interface successfully surpassed the inherently lower interlaminar strength of the recycled composite.
- **As-received groups (J to M):** The untextured as-received plates demonstrated distinct behaviour. Despite many specimens being visually classified as Adhesive or Mixed-mode failures, these groups consistently achieved exceptionally high **LSS** values (e.g., L1 = 22.57 MPa). This reinforces the difficulty in macroscopic classification: because the polymer matrix and the **ED** are identical, a failure that visually appears interfacial has likely involved significant molecular diffusion. The high mechanical strength suggests that micro-tearing of the polymer matrix occurred, even if massive fiber pull-out was not macroscopically evident.

5.4.2 Statistical Analysis of the Failure Modes

To quantify the relationship between the macroscopic failure mechanism and the joint's mechanical performance, a statistical analysis was performed by grouping the specimens exclusively by their observed failure mode. The metrics are detailed in Table 5.9 and Figure 5.9.

Table 5.9: Statistical overview of the Lap Shear Strength (**LSS**) in MPa categorised by macroscopic failure mode.

Failure Mode	Min.	Max.	Average	Std. Dev.	CV (%)
Adhesive	3.07	22.57	11.62	5.68	49
Mixed / Adhesive	5.96	22.08	13.34	5.33	40
Mixed	8.36	19.47	13.43	4.23	31
Substrate	10.32	22.45	14.96	3.89	26
<i>Global</i>	-	-	13.29	-	37

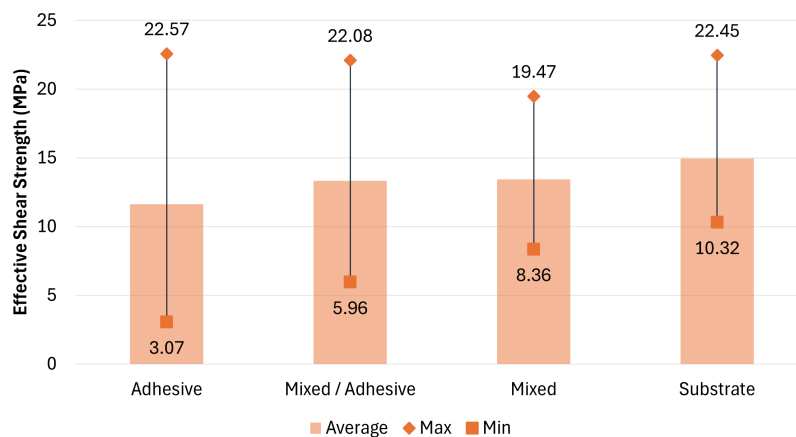


Figure 5.9: Dispersion of the apparent Lap Shear Strength (**LSS**) according to the observed macroscopic failure mode. The chart highlights the progressive reduction in mechanical scatter as the failure shifts towards the substrate.

Two critical trends regarding structural integrity emerge:

1. **Increase in Load-Bearing Capacity:** The average **LSS** progressively increases as the failure mode shifts from adhesive (interfacial) failure (≈ 11.62 MPa) to substrate failure (≈ 14.96 MPa), confirming that the latter represents the optimal consolidation state.
2. **Increase in Process Reliability:** The most significant finding is the drastic reduction in data spread. Adhesive (interfacial) failures exhibit a highly scattered response (**CV** = 49%), primarily driven by the mix of poorly consolidated recycled specimens and highly wetted as-received specimens. In contrast, substrate failures demonstrate the highest predictability, yielding the lowest standard deviation (3.89 MPa) and a **CV** of only 26%.

5.4.3 Limitations of Macroscopic Inspection in Polymer Welding

As highlighted throughout this section, macroscopic visual inspection presents inherent limitations in thermoplastic welding. Distinguishing between a true adhesive failure and a shallow substrate failure is highly complex because the matrix and the **ED** fuse into a single monolithic polymer phase.

Furthermore, pure cohesive failure within the weld line is essentially unobservable without a significantly larger initial volume of **ED** material. The crack propagation path naturally seeks the path of least resistance, which often weaves dynamically between the highly crystallized interface and the immediate sub-surface composite layers, creating what is broadly classified as a "mixed" mode. For a definitive characterisation of these fracture micromechanisms, future investigations must rely on advanced techniques, such as Scanning Electron Microscopy (**SEM**), to observe localised matrix yielding, micro-cracking, and the exact degree of polymer inter-diffusion.

5.5 Process Optimisation

To identify the ideal processing window, a multi-response optimisation was conducted targeting the maximisation of Lap Shear Strength (**LSS**) and welded area while minimizing material squeezing. The complete definition of the optimisation goals, individual desirability functions, and the constraint settings used in Minitab® are detailed in Appendix J. The resulting optimisation plots (Figure 5.10) confirm that distinct strategies are required for each material condition.

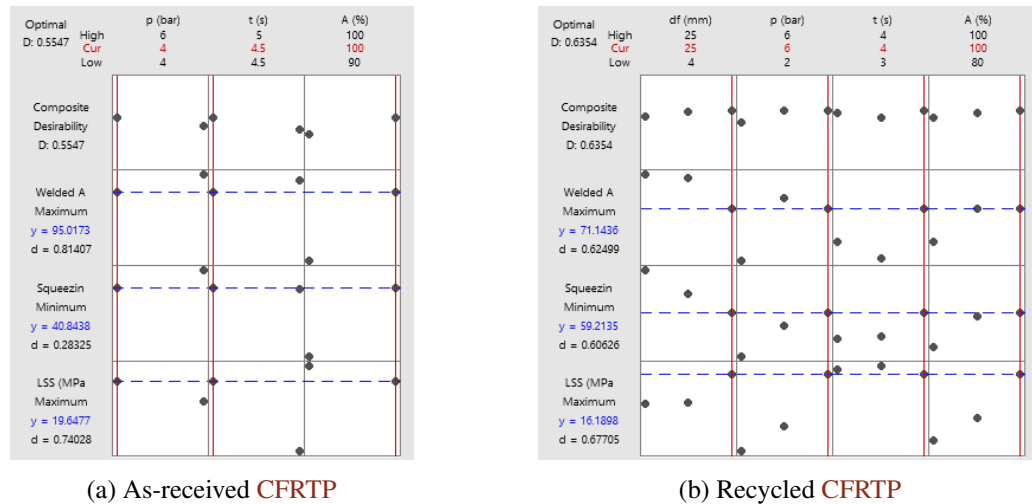


Figure 5.10: Multi-response optimisation plots comparison. (a) As-received material optimum found at 4.5 s (avoiding degradation); (b) Recycled material suggests a boundary solution, requiring maximised energy inputs.

For the as-received CF RTP (Predicted Peak: 19.6 MPa), the statistical model identifies the optimum at Pressure = 4 bar, Time = 4.5 s, and Amplitude = 100% (Figure 5.10a). Crucially, the desirability curve drops beyond 4.5 s, indicating that the material is susceptible to thermal degradation if over-processed.

Conversely, the recycled CF RTP (Predicted Peak: ≈ 16.2 MPa) presents a "boundary solution" (Figure 5.10b). The model suggests maximising all available inputs: Pressure = 6 bar, Time = 4.0 s, Amplitude = 100%, and the largest fibre size (d_f). The absence of a degradation peak within the tested range suggests that the recycled joint strength is currently limited by the machine's maximum capacity and feedstock heterogeneity rather than polymer overheating.

5.6 Displacement Verification and Failure Analysis using DIC

The implementation of Digital Image Correlation (**DIC**) in this study was explored not merely as an alternative measurement tool, but as an advanced non-contact optical technique to accurately capture the true mechanics of the welded joints. Traditional machine data often includes system compliance and micro-slippage at the grips, which can distort the actual mechanical response of the weld. By isolating the relative motion of the substrates, **DIC** provides a high-fidelity evaluation of joint integrity.

5.6.1 Rigid Body Behavior and Strain Distribution

Full-field strain analysis was conducted to observe load distribution across the welded area. As depicted in the longitudinal strain maps (ϵ_{xx}) in Figure 5.11, the composite substrates exhibited no significant localized yielding or heterogeneity prior to failure. Instead, the material behaved predominantly as a rigid body. The uniform coloration across the tracking area indicates that the deformation is concentrated entirely at the microscopic polymer interface rather than within the bulk composite substrates.

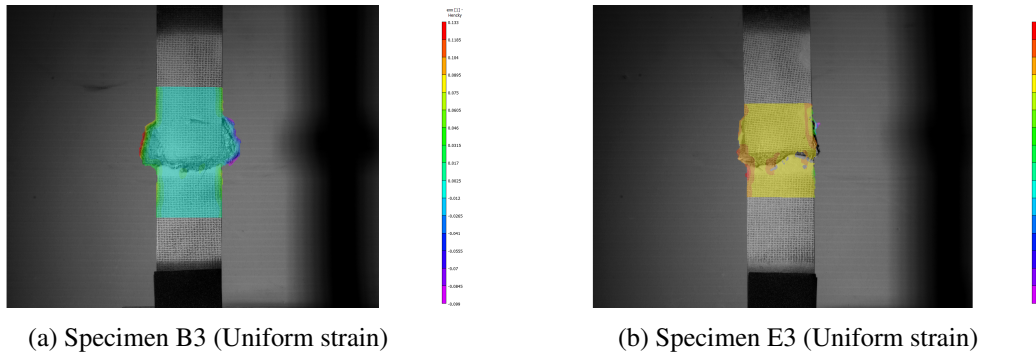


Figure 5.11: Longitudinal strain (ϵ_{xx}) maps. Both well-bonded (B3) and poorly-bonded (E3) specimens lack significant local plasticity, behaving globally as rigid bodies under tension.

5.6.2 Displacement Asymmetry and Weld Uniformity

Although the strain fields were uniform, the full-field vertical displacement maps (V) revealed crucial differences in how individual specimens responded to the load. Figure 5.12 compares a well-bonded sample (B3) with an underperforming sample (E3). While specimen B3 displays a highly symmetrical horizontal displacement gradient, specimen E3 exhibits heavily skewed and angled contour lines. This asymmetry in the vertical displacement indicates torsion or bending during the tensile test, a direct consequence of a non-uniform welded area causing eccentric load transmission.

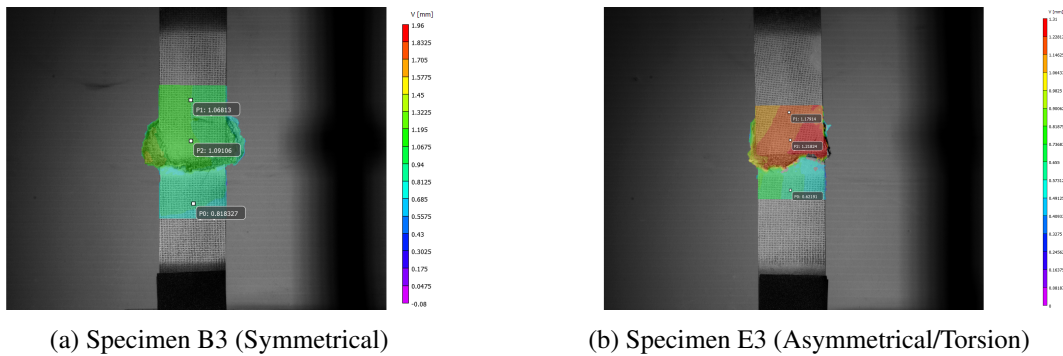


Figure 5.12: Full-field vertical displacement (V) maps. The skewed contours in E3 highlight uneven load distribution and structural torsion due to defective weld geometries.

5.6.3 True Elongation and Local Brittle Fracture

To quantify this behavior and exclude machine compliance, a virtual extensometer was set up using two tracking points: P0 on the bottom (fixed) laminate and P1 on the top (moving) laminate. The true joint elongation is calculated as $\delta_{\text{true}} = V_{P1} - V_{P0}$.

The evolution of these displacements (Figure 5.13) highlights two critical phenomena. Firstly, the gradual increase in P0 confirms compliance and slight slippage in the testing fixtures, proving that the raw machine data overestimates the joint's ductility. Secondly, the true elongation curve remains remarkably stiff and linear until a sharp, instantaneous vertical jump occurs. This abrupt discontinuity confirms the occurrence of a local, highly brittle fracture at the welded interface, further validating that the non-linearities seen in standard force-displacement curves are artifacts of grip settling, not true interfacial plasticity.

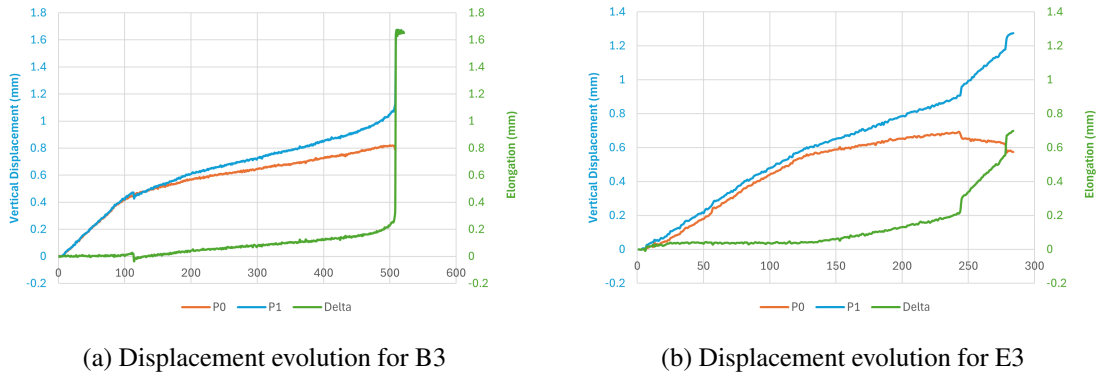


Figure 5.13: Vertical displacement vs. Time/Frames. The divergence between P0 and P1 represents the actual joint deformation, culminating in a sharp, brittle failure.

5.7 Discussion and Chapter Conclusions

The results of this study are herein discussed in light of the three fundamental research questions and the established literature on the ultrasonic welding of high-performance composites.

5.7.1 Process Feasibility and Energy Window (RQ1)

Joint formation in ultrasonic welding is primarily driven by the mechanical energy dissipated through frictional heating and viscoelastic losses. However, this study demonstrates that relying on a global "Welding Energy" descriptor is fundamentally insufficient for heterogeneous recycled composites ($R^2 < 20\%$).

As observed, as-received **CFRTP** operates within a highly stable processing window. Its continuous fibre architecture accommodates longer welding times (optimum at $\approx 4.5\text{--}5.0$ s) before the onset of thermal degradation, a stability similarly noted by Bonmatin et al. [58].

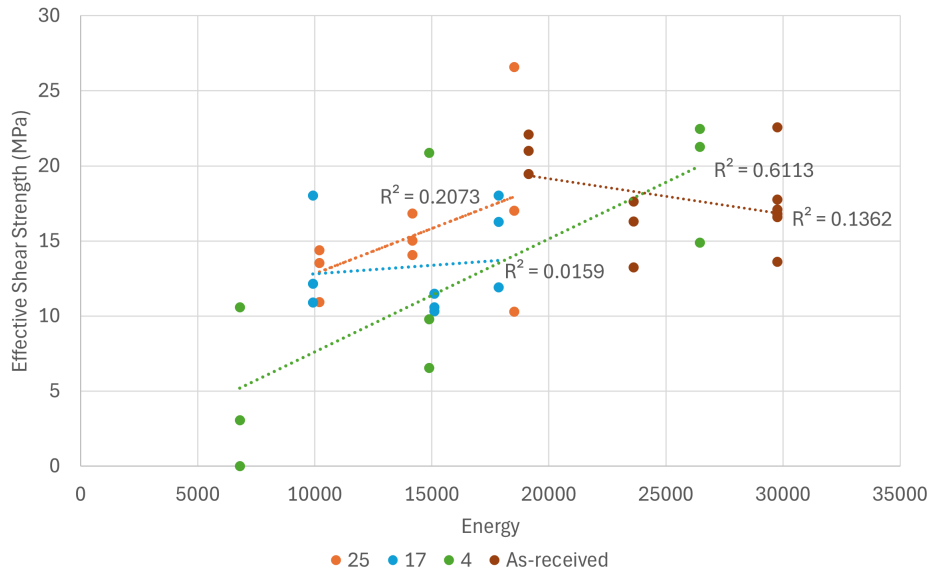


Figure 5.14: Correlation between nominal welding energy and effective **LSS**. The scatter highlights that while as-received joints plateau, the recycled joints exhibit high variance for similar energy inputs, proving that energy alone is an inadequate control metric.

Conversely, the recycled **CFRTP** exhibits severe thermal sensitivity. To overcome surface irregularities and internal porosity without triggering uncontrolled melt-collapse, the process requires a "boundary" parametric approach: maximizing clamping pressure (e.g., 6 bar) and amplitude to enforce rapid intermolecular diffusion, but strictly limiting the welding time (to ≈ 3.5 – 4.0 s). This contrasts with traditional assumptions that highly porous interfaces simply require more overall energy, aligning instead with Yang et al. [59], who suggest that the dynamic rate of heat generation is more critical than the total energy in discontinuous architectures.

This thermal and structural sensitivity is further evidenced by evaluating the optimal energy boundaries of the joints. Because recycled composites require strictly limited welding times to prevent uncontrolled material expulsion, their optimal consolidation is achieved at a significantly lower energy input. On average, the welding energy applied to the optimal recycled specimens was 14 882 J, representing a 42% reduction compared to the 25 571 J average of the as-received **CFRTP**. Exceeding this lower energy threshold in recycled joints does not improve interfacial bonding; rather, the excess energy is rapidly diverted into adverse lateral material expulsion (squeezing) due to the premature melt-collapse of the chopped-fibre internal structure. This proves that energy alone is an inadequate control metric, as the two materials possess fundamentally different energy tolerance limits.

5.7.2 Morphological Influence on Consolidation (RQ2)

The morphology of the chopped feedstock intrinsically alters the consolidation kinematics. Instead of the molten polymer spreading laterally to increase the bonded interface, the ultrasonic energy in recycled joints is heavily consumed in the vertical axis (compressing voids and internal gaps).

This physical constraint explains the observed 37% reduction in effective welded area and the corresponding 17% increase in lateral material squeezing when compared to the continuous-fibre baseline.

Within this chaotic flow, the initial fibre size (d_f) acts as a critical structural variable. As validated by the ANOVA (Section 5.3), larger discontinuous fibres (e.g., 25 mm) resist the squeeze flow more effectively, "bridging" the weld line and maintaining load-bearing capacity. Shorter fibres are easily displaced by the matrix flush, leading to severe flash formation and interfacial failures, corroborating the mechanics described in the literature for random-fibre orientations [59].

5.7.3 Performance, Robustness, and Repeatability (RQ3)

While the absolute average mechanical performance of recycled joints (11.44 – 12.49 MPa) is approximately 30% lower than the as-received baseline (16.78 MPa), their peak structural potential is remarkable. Under optimal processing conditions, recycled joints reached peak strengths up to 22.45 MPa, successfully shifting the failure mechanism from adhesive (interfacial) failure to substrate failure. This proves that the strength of the welded interface can surpass the inherent local strength of the recycled base material itself.

However, industrial robustness remains significantly compromised. For the as-received material, machine parameters strictly dictate joint strength. In contrast, the overwhelming error term in the recycled ANOVA confirms that response scatter is predominantly driven by material "noise", local fibre agglomerations, void clusters, and random orientations, rather than machine precision.

6. Conclusions and Future Works

The present dissertation investigated the feasibility of joining recycled Carbon Fibre Reinforced Thermoplastic (**CFRTP**) composites using ultrasonic welding, comparing their processability and mechanical performance against as-received materials. Through a combination of rigorous statistical parametric analysis, multi-response optimisation, and advanced optical monitoring (**DIC**), the study successfully addressed the primary research questions posed in the introduction and validated the structural potential of recycled composites.

6.1 Summary of the main findings

Based on the experimental characterisation and statistical analysis, the main findings of this research can be summarised as follows:

- Energy Thresholds and Process Control (RQ1):** Energy-based control is insufficient for heterogeneous recycled composites. Due to their porous and discontinuous internal architecture, recycled **CFRTPs** reach their optimal melt and consolidation state at a much lower energy threshold than continuous-fibre baselines. On average, optimal recycled joints required 42% less energy (14 882 J) compared to the as-received material (25 571 J). Exceeding this limit in recycled composites triggers premature melt-collapse and adverse lateral squeezing, proving that time, pressure, and amplitude must be strictly decoupled rather than grouped into a single energy parameter.
- **Consolidation Kinematics (RQ2):** This constraint resulted in a 37% reduction in effective bonded area and an average 17% increase in material squeezing, highlighting the absolute necessity for active vertical displacement (melt-collapse) control in future industrial applications.
- **Impact of Fibre Length (d_f):** Larger discontinuous fibres (e.g., 25 mm) proved crucial for melt-flow stability, yielding higher mechanical resistance and mitigating excessive lateral flash. Conversely, smaller fibres offered negligible structural resistance to the sonotrode, exacerbating the squeezing phenomenon. This dynamic directly replicates the strength loss observed in the base material after the shredding process.
- **Distinct Processing Windows:** To mitigate morphological sensitivity, recycled **CFRTP** requires a distinct parametric approach: higher clamping pressures (6 bar) to ensure intimate contact, combined with strictly limited welding times (3.5–4.0 s) to prevent uncontrolled material expulsion.
- **Comparative Mechanical Performance (RQ3):** While the average effective **LSS** of recycled joints was approximately 30% lower than the as-received baseline, their peak structural potential is highly competitive. Optimal recycled joints reached peak strengths up

to 22.45 MPa (rivaling the 22.57 MPa of virgin joints), successfully shifting the dominant failure mode from **adhesive (interfacial) failure** to **substrate failure**.

- **True Joint Kinematics:** **DIC** analysis successfully isolated the true joint elongation from machine compliance, proving that the structural failure of the weld is highly localised and brittle, and establishing a rigorous protocol for testing stiff composite lap joints.

6.2 Contributions of the study

This research provides significant contributions to the field of composite manufacturing and sustainability:

- **Validation of Circular Economy in Composites:** The study provides empirical evidence that recycled **CFRTP** can be ultrasonically welded with peak mechanical performances comparable to as-received materials. This supports the reintroduction of high-value waste into the industrial value chain, promoting sustainability in the automotive and aerospace sectors.
- **Methodological Framework for Optimisation:** It established that multi-response optimisation (considering Strength, Area, and Squeezing) is superior to simple energy-based control. This framework is essential for industrial implementation, where maximising strength while maintaining geometric tolerances (minimising squeezing) is a conflicting but necessary requirement.
- **Enhanced Characterisation Techniques:** By integrating **DIC** for true displacement verification, this work highlights the importance of eliminating machine compliance errors when characterising stiff composite joints, offering a more rigorous protocol for future lap shear testing.

6.3 Perspectives for future research

To further validate the implementation of recycled **CFRTPs** in structural applications, the following research lines are suggested:

- **Microstructural Characterisation:** Conducting cross-sectional microscopy (e.g., optical microscopy or Scanning Electron Microscopy) to definitively validate the hypotheses regarding internal void collapse, polymer squeeze flow, and discontinuous fibre reorientation at the weld interface. This would provide micro-scale proof of the macroscopic behaviours observed in this study.
- **Lifecycle and Reprocessability Analysis:** Investigating the maximum number of recycling cycles the **CFRTP** can undergo before critical structural degradation occurs. This involves evaluating the thermo-mechanical aging of the polymer matrix and the progressive reduction in fibre length across multiple shredding and consolidation cycles.

- **Displacement-Controlled Welding:** To overcome the material sensitivity and excessive squeezing identified in this work, future studies should employ servo-driven ultrasonic welders or setups with active "Melt-Collapse" modes. Controlling the weld by a specific vertical distance (e.g., stopping after 0.1 mm of collapse) rather than time would ensure a consistent bond line thickness.
- **Fatigue Performance:** Evaluating the mechanical fatigue life (S-N curves) of the welded recycled joints is crucial, as void content or inhomogeneities in the chopped fibre matrix may act as crack initiation sites under continuous cyclic loading.
- **Hygrothermal Aging:** Investigating the degradation of the welded interface under varying temperature and humidity conditions is essential to assess the long-term environmental durability of the recycled joints.
- **Flash Control Tooling:** Developing joint designs with "flash traps" or constrained welding fixtures that physically contain the polymer flow could prevent lateral material expulsion, allowing for higher energy inputs without compromising geometric tolerances.

References

- [1] United Nations. *The 17 sustainable development goals*. United Nations, 2015. URL: <https://sdgs.un.org/goals>.
- [2] J.P. Carey. “1 - Introduction to braided composites”. In: *Handbook of Advances in Braided Composite Materials*. Ed. by Jason P. Carey. Woodhead Publishing, 2017, pp. 1–21. ISBN: 978-0-08-100369-5. DOI: <https://doi.org/10.1016/B978-0-08-100369-5.00001-5>.
- [3] S. Sajan and D. Philip Selvaraj. “A review on polymer matrix composite materials and their applications”. In: *Materials Today: Proceedings* 47 (2021). International Conference on Sustainable materials, Manufacturing and Renewable Technologies 2021, pp. 5493–5498. ISSN: 2214-7853. DOI: <https://doi.org/10.1016/j.matpr.2021.08.034>.
- [4] Khubab Shaker and Abdelghani Saouab. “Composite Materials”. In: *Engineering Materials: Fundamentals, Processing and Properties*. Ed. by Khubab Shaker and Yasir Nawab. Cham: Springer Nature Switzerland, 2025, pp. 153–180. ISBN: 978-3-031-72263-9. DOI: [10.1007/978-3-031-72263-9_7](https://doi.org/10.1007/978-3-031-72263-9_7).
- [5] João Pedro Reis, Marcelo de Moura, and Sylwester Samborski. “Thermoplastic Composites and Their Promising Applications in Joining and Repair Composites Structures: A Review”. In: *Materials* 13.24 (2020). ISSN: 1996-1944. DOI: [10.3390/ma13245832](https://doi.org/10.3390/ma13245832).
- [6] Przemyslaw Daniel Pastuszak and Aleksander Muc. “Application of Composite Materials in Modern Constructions”. In: *Key Engineering Materials* 542 (Feb. 2013), pp. 119–129. DOI: [10.4028/www.scientific.net/KEM.542.119](https://doi.org/10.4028/www.scientific.net/KEM.542.119).
- [7] Raymond F. Wegman and James Van Twisk. “8 - Plastics”. In: *Surface Preparation Techniques for Adhesive Bonding (Second Edition)*. Ed. by Raymond F. Wegman and James Van Twisk. Second Edition. William Andrew Publishing, 2013, pp. 115–130. ISBN: 978-1-4557-3126-8. DOI: <https://doi.org/10.1016/B978-1-4557-3126-8.00008-7>. URL: <https://www.sciencedirect.com/science/article/pii/B9781455731268000087>.
- [8] Pollen AM | *Thermoplastic elastomers*. Pollen.am, 2025. URL: https://www.pollen.am/thermoplastic_elastomers_general_introduction/ (visited on 11/02/2025).
- [9] VICTREX LMPAEK™ UDT AS4-143-34. Victrex, 2025. URL: <https://www.victrex.com/en/downloads/datasheets/victrex-lmpaek-udt> (visited on 11/16/2025).
- [10] Granta Design Limited. *Ansys Granta EduPack 2025 2R*. Software. Ansys Granta Design, Cambridge, UK. Versão 2025 2R, consultado em março de 2025. 2025.
- [11] Grand View Research. *Carbon Fiber Market Size, Share & Trends Analysis Report*. 2024. URL: <https://www.grandviewresearch.com/industry-analysis/carbon-fiber-market-analysis> (visited on 01/29/2025).
- [12] Plastics Europe. *Plastics - the fast Facts 2024*. Report. Plastics Europe, 2024. URL: <https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2024/>.
- [13] Plastics Europe. *The Circular Economy for Plastics: A European Analysis*. Report. Plastics Europe, Mar. 2024. URL: <https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-analysis-2024/>.

- [14] Jin Zhang et al. “Current status of carbon fibre and carbon fibre composites recycling”. In: *Composites Part B: Engineering* 193 (2020), p. 108053. ISSN: 1359-8368. DOI: <https://doi.org/10.1016/j.compositesb.2020.108053>. URL: <https://www.sciencedirect.com/science/article/pii/S135983681936946X>.
- [15] Arnt R. Offringa. “Thermoplastic composites—rapid processing applications”. In: *Composites Part A: Applied Science and Manufacturing* 27.4 (1996). 4th International Conference on Automated Composites, pp. 329–336. ISSN: 1359-835X. DOI: [https://doi.org/10.1016/1359-835X\(95\)00048-7](https://doi.org/10.1016/1359-835X(95)00048-7). URL: <https://www.sciencedirect.com/science/article/pii/1359835X95000487>.
- [16] Wang, Yue et al. “Temperature Effects on Mechanical Properties of Woven Thermoplastic Composites for Secondary Aircraft Structure Applications”. In: *MATEC Web Conf.* 108 (2017), p. 01009. DOI: [10.1051/mateconf/201710801009](https://doi.org/10.1051/mateconf/201710801009). URL: <https://doi.org/10.1051/mateconf/201710801009>.
- [17] Rokas Garmasukis et al. “Rapid prototyping of microfluidic chips enabling controlled biotechnology applications in microspace”. In: *Current Opinion in Biotechnology* 81 (2023), p. 102948. ISSN: 0958-1669. DOI: <https://doi.org/10.1016/j.copbio.2023.102948>. URL: <https://www.sciencedirect.com/science/article/pii/S0958166923000587>.
- [18] Yongxiang Yang et al. “Recycling of composite materials”. In: *Chemical Engineering and Processing: Process Intensification* 51 (2012). Delft Skyline Debate, pp. 53–68. ISSN: 0255-2701. DOI: <https://doi.org/10.1016/j.cep.2011.09.007>. URL: <https://www.sciencedirect.com/science/article/pii/S0255270111002029>.
- [19] Géraldine Oliveux, Luke O. Dandy, and Gary A. Leeke. “Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties”. In: *Progress in Materials Science* 72 (2015), pp. 61–99. ISSN: 0079-6425. DOI: <https://doi.org/10.1016/j.pmatsci.2015.01.004>. URL: <https://www.sciencedirect.com/science/article/pii/S0079642515000316>.
- [20] T. Niemelä and M. Kellomäki. “11 - Bioactive glass and biodegradable polymer composites”. In: *Bioactive Glasses*. Ed. by Heimo O. Ylänen. Woodhead Publishing Series in Biomaterials. Woodhead Publishing, 2011, pp. 227–245. ISBN: 978-1-84569-768-6. DOI: <https://doi.org/10.1533/9780857093318.2.227>. URL: <https://www.sciencedirect.com/science/article/pii/B9781845697686500119>.
- [21] Anahi Costa et al. “A Review of Welding Technologies for Thermoplastic Composites in Aerospace Applications”. In: *Journal of Aerospace Technology and Management* 4 (Sept. 2012), pp. 255–265. DOI: [10.5028/jatm.2012.04033912](https://doi.org/10.5028/jatm.2012.04033912).
- [22] Romain G. Martin et al. “CF/PEEK skins assembly by induction welding for thermoplastic composite sandwich panels”. In: *Composites Part B: Engineering* 284 (2024), p. 111676. ISSN: 1359-8368. DOI: <https://doi.org/10.1016/j.compositesb.2024.111676>. URL: <https://www.sciencedirect.com/science/article/pii/S1359836824004888>.
- [23] Sandi G Miller et al. *Assessment of Thermoplastic Composite Joining by Resistance, Induction, and Ultrasonic Welding*. Nasa.gov, July 2025. URL: <https://ntrs.nasa.gov/citations/20250006527> (visited on 10/08/2025).
- [24] Romain Martin et al. “Material Selection Methodology for an Induction Welding Magnetic Susceptor Based on Hysteresis Losses”. In: *Advanced Engineering Materials* 24 (Oct. 2021). DOI: [10.1002/adem.202100877](https://doi.org/10.1002/adem.202100877).

- [25] “Chapter 11 - Induction Welding”. In: *Handbook of Plastics Joining (Second Edition)*. Ed. by Michael J. Troughton. Second Edition. Boston: William Andrew Publishing, 2009, pp. 113–120. ISBN: 978-0-8155-1581-4. DOI: <https://doi.org/10.1016/B978-0-8155-1581-4.50013-5>. URL: <https://www.sciencedirect.com/science/article/pii/B9780815515814500135>.
- [26] S. Becker and P. Mitschang. “Process Improvement of Continuous Induction Welding of Carbon Fiber-Reinforced Polymer Composites”. In: *Journal of Materials Engineering and Performance* 31.9 (Sept. 2022), pp. 7049–7060. ISSN: 1544-1024. DOI: [10.1007/s11665-022-06842-0](https://doi.org/10.1007/s11665-022-06842-0). URL: <https://doi.org/10.1007/s11665-022-06842-0>.
- [27] Irene Fernandez Villegas et al. “Process and performance evaluation of ultrasonic, induction and resistance welding of advanced thermoplastic composites”. In: *Journal of Thermoplastic Composite Materials* 26.8 (2013), pp. 1007–1024. DOI: [10.1177/0892705712456031](https://doi.org/10.1177/0892705712456031). URL: <https://doi.org/10.1177/0892705712456031>.
- [28] T.J. Ahmed et al. “Induction welding of thermoplastic composites—an overview”. In: *Composites Part A: Applied Science and Manufacturing* 37.10 (2006), pp. 1638–1651. ISSN: 1359-835X. DOI: <https://doi.org/10.1016/j.compositesa.2005.10.009>. URL: <https://www.sciencedirect.com/science/article/pii/S1359835X05003957>.
- [29] Bo-Kyung Choi et al. “Effect of Processing Parameters on Bonding Performance of a Carbon Fiber/Polyetheretherketone Thermoplastic Composite Prepared by Induction Welding”. In: *Materials* 16.11 (2023). ISSN: 1996-1944. DOI: [10.3390/ma16113954](https://doi.org/10.3390/ma16113954). URL: <https://www.mdpi.com/1996-1944/16/11/3954>.
- [30] “Chapter 10 - Resistive Implant Welding”. In: *Handbook of Plastics Joining (Second Edition)*. Ed. by Michael J. Troughton. Second Edition. Boston: William Andrew Publishing, 2009, pp. 105–111. ISBN: 978-0-8155-1581-4. DOI: <https://doi.org/10.1016/B978-0-8155-1581-4.50012-3>. URL: <https://www.sciencedirect.com/science/article/pii/B9780815515814500123>.
- [31] “Chapter 2 - Ultrasonic Welding”. In: *Handbook of Plastics Joining (Second Edition)*. Ed. by Michael J. Troughton. Second Edition. Boston: William Andrew Publishing, 2009, pp. 15–35. ISBN: 978-0-8155-1581-4. DOI: <https://doi.org/10.1016/B978-0-8155-1581-4.50004-4>. URL: <https://www.sciencedirect.com/science/article/pii/B9780815515814500044>.
- [32] Adrian Korycki et al. “Assembling of Carbon Fibre/PEEK Composites: Comparison of Ultrasonic, Induction, and Transmission Laser Welding”. In: *Materials* 15.18 (2022). Cited by: 20; All Open Access, Gold Open Access, Green Open Access. DOI: [10.3390/ma15186365](https://doi.org/10.3390/ma15186365). URL: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85138823825&doi=10.3390%2fma15186365&partnerID=40&md5=b7a84d0df9240d59244eb6c1670406b7>.
- [33] Dong Quan et al. “Significantly enhanced structural integrity of adhesively bonded PPS and PEEK composite joints by rapidly UV-irradiating the substrates”. In: *Composites Science and Technology* 199 (2020). Cited by: 36; All Open Access, Hybrid Gold Open Access. DOI: [10.1016/j.compscitech.2020.108358](https://doi.org/10.1016/j.compscitech.2020.108358). URL: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85088090749&doi=10.1016%2fj.compscitech.2020.108358&partnerID=40&md5=a615566351c672a0da4822510bd7a99f>.

- [34] Yongsoon Shin et al. “Enhanced adhesive bonding at the adhesive-CFRTP interface via plasma and silane coupling agents in adhesively-bonded metal-CFRTP joints”. In: *Composites Part B: Engineering* 308 (2026). Cited by: 3. DOI: [10.1016/j.compositesb.2025.113009](https://doi.org/10.1016/j.compositesb.2025.113009). URL: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-105015541254&doi=10.1016%2fj.compositesb.2025.113009&partnerID=40&md5=b9ffa3aeefae241007d6279028bba921>.
- [35] Yujie Xie et al. “Synergistic enhancement of PEEK bonding performance and thermal shock resistance through combined surface treatment”. In: *Chemical Engineering Science* 325 (2026). Cited by: 0. DOI: [10.1016/j.ces.2026.123397](https://doi.org/10.1016/j.ces.2026.123397). URL: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-105027989455&doi=10.1016%2fj.ces.2026.123397&partnerID=40&md5=72517346222adb314c7e3b890aa4e3aa>.
- [36] Murtaza Hussain et al. “Evaluation of adhesion strength of pure PEEK and glass reinforced PEEK with titanium using different bonding methods- a systematic review”. In: *BMC Oral Health* 26.1 (2026). Cited by: 0; All Open Access, Gold Open Access, Green Open Access. DOI: [10.1186/s12903-025-07323-1](https://doi.org/10.1186/s12903-025-07323-1). URL: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-105028508900&doi=10.1186%2fs12903-025-07323-1&partnerID=40&md5=ede8cb4ff8e92751dab395d55ffae9ff>.
- [37] John M. Cimbala. *Experimental Design*. Learning Module, Penn State University. Latest revision: 17 September 2014. 2014.
- [38] Raghu N. Kacker, Eric S. Lagergren, and James J. Filliben. “Taguchi’s Orthogonal Arrays Are Classical Designs of Experiments”. In: *Journal of Research of the National Institute of Standards and Technology* 96.5 (1991), pp. 577–591.
- [39] Genichi Taguchi. *System of Experimental Design: Engineering Methods to Optimize Quality and Minimize Costs*. Unipub/Kraus International Publications, 1987.
- [40] O. Mohammadbeigi, Seyedmasoud Hassani, and S.H. Mazloumi. “Numerical investigation and hybrid optimization of pin-fin microchannel heat sinks using Taguchi-ANOVA and AHP-TOPSIS methods”. In: *International Communications in Heat and Mass Transfer* 172 (2026), p. 110284. ISSN: 0735-1933. DOI: <https://doi.org/10.1016/j.icheatmasstransfer.2025.110284>. URL: <https://www.sciencedirect.com/science/article/pii/S0735193325017105>.
- [41] I. Swentek and J. T. Wood. “Using the lap-shear test to measure polymer composite interfacial strength”. In: *Proceedings of the 19th International Conference on Composite Materials (ICCM19)*. Montreal, Canada, 2013.
- [42] Muhammad Aamir et al. “Recent advances in drilling of carbon fiber reinforced polymers for aerospace applications: A review”. In: *International Journal of Advanced Manufacturing Technology* (Dec. 2019). DOI: [10.1007/s00170-019-04348-z](https://doi.org/10.1007/s00170-019-04348-z).
- [43] R Travieso-Puente et al. “ECO-CLIP: circular economy from factory waste material towards aircraft structural components”. In: *IOP Conference Series: Materials Science and Engineering* 1226 (Feb. 2022), p. 012104. DOI: [10.1088/1757-899X/1226/1/012104](https://doi.org/10.1088/1757-899X/1226/1/012104).
- [44] Wendy Duivestijn. *R&D case: STUNNING: the world’s largest known thermoplastic aircraft structures - Nederlands Lucht- en Ruimtevaartcentrum*. Nederlands Lucht- en Ruimtevaartcentrum, Feb. 2023. URL: <https://www.nlr.org/newsroom/case/stunning-the-worlds-largest-known-thermoplastic-aircraft-structures/> (visited on 02/25/2026).

- [45] Grace Stubbins. *STUNNING project successfully develops 8.5-meter thermoplastic fuselage skin*. Compositesworld.com. Feb. 2026. URL: <https://www.compositesworld.com/news/stunning-project-successfully-develops-85-meter-thermoplastic-fuselage-skin-> (visited on 02/25/2026).
- [46] Grace Stubbins. *STUNNING project completes lower half of MFFD*. Compositesworld.com. July 2026. URL: <https://www.compositesworld.com/news/stunning-project-completes-lower-half-of-mffd> (visited on 02/25/2026).
- [47] Howard Wang et al. “Carbon Fiber Reinforced Thermoplastics: From Materials to Manufacturing and Applications”. In: *Advanced Materials* 37.27 (2025). Cited by: 57; All Open Access, Green Open Access, Hybrid Gold Open Access. DOI: 10.1002/adma.202418709. URL: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-105003206691&doi=10.1002%2fadma.202418709&partnerID=40&md5=b3876e90e5e41904a6375710a84a7ff9>.
- [48] CompositesWorld. *Partners recycle A350 composite production waste into adjustable-length rods for MFFD*. 2021. URL: <https://www.compositesworld.com/news/partners-recycle-a350-composite-production-waste-into-adjustable-length-rods-for-mffd> (visited on 01/08/2026).
- [49] Yanrui Li et al. “High-Quality Spot and Continuous Ultrasonic Welding of Carbon Fiber Reinforced Polyetheretherketone (CF/PEEK) Composites Using PEEK Mesh Energy Directors”. In: *Applied Composite Materials* 33.1 (Jan. 2026), p. 46. ISSN: 1573-4897. DOI: 10.1007/s10443-025-10419-0. URL: <https://doi.org/10.1007/s10443-025-10419-0>.
- [50] Junxian Xiang et al. “Enhancement of ultrasonically welded CF/PEEK joints via zone-designed and post-inserted energy directors”. In: *Journal of Manufacturing Processes* 158 (2026), pp. 329–343. ISSN: 1526-6125. DOI: <https://doi.org/10.1016/j.jmapro.2025.12.055>. URL: <https://www.sciencedirect.com/science/article/pii/S1526612525013751>.
- [51] Portugal 2020. *ReCAP – Recycled Composites for High Performance Applications: Aircraft Components and Support Structures*. Operation code: POCI-01-0247-FEDER-046966. 2023. URL: <https://transparencia.gov.pt/...>
- [52] Pablo Resende Oliveira et al. “Ultrasonically welded eco-friendly sandwich panels based on upcycled thermoplastic core: An eco-mechanical characterisation”. In: *Resources, Conservation & Recycling Advances* 20 (2023), p. 200187. ISSN: 2667-3789. DOI: <https://doi.org/10.1016/j.rcradv.2023.200187>. URL: <https://www.sciencedirect.com/science/article/pii/S2667378923000597>.
- [53] Harry Frederick, Wencai Li, and Genevieve Palardy. “Disassembly Study of Ultrasonically Welded Thermoplastic Composite Joints via Resistance Heating”. In: *Materials* 14.10 (2021). ISSN: 1996-1944. DOI: 10.3390/ma14102521. URL: <https://www.mdpi.com/1996-1944/14/10/2521>.
- [54] Timothy Yap et al. “In-plane properties of an in-situ consolidated automated fiber placement thermoplastic composite”. In: *Composites Part A: Applied Science and Manufacturing* 188 (2025), p. 108525. ISSN: 1359-835X. DOI: <https://doi.org/10.1016/j.compositesa.2024.108525>. URL: <https://www.sciencedirect.com/science/article/pii/S1359835X24005232>.

- [55] Alex Brasington et al. “Automated fiber placement: A review of history, current technologies, and future paths forward”. In: *Composites Part C: Open Access* 6 (2021), p. 100182. ISSN: 2666-6820. DOI: <https://doi.org/10.1016/j.jcomc.2021.100182>. URL: <https://www.sciencedirect.com/science/article/pii/S2666682021000773>.
- [56] Irene Fernandez Villegas. “Strength development versus process data in ultrasonic welding of thermoplastic composites with flat energy directors and its application to the definition of optimum processing parameters”. In: *Composites Part A: Applied Science and Manufacturing* 65 (2014), pp. 27–37. ISSN: 1359-835X. DOI: <https://doi.org/10.1016/j.compositesa.2014.05.019>. URL: <https://www.sciencedirect.com/science/article/pii/S1359835X14001614>.
- [57] C.B.G. Brito et al. “Ultrasonic welding of thermoplastic composites: A comparison between polyetheretherketone and low-melt polyaryletherketone as resin in the adherends and energy directors”. In: *Composites Part B: Engineering* 296 (2025), p. 112264. ISSN: 1359-8368. DOI: <https://doi.org/10.1016/j.compositesb.2025.112264>. URL: <https://www.sciencedirect.com/science/article/pii/S1359836825001544>.
- [58] Margot Bonmatin et al. “Ultrasonic welding of CF/PEEK composites: Influence of welding parameters on interfacial temperature profiles and mechanical properties”. In: *Composites Part A: Applied Science and Manufacturing* 162 (July 2022), p. 107074. DOI: [10.1016/j.compositesa.2022.107074](https://doi.org/10.1016/j.compositesa.2022.107074).
- [59] Yuanduo Yang et al. “Ultrasonic welding of short carbon fiber reinforced PEEK with spherical surface anvils”. In: *Composites Part B: Engineering* 231 (2022), p. 109599. ISSN: 1359-8368. DOI: <https://doi.org/10.1016/j.compositesb.2021.109599>. URL: <https://www.sciencedirect.com/science/article/pii/S1359836821009653>.

A. Queries Used in Scopus

A.1 Scope and general search strategy

This appendix presents the search queries used in the Scopus database to perform the bibliometric analysis discussed in Chapter 3. All searches were conducted using combinations of title, abstract, and keyword fields (TITLE-ABS-KEY) to capture both explicit and implicit references to CF RTP welding technologies.

No temporal, document type, language, or subject-area filters were applied. The queries were designed to progressively narrow the scope from a general overview of CF RTP welding research to process-specific studies and, finally, to publications explicitly addressing recycled materials or comparative analyses between primary and secondary CF RTPs.

A.2 General CF RTP welding queries

The following queries were used to identify publications addressing welding of CF RTPs, both in a broad sense and with a specific focus on induction welding (IW), resistance welding (RW), and ultrasonic welding (UW).

CF RTP welding – general overview

```
TITLE-ABS-KEY("CF RTP" OR "carbon fiber reinforced thermoplastic" OR  
"carbon fibre reinforced thermoplastic" OR "high-performance  
thermoplastic composite*" OR "thermoplastic composite*") AND  
TITLE-ABS-KEY(weld* OR "fusion bonding" OR "thermo-welding" OR  
"induction welding" OR "resistance welding" OR "resistive welding" OR  
"ultrasonic welding" OR "ultrasonic consolidation" OR "laser welding"  
OR "laser transmission welding" OR "hot plate welding" OR "hot-plate  
welding" OR "vibration welding" OR "infrared welding" OR "IR  
welding")
```

CF RTP welding – induction, resistance and ultrasonic welding

```
TITLE-ABS-KEY("CF RTP" OR "carbon fiber reinforced thermoplastic" OR  
"carbon fibre reinforced thermoplastic" OR "high-performance  
thermoplastic composite*" OR "thermoplastic composite*") AND  
TITLE-ABS-KEY("induction welding" OR "resistance welding" OR  
"resistive welding" OR "ultrasonic welding" OR "ultrasonic  
consolidation")
```

A.3 General recycling-focused queries

To investigate the role of recycled materials in **CFRTP** welding, keyword groups related to recycling, reuse, and end-of-life condition were incorporated into the general queries.

CFRTP welding involving recycled materials

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY(weld* OR "fusion bonding" OR "thermo-welding" OR
"induction welding" OR "resistive welding" OR "resistance welding" OR
"ultrasonic welding" OR "ultrasonic consolidation") AND
TITLE-ABS-KEY(recycl* OR recycled OR reused OR reclaimed OR
reprocessed OR secondary OR "end-of-life")
```

Induction, resistance and ultrasonic welding involving recycled materials

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY("induction welding" OR "resistance welding" OR
"resistive welding" OR "ultrasonic welding" OR "ultrasonic
consolidation") AND TITLE-ABS-KEY(recycl* OR recycled OR reused OR
reclaimed OR reprocessed OR secondary OR "end-of-life")
```

A.4 Process-specific queries for **CFRTP** welding

This section presents the Scopus queries used to analyse publication trends on **CFRTPs** associated with individual welding processes.

Induction welding (**IW**) applied to **CFRTPs**

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY("induction weld*" OR "induction joining")
```

Resistance welding (RW) applied to CFRTPs

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY("resistance welding" OR "resistive welding")
```

Ultrasonic welding (UW) applied to CFRTPs

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY("ultrasonic weld*" OR "ultrasonic consolidation")
```

A.5 Process-specific queries for recycled **CFRTP welding**

This section presents the Scopus queries used to analyse publication trends associated with individual welding processes (induction, resistance, and ultrasonic) applied specifically to recycled **CFRTPs**.

Induction welding (IW) applied to recycled CFRTPs

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY("induction weld*" OR "induction joining") AND
TITLE-ABS-KEY(recycl* OR recycled OR reused OR reclaimed OR
reprocessed OR secondary OR "end-of-life")
```

Resistance welding (RW) applied to recycled CFRTPs

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY("resistance welding" OR "resistive welding") AND
TITLE-ABS-KEY(recycl* OR recycled OR reused OR reclaimed OR
reprocessed OR secondary OR "end-of-life")
```

Ultrasonic welding (UW) applied to recycled CFRTPs

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY("ultrasonic weld*" OR "ultrasonic consolidation") AND
TITLE-ABS-KEY(recycl* OR recycled OR reused OR reclaimed OR
reprocessed OR secondary OR "end-of-life")
```

A.6 Comparative queries: Primary vs. secondary CFRTPs

This section presents the Scopus queries used to identify studies explicitly comparing primary (as-received, pristine) and secondary (recycled, reprocessed) CFRTPs in welding applications.

Primary vs. secondary CFRTP welding (all welding processes)

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY(weld* OR "fusion bonding" OR "thermo-welding" OR
"induction welding" OR "resistance welding" OR "resistive welding" OR
"ultrasonic welding" OR "ultrasonic consolidation" OR "laser welding"
OR "laser transmission welding" OR "hot plate welding" OR "hot-plate
welding" OR "vibration welding" OR "infrared welding" OR "IR
welding") AND TITLE-ABS-KEY("as-received" OR pristine OR neat OR
baseline OR primary OR "non-recycled") AND TITLE-ABS-KEY(recycl* OR
recycled OR reused OR reclaimed OR reprocessed OR secondary OR
recovered OR "post-consumer" OR "post-industrial" OR "second-life" OR
"end-of-life")
```

Primary vs. secondary CFRTP welding (induction, resistance and ultrasonic welding)

```
TITLE-ABS-KEY("CFRTP" OR "carbon fiber reinforced thermoplastic" OR
"carbon fibre reinforced thermoplastic" OR "high-performance
thermoplastic composite*" OR "thermoplastic composite*") AND
TITLE-ABS-KEY("induction welding" OR "resistance welding" OR
"resistive welding" OR "ultrasonic welding" OR "ultrasonic
consolidation") AND TITLE-ABS-KEY("as-received" OR pristine OR neat
OR baseline OR primary OR "non-recycled") AND TITLE-ABS-KEY(recycl*
OR recycled OR reused OR reclaimed OR reprocessed OR secondary OR
"end-of-life")
```

B. Statistical Analysis Procedure

This appendix describes the statistical analysis workflow adopted in this study. All analyses were performed using Minitab® Statistical Software. To ensure a comprehensive overview, results for both recycled and as-received materials are presented where relevant.

B.1 Data Organisation and Response Definition

The experimental results were organised in a structured dataset within Minitab®, where each row corresponds to a single welded specimen and each column represents either a process parameter or a measured response.

✱	C1-T	C2	C3	C4	C5	C6	C7	C8
	Design.	df (mm)	p (bar)	t (s)	A (%)	LSS (MPa)	Squeezing (%)	Welded Area (%)
1	A	4	2	3.0	80	3.07	16.76	28.79
2	A	4	2	3.0	80	12.84	9.68	34.88
3	B	4	4	3.5	90	6.54	38.82	46.56
4	B	4	4	3.5	90	11.92	52.10	57.33
5	B	4	4	3.5	90	12.90	85.55	100.00
6	C	4	6	4.0	100	22.45	101.94	100.00
7	C	4	6	4.0	100	8.91	26.79	59.43
8	C	4	6	4.0	100	12.90	142.03	100.00
9	D	17	2	3.5	100	18.01	30.16	46.87
10	D	17	2	3.5	100	5.96	5.99	23.05
11	D	17	2	3.5	100	10.26	31.80	44.19
12	E	17	4	4.0	80	10.32	41.20	87.86
13	E	17	4	4.0	80	8.40	35.94	64.58
14	E	17	4	4.0	80	8.36	34.86	69.59
15	F	17	6	3.0	90	11.92	35.06	69.65
16	F	17	6	3.0	90	9.19	18.24	39.32
17	F	17	6	3.0	90	17.41	97.34	100.00
18	G	25	2	4.0	90	14.39	32.43	61.80
19	G	25	2	4.0	90	4.20	7.73	23.73
20	G	25	2	4.0	90	12.12	30.11	55.32
21	H	25	4	3.0	100	14.07	31.96	63.35
22	H	25	4	3.0	100	8.05	10.72	33.92
23	H	25	4	3.0	100	19.45	46.27	83.81
24	I	25	6	3.5	80	10.29	29.02	42.01
25	I	25	6	3.5	80	10.92	5.43	26.93
26	I	25	6	3.5	80	18.90	13.87	29.94

Figure B.1: Experimental dataset organised in Minitab®, including Taguchi design identification, welding parameters, and response variables.

The analysed response variables were:

- **Lap Shear Strength (LSS)**, expressed in MPa;
- **Squeezing**, expressed as a percentage (%);
- **Welded Area**, expressed as a percentage (%).

B.2 Taguchi Main Effects Analysis

The influence of the welding parameters was first investigated using Taguchi Main Effects Analysis to identify dominant trends. Figure B.2 presents the main effects for Lap Shear Strength for both material types.

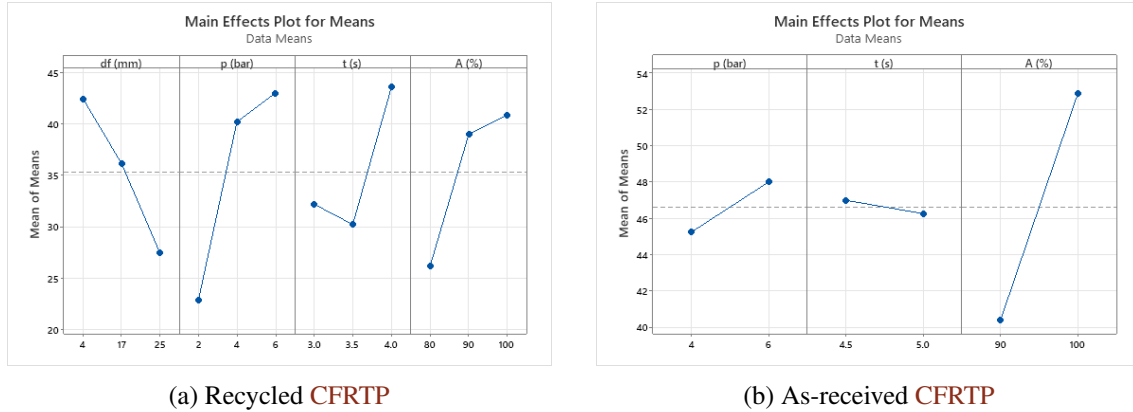


Figure B.2: Comparison of Main Effects Plots for Lap Shear Strength (LSS) obtained from Taguchi analysis.

B.3 Interaction Analysis (Contour Plots)

To visualise the combined effect of the process parameters, contour plots were generated. These plots help identify the direction of steepest ascent for mechanical strength and highlight the differences between material conditions.

B.3.1 Pressure and Time Interaction

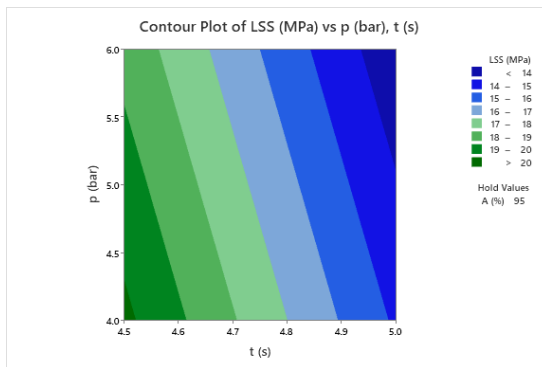
Figure B.3 shows the interaction between the two primary mechanical factors. For the as-received material, a clear "sweet spot" is visible, whereas the recycled material shows a broader, less defined region, consistent with the high noise observed in the ANOVA.

B.3.2 Amplitude and Time Interaction

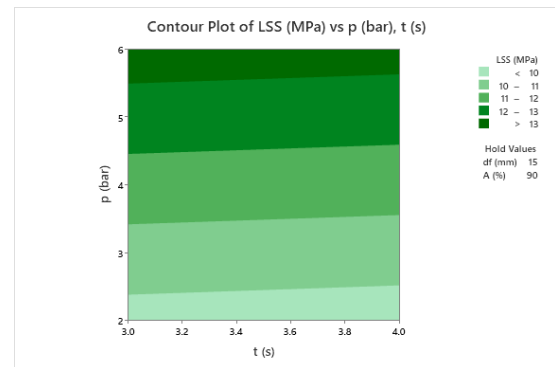
Figure B.4 illustrates the effect of energy delivery rate (Amplitude). The as-received material shows sensitivity to high amplitudes combined with long times (potential degradation zone), while the recycled material benefits from higher energy inputs to promote flow.

B.3.3 Effect of Fibre Size (Recycled Material)

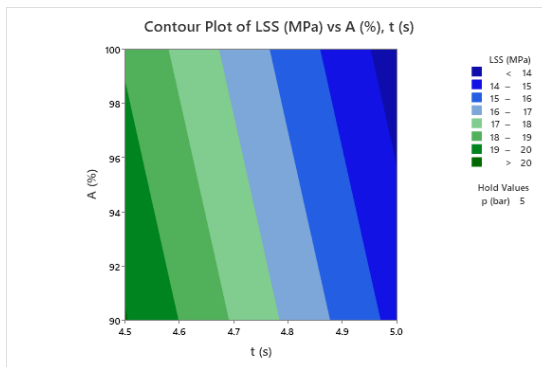
For the recycled CF RTP, the size of the shredded flakes (d_f) introduces a third dimension to the processing window. Figure B.5 demonstrates the interaction with mechanical parameters (Pressure and Time), generally showing that larger fibre sizes yield better performance.



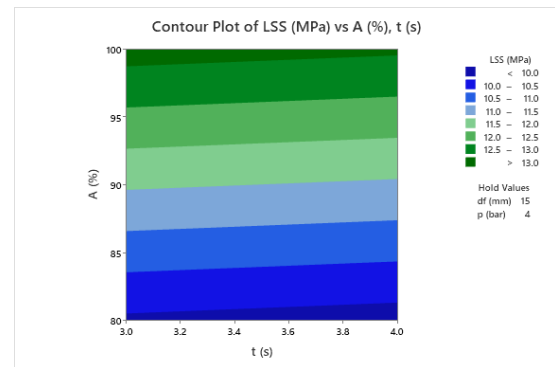
(a) As-received CF RTP



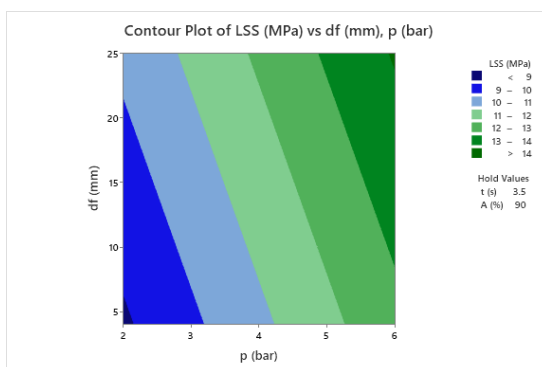
(b) Recycled CF RTP

Figure B.3: Contour plots: Pressure (p) vs. Welding Time (t).

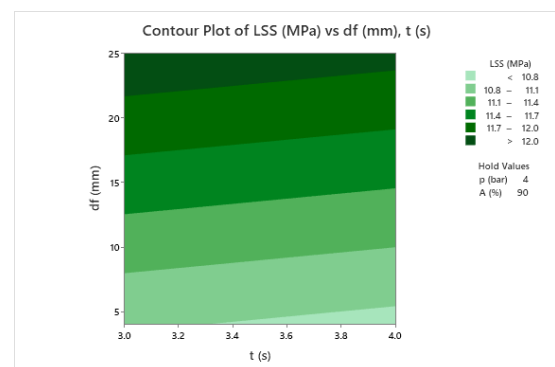
(a) As-received CF RTP



(b) Recycled CF RTP

Figure B.4: Contour plots: Amplitude (A) vs. Welding Time (t).

(a) Fibre Size vs. Pressure



(b) Fibre Size vs. Time

Figure B.5: Influence of Fibre Size (d_f) on the strength of Recycled CF RTP joints (vs Pressure and Time).

Furthermore, the interaction between Fibre Size and Amplitude (Figure B.6) reveals that to maximise the potential of larger flakes ($d_f = 25$ mm), higher amplitudes are required. The highest strength values (> 13 MPa) are found in the upper-right corner, indicating that higher energy input is necessary to fully melt and integrate the larger composite flakes.

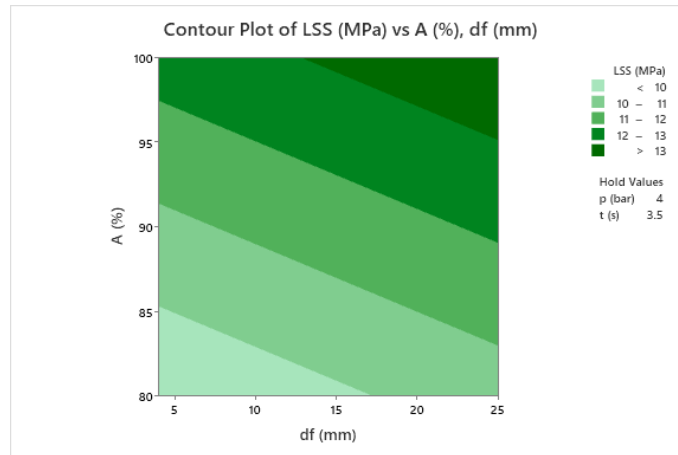


Figure B.6: Contour plot showing the interaction between Amplitude (A) and Fibre Size (d_f) for Recycled **CFRTP**.

B.4 Linear Regression Analysis (Energy Correlation)

To assess the feasibility of using Total Energy as a reliable process control variable, a simple linear regression was performed relating Energy (Predictor) to Lap Shear Strength (Response).

Table B.1 summarises the model performance. The analysis reveals that for both materials, the relationship is not statistically significant at the 95% confidence level ($p > 0.05$).

Table B.1: Summary of Linear Regression Analysis: Energy vs. Lap Shear Strength (**LSS**).

Material	R-sq	R-sq(adj)	F-Value	P-Value	Result
As-received	18.47%	10.31%	2.26	0.163	Not Significant
Recycled	10.97%	7.26%	2.96	0.098	Not Significant

The extremely low coefficients of determination ($R^2 < 20\%$) indicate that the Total Energy input explains very little of the variability in joint strength. This confirms that monitoring energy alone is insufficient; the specific combination of parameters (Pressure, Time, Amplitude) determines how that energy is converted into a viable weld.

Figure B.7 illustrates this high scattering of data points around the regression line.

B.5 Analysis of Variance using the General Linear Model

The quantitative assessment of statistical significance was performed using Analysis of Variance (**ANOVA**) based on a General Linear Model (**GLM**).

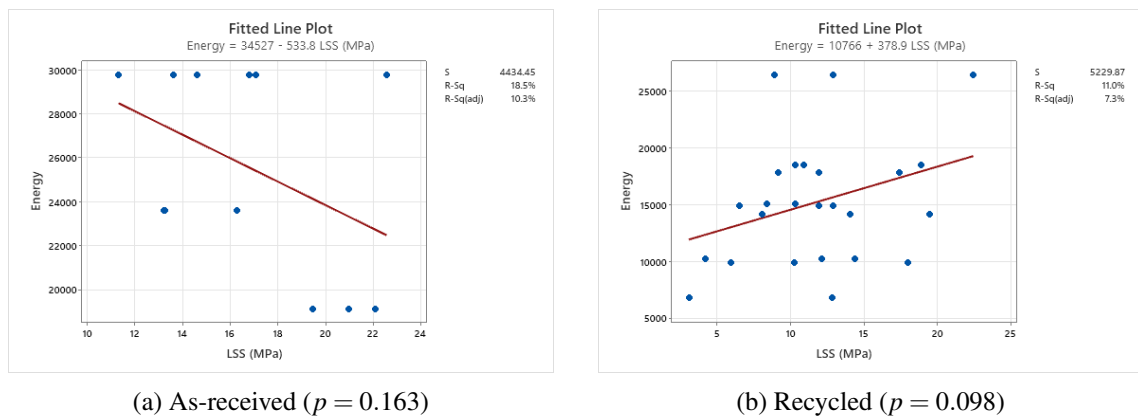


Figure B.7: Fitted Line Plots showing high residual variability. The lack of a strong linear trend confirms that Energy is not a direct predictor of Strength in this setup.

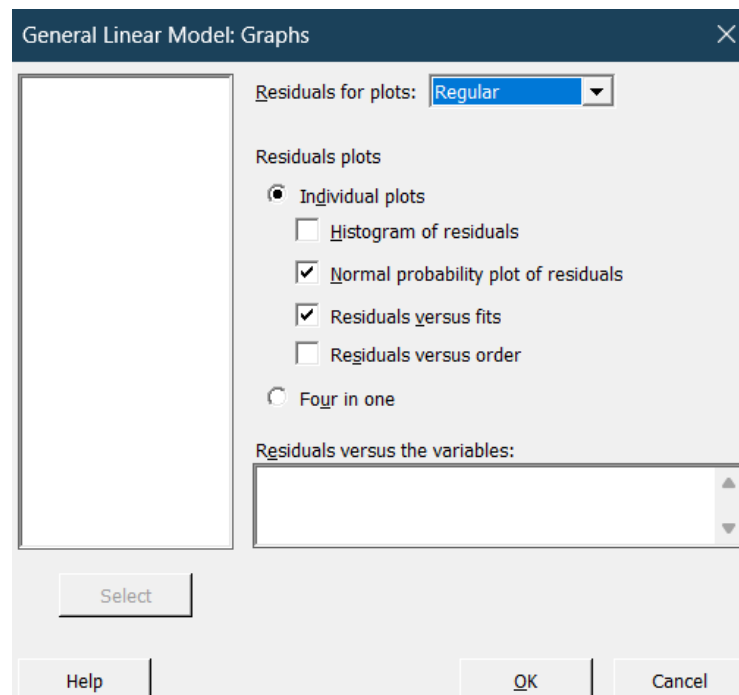


Figure B.8: General Linear Model setup in Minitab®, showing the selection of responses and welding parameters as fixed factors.

B.6 Residual Analysis and Model Validation

To validate the ANOVA models presented in Chapter 5, normal probability plots of residuals were analysed. As shown in Figure B.9, the residuals for the Lap Shear Strength model follow a straight line, confirming the normality assumption required for the F-tests validity.

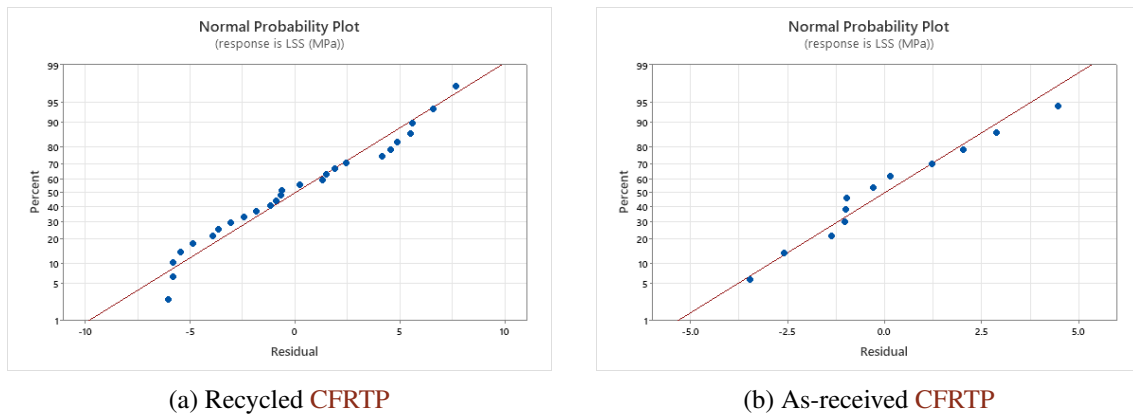


Figure B.9: Normal probability plots of residuals for Lap Shear Strength, validating the ANOVA model assumptions.

B.7 Multi-Response Optimisation

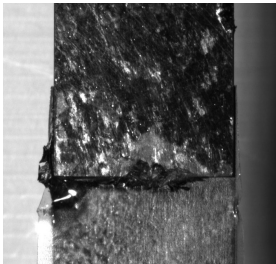
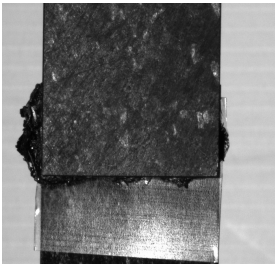
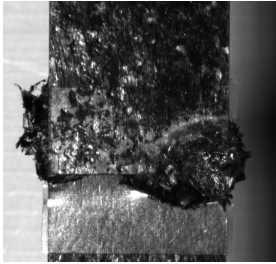
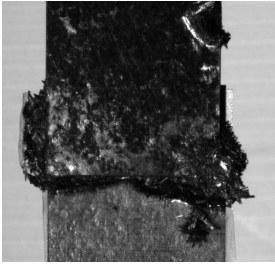
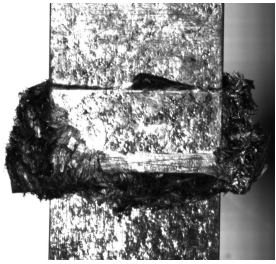
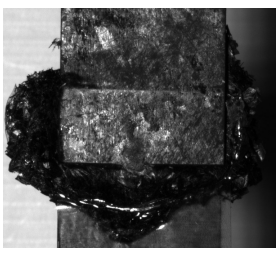
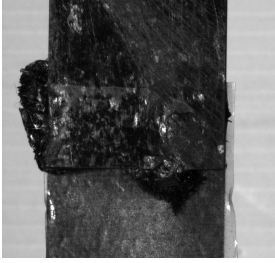
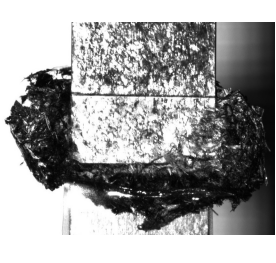
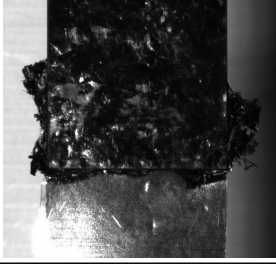
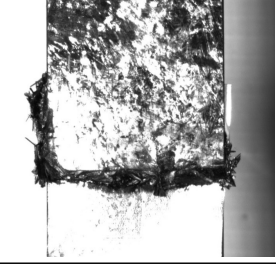
Following the ANOVA and residual validation, a multi-response optimisation was performed to identify the optimal parameter combinations. The detailed definition of the optimisation objectives, constraints, desirability functions, and the resulting optimal parameter plots are presented in Chapter 5 (Section 5.5) and Appendix J.

B.8 Concluding Remarks

This appendix documented the statistical workflow adopted for the analysis of the ultrasonic welding experiments. The inclusion of interaction plots and residual validation ensures that the conclusions drawn regarding the optimal processing window are statistically robust.

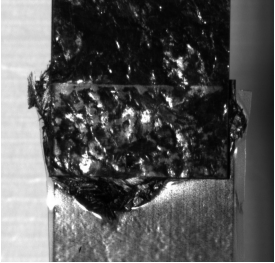
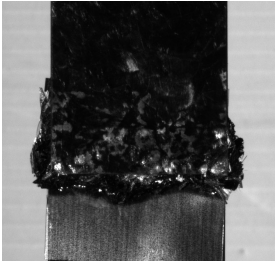
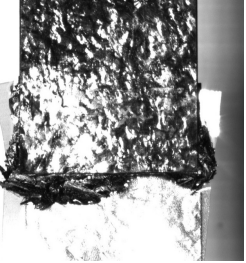
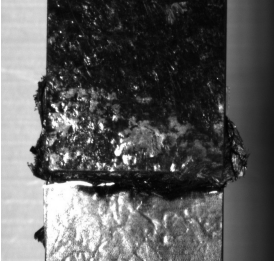
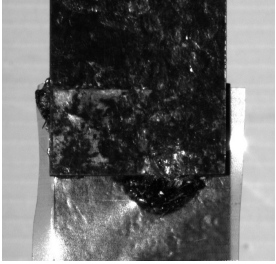
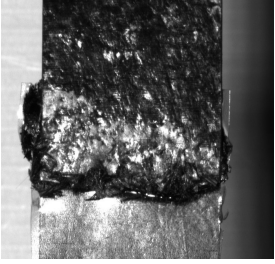
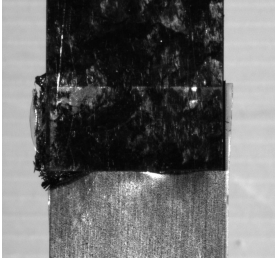
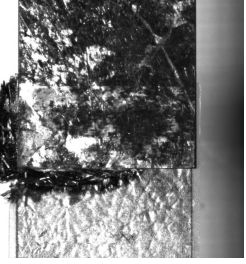
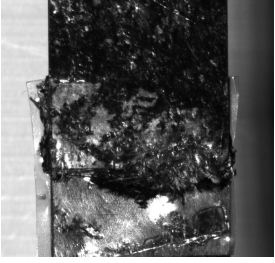
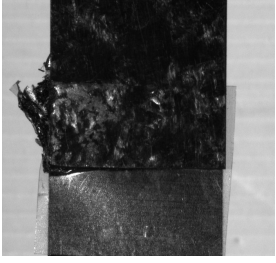
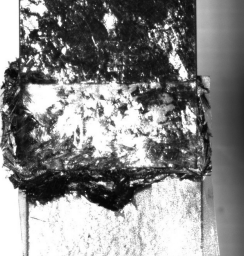
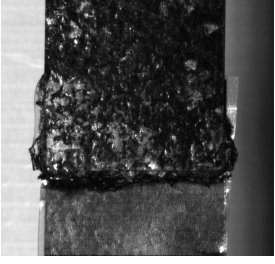
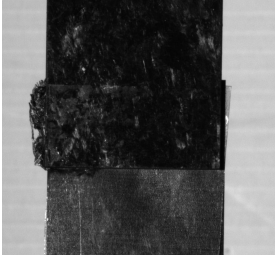
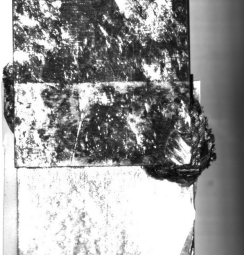
C. Visual Matrix of Initial Specimen States

This appendix presents the pre-test images for all tested specimens prior to mechanical loading. Groups A to I correspond to the recycled **CFRTP** adherends, while Groups J to M represent the as-received material configurations. Images are cropped to the joint overlap area for better visualisation of material squeezing. * Specimen A3 failed prior to testing and was consequently excluded from the morphological and mechanical analyses.

Condition	Replicate 1 ($n = 1$)	Replicate 2 ($n = 2$)	Replicate 3 ($n = 3$)
Group A			<i>Excluded *</i>
Group B			
Group C			
Group D			

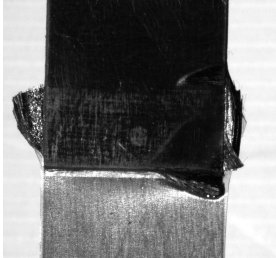
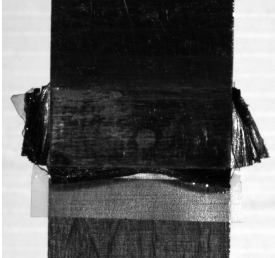
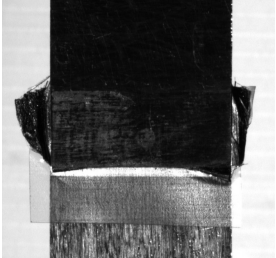
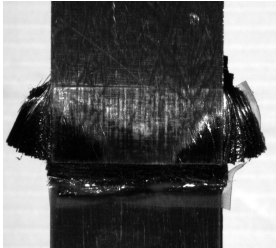
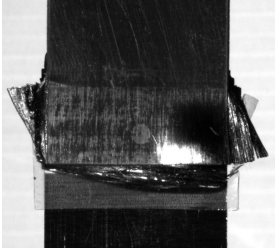
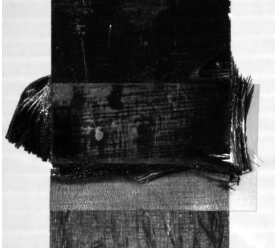
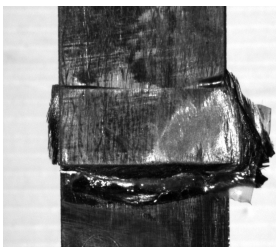
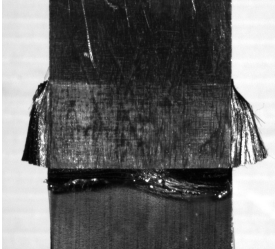
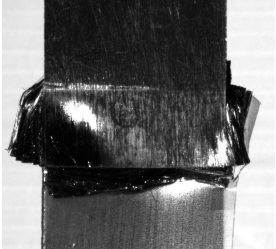
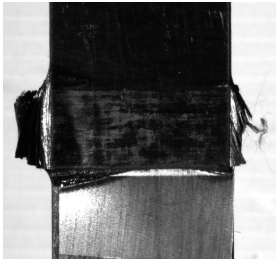
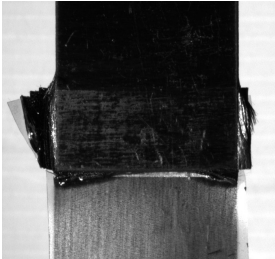
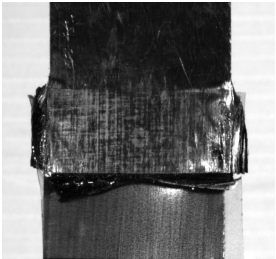
Continued on next page

Table C.1 – continued from previous page

Condition	Replicate 1 ($n = 1$)	Replicate 2 ($n = 2$)	Replicate 3 ($n = 3$)
Group E			
Group F			
Group G			
Group H			
Group I			

Continued on next page

Table C.1 – continued from previous page

Condition	Replicate 1 ($n = 1$)	Replicate 2 ($n = 2$)	Replicate 3 ($n = 3$)
Group J			
Group K			
Group L			
Group M			

D. Octave Scripts for Image Analysis

This appendix presents the GNU Octave scripts developed to quantify material squeezing and the effective welded area based on the processed images described in Chapter 4. These scripts were employed exclusively for post-processing and data extraction to ensure the objectivity and reproducibility of the measurements.

The algorithms were applied uniformly to all specimens, covering both recycled (A–I) and as-received (J–M) **CFRTP** samples. Three image sets were analysed per experimental condition to account for variability.

D.1 Squeezing Calculation Script

This script quantifies the material squeezing (expulsion) based on binarised images captured at the onset of the lap shear test. The analysis estimates the area of the material expelled beyond the nominal overlap region.

The script processes a batch of images where the background has been removed. Each image is converted to grayscale and binarised using a sensitivity threshold. The script counts the total number of pixels representing the specimen and subtracts the pixel count equivalent to the nominal overlap area ($25 \times 12.7 \text{ mm}^2$). The squeezing metric is expressed as the excess area percentage relative to the nominal area.

Listing D.1: Octave script for squeezing calculation.

```
1 pkg load image
2 close all; clear; clc;
3
4 % =====
5 % INPUT PARAMETERS
6 % =====
7 % List of image files
8 file_list = {
9     "a1.png"; "b1.png"; "c1.png";
10    "d1.png"; "e1.png"; "f1.png";
11    "g1.png"; "h1.png"; "i1.png";
12 };
13
14 % Calibration factor (based on reference scale)
15 pixels_per_mm = 18.04;
16
17 % Binarization threshold (0.001 = 0.1% of max intensity)
18 threshold_white = 0.001;
19
20 known_area_mm2 = 25 * 12.7;          % Nominal area in mm^2
```

```

21 pixels_per_mm2 = pixels_per_mm^2;
22 known_area_pixels = known_area_mm2 * pixels_per_mm2;
23
24 % =====
25 % PREPARE OUTPUT VECTORS
26 % =====
27 n_files = length(file_list);
28 n_pix_total = zeros(n_files, 1);      % Total pixels above threshold
29 excess_pixels = zeros(n_files, 1);    % Excess pixels
30 excess_ratio_percent = zeros(n_files, 1); % Squeezing (%)
31
32 % =====
33 % PROCESS EACH IMAGE
34 % =====
35 for sample = 1:n_files
36     file = file_list{sample};
37
38     % --- Load image ---
39     img = imread(file);
40
41     % --- Convert to grayscale if needed ---
42     if ndims(img) == 3
43         img = rgb2gray(img);
44     endif
45
46     % --- Normalize to [0,1] if uint8 ---
47     if isa(img, "uint8")
48         img = double(img) / 255;
49     endif
50
51     % --- Binary mask: pixels above threshold ---
52     im_bin = img > threshold_white;
53     n_pix_total(sample) = sum(im_bin(:));
54
55     % --- Calculate excess (Squeezing) ---
56     excess_pixels(sample) = n_pix_total(sample) - known_area_pixels;
57
58     % Sanity check: prevent negative values
59     if excess_pixels(sample) < 0
60         excess_pixels(sample) = 0;
61     endif
62
63     % --- Calculate Percentage ---
64     if known_area_pixels > 0

```

```

65         excess_ratio_percent(sample) = (excess_pixels(sample) /
66             known_area_pixels) * 100;
67     else
68         excess_ratio_percent(sample) = 0;
69     endif
70
71     % --- Visualization (Optional) ---
72     % figure(1); imshow(img); title(["Original - ", file]);
73     % figure(2); imshow(im_bin); title(["Binary Mask - ", file]);
74
75     % --- Save binary mask for validation ---
76     name_bin = strcat(file(1:end-4), "_bin.jpg");
77     imwrite(im_bin, name_bin);
78 end
79
80 % =====
81 % DISPLAY RESULTS
82 % =====
83 disp("Results per image:");
84 for sample = 1:n_files
85     file = file_list{sample};
86     fprintf("Image: %s\n", file);
87     fprintf("  Total Pixels: %.0f\n", n_pix_total(sample));
88     fprintf("  Nominal Area (pix): %.0f\n", known_area_pixels);
89     fprintf("  Excess Pixels: %.0f\n", excess_pixels(sample));
90     fprintf("  Squeezing: %.2f %%\n", excess_ratio_percent(sample));
91     fprintf("\n");
92 end
93
94 % =====
95 % SAVE DATA
96 % =====
97 save("squeezing_results.txt", "excess_ratio_percent");
98 save("squeezing_full_data.mat");

```

D.2 Welded Area Calculation Script

This script determines the effective welded area using binarised images of the fracture surfaces obtained via digital microscopy. In these images, the non-welded regions (defects or lack of fusion) are identified by high-contrast pixel intensity.

The script converts the input images to binary masks where white pixels correspond to non-welded regions. By subtracting the count of these pixels from the total nominal overlap area, the effective welded area is derived. The result is expressed as a percentage of the total overlap area, serving as a key response variable for the statistical analysis in Chapter 5.

Listing D.2: Octave script for welded area calculation.

```

1  pkg load image
2  close all; clear; clc;
3
4  % =====
5  % INPUT PARAMETERS
6  % =====
7  file_list = {
8      "a1.png"; "b1.png"; "c1.png";
9      "d1.png"; "e1.png"; "f1.png";
10     "g1.png"; "h1.png"; "i1.png";
11 };
12
13 % Calibration factor (Fracture surface zoom level)
14 pixels_per_mm = 17.55;
15 threshold_white = 0.001;
16
17 known_area_mm2 = 25 * 12.7;
18 pixels_per_mm2 = pixels_per_mm^2;
19 known_area_pixels = known_area_mm2 * pixels_per_mm2;
20
21 % =====
22 % OUTPUT VECTORS
23 % =====
24 n_files = length(file_list);
25 non_welded_pixels = zeros(n_files, 1); % Pixels representing defects
26 welded_pixels = zeros(n_files, 1); % Effective welded pixels
27 welded_ratio_percent = zeros(n_files, 1); % Welded Area (%)
28
29 % =====
30 % PROCESS EACH IMAGE
31 % =====
32 for sample = 1:n_files
33     file = file_list{sample};

```

```

34
35 % --- Load and Pre-process ---
36 img = imread(file);
37
38 if ndims(img) == 3
39     img = rgb2gray(img);
40 endif
41
42 if isa(img, "uint8")
43     img = double(img) / 255;
44 elseif islogical(img)
45     img = double(img);
46 else
47     img = double(img);
48 endif
49
50 % --- Binary mask: Count NON-WELDED pixels ---
51 im_bin = img > threshold_white;
52 non_welded_pixels(sample) = sum(im_bin(:));
53
54 % --- Calculate Effective Welded Area ---
55 welded_pixels(sample) = known_area_pixels - non_welded_pixels(sample);
56
57 % Boundary conditions
58 if welded_pixels(sample) < 0
59     welded_pixels(sample) = 0;
60 elseif welded_pixels(sample) > known_area_pixels
61     welded_pixels(sample) = known_area_pixels;
62 endif
63
64 % --- Calculate Percentage ---
65 if known_area_pixels > 0
66     welded_ratio_percent(sample) = (welded_pixels(sample) /
67         known_area_pixels) * 100;
68 else
69     welded_ratio_percent(sample) = 0;
70 endif
71
72 % --- Save binary mask ---
73 name_bin = strcat(file(1:end-4), "_bin.jpg");
74 imwrite(im_bin, name_bin);
75 end
76
77 % =====
78 % DISPLAY RESULTS

```

```

78 % =====
79 disp("Results per image:");
80 for sample = 1:n_files
81     file = file_list{sample};
82     fprintf("Image: %s\n", file);
83     fprintf("  Non-welded pixels: %.0f\n", non_welded_pixels(sample));
84     fprintf("  Nominal Area (pix): %.0f\n", known_area_pixels);
85     fprintf("  Welded Area (pix): %.0f\n", welded_pixels(sample));
86     fprintf("  Effective Welded Area: %.2f %%\n", welded_ratio_percent(
        sample));
87     fprintf("\n");
88 end
89
90 % =====
91 % SAVE DATA
92 % =====
93 save("welded_area_results.txt", "welded_ratio_percent");
94 save("welded_area_full_data.mat");

```

E. Additional Image Processing Results

This appendix contains the visual results for the squeezing and effective welded area quantification for the remaining specimens not shown in Chapter 4.

E.1 Squeezing Image Processing Results

This section presents the binarised images used to quantify the amount of material expelled during the welding process. The images correspond to the specimens selected for the Digital Image Correlation (DIC) analysis (Group 3).

Figure E.1 displays the recycled **CFRTP** specimens (A–I), while Figure E.2 presents the as-received (virgin) **CFRTP** specimens (J–M).

The binarised masks below represent the total projected area of the joint (nominal area + flash). These images were used to calculate the squeezing percentage by measuring the excess material that flowed beyond the nominal overlap edges.

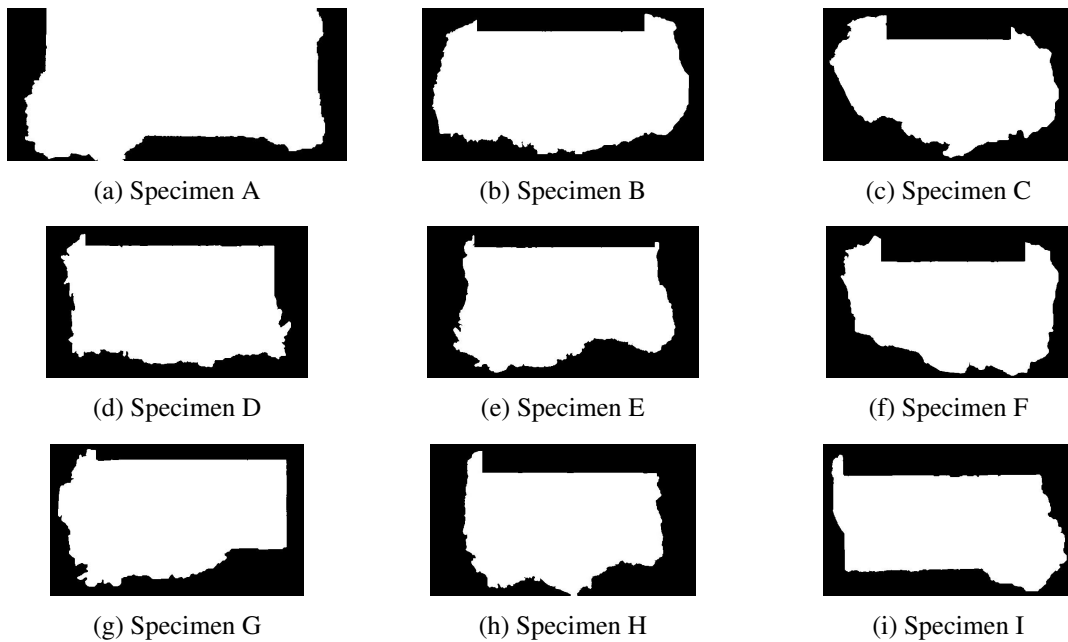


Figure E.1: Binarised images used for squeezing calculation (material expulsion): Recycled **CFRTP** specimens (Group 3).

E.2 Welded Area Image Processing Results

This section presents the binarised post-lap shear images used to determine the effective welded area. Figure E.3 corresponds to the recycled material, while Figure E.4 shows the as-received material.

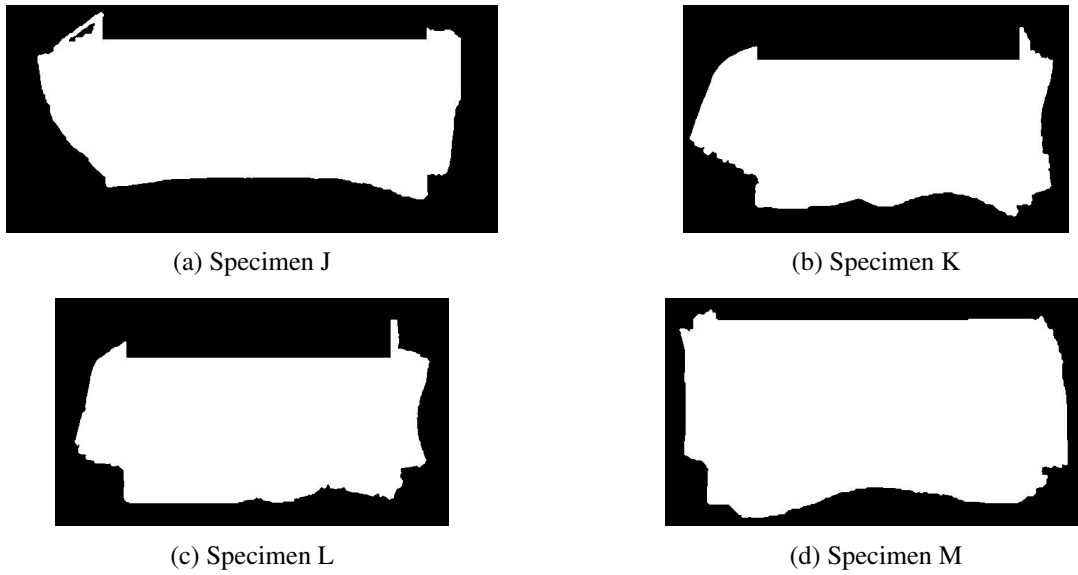


Figure E.2: Binarised images used for squeezing calculation (material expulsion): As-received **CF RTP** specimens (Group 3).

These images differentiate between the bonded material and the defects within the overlap region. Specifically, the white regions correspond to non-welded areas (voids or delaminations), while the dark regions represent the effectively bonded area used for the calculations.

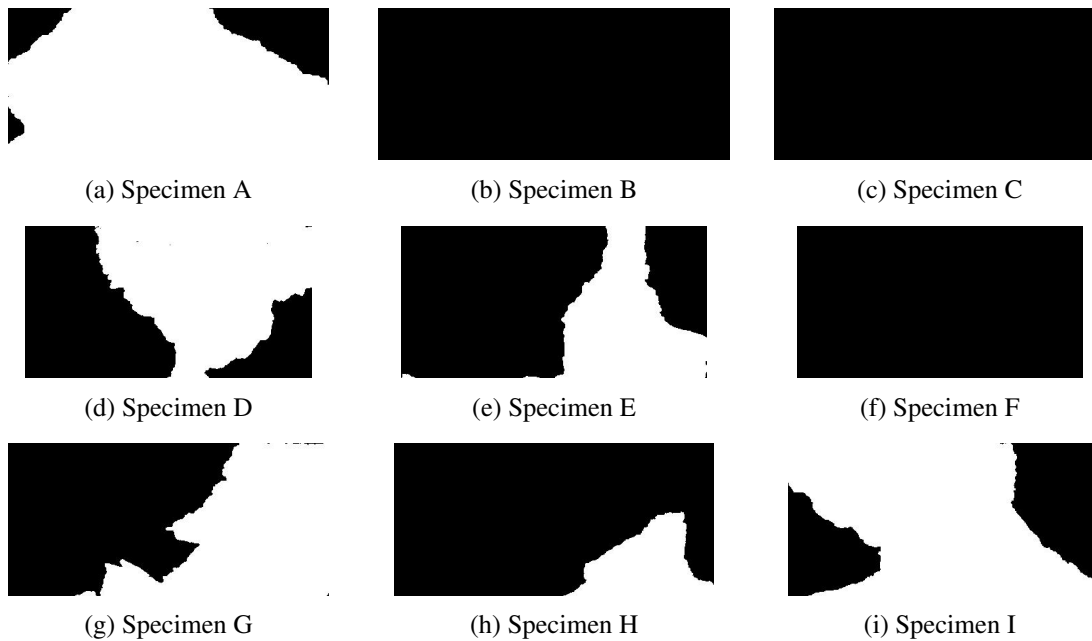


Figure E.3: Binarised post-lap shear images for effective welded area (White = Non-welded): Recycled **CF RTP** specimens (Group 3).

The complete quantitative results derived from these images are reported and discussed in Chapter 5.

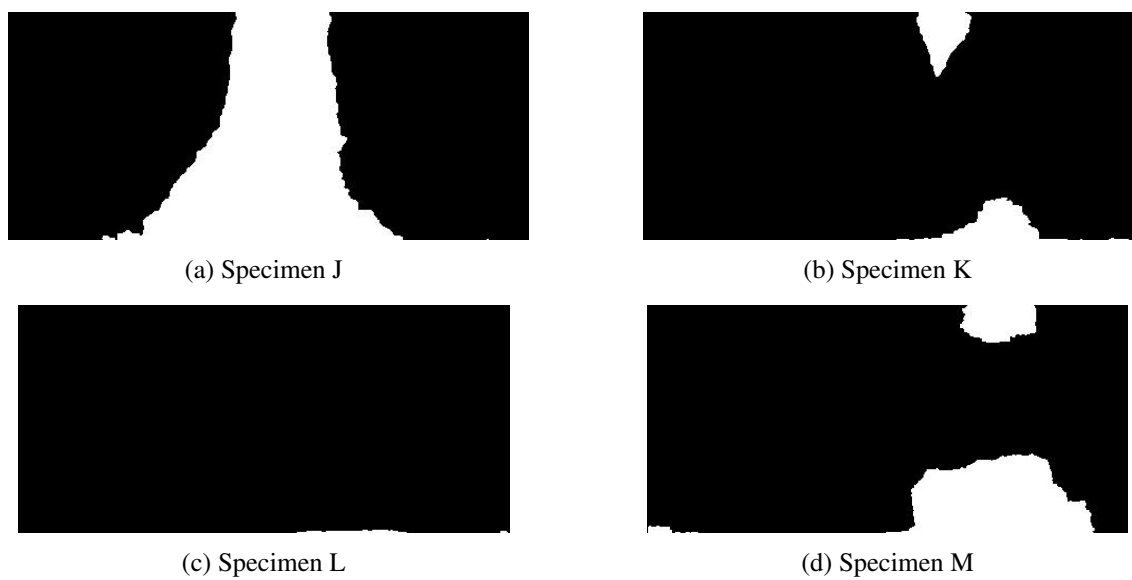
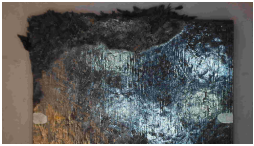
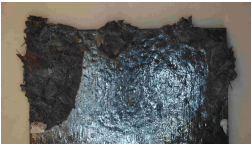
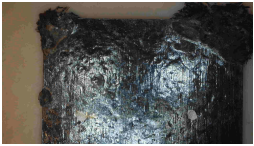
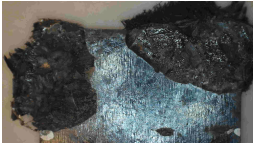
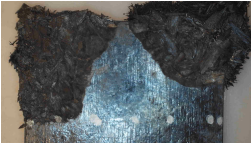
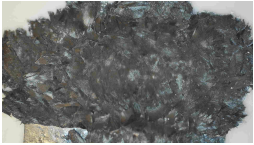
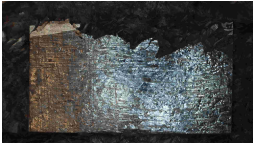
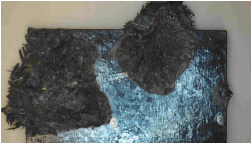
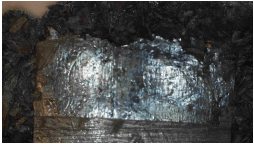
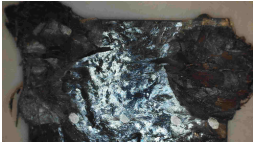
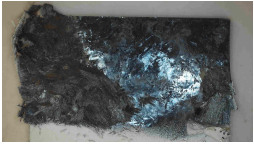
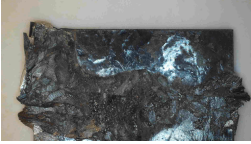
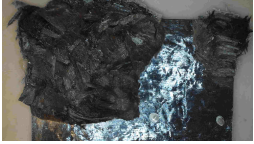
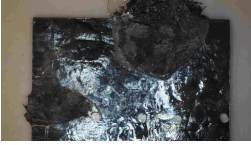
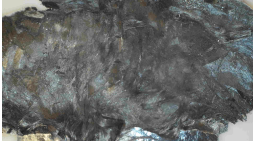
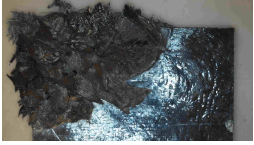
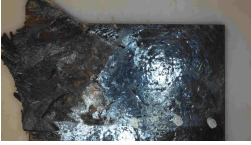
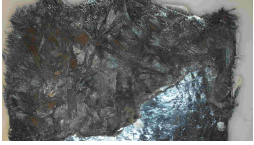
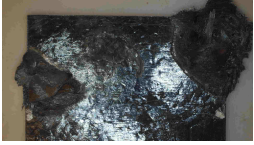


Figure E.4: Binarised post-lap shear images for effective welded area (White = Non-welded): As-received **CFRTP** specimens (Group 3).

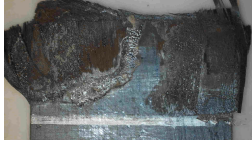
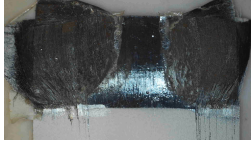
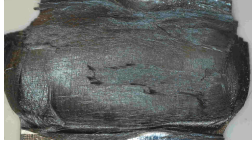
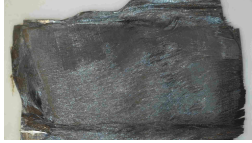
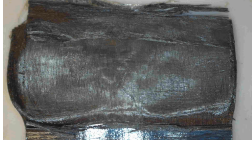
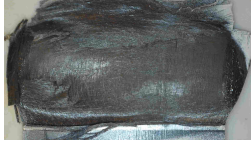
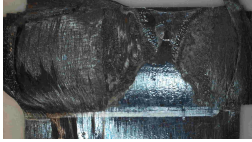
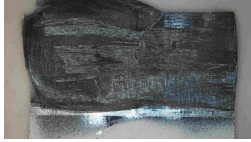
F. Visual Matrix of Welded Areas

This appendix presents the post-test fracture surface images for all specimens after the lap shear testing, acquired using a digital microscope. These images were utilised for the effective welded area quantification. Groups A to I correspond to the recycled **CFRTP** adherends, while Groups J to M represent the as-received material configurations.

Condition	Replicate 1 ($n = 1$)	Replicate 2 ($n = 2$)	Replicate 3 ($n = 3$)
Group A			
Group B			
Group C			
Group D			
Group E			
Group F			
Group G			
Group H			
Group I			

Continued on next page

Table F.1 – continued from previous page

Condition	Replicate 1 ($n = 1$)	Replicate 2 ($n = 2$)	Replicate 3 ($n = 3$)
Group J			
Group K			
Group L			
Group M			

G. Summary of Experimental Data

This appendix presents the detailed experimental results obtained for the recycled **CFRTP** joints, summarising the nominal energy input, individual repetition values, and the corresponding statistical metrics. The data is divided into two main categories: the effective Lap Shear Strength (**LSS**) in Table **G.1**, and the effective welded area in Table **G.2**.

Table G.1: Detailed experimental data for the Effective Lap Shear Strength (**LSS**) in MPa for all **CFRTP** groups.

Group	Material	Energy (J)	Rep 1	Rep 2	Rep 3	Min.	Max.	Average	Std. Dev.	CV (%)
A	Recycled	6803	3.07	12.84	-	3.07	12.84	7.95	4.89	61
B	Recycled	14882	6.54	11.92	12.90	6.54	12.90	10.46	2.80	27
C	Recycled	26457	22.45	8.91	12.90	8.91	22.45	14.76	5.68	38
D	Recycled	9921	18.01	5.96	10.26	5.96	18.01	11.41	4.99	44
E	Recycled	15118	10.32	8.40	8.36	8.36	10.32	9.03	0.92	10
F	Recycled	17858	11.92	9.19	17.41	9.19	17.41	12.84	3.42	27
G	Recycled	10205	14.39	4.20	12.12	4.20	14.39	10.24	4.37	43
H	Recycled	14173	14.07	8.05	19.45	8.05	19.45	13.86	4.66	34
I	Recycled	18520	10.29	10.92	18.90	10.29	18.90	13.37	3.92	29
J	As-received	19134	21.00	19.47	22.08	19.47	22.08	20.85	1.07	5
K	As-received	23622	13.23	16.29	13.28	13.23	16.29	14.26	1.43	10
L	As-received	29764	22.57	17.09	14.62	14.62	22.57	18.09	3.32	18
M	As-received	29764	16.79	13.62	11.32	11.32	16.79	13.91	2.24	16

Note: Rep 3 for Group A was not tested or the data was excluded.

Table G.2: Detailed experimental data for the Effective Welded Area (%) for all **CFRTP** groups.

Group	Material	Energy (J)	Rep 1	Rep 2	Rep 3	Min.	Max.	Average	Std. Dev.	CV (%)
A	Recycled	6803	28.79	34.88	15.80	15.80	34.88	26.49	7.96	30
B	Recycled	14882	46.56	57.33	100.00	46.56	100.00	67.96	23.08	34
C	Recycled	26457	100.00	59.43	100.00	59.43	100.00	86.48	19.12	22
D	Recycled	9921	46.87	23.05	44.19	23.05	46.87	38.04	10.65	28
E	Recycled	15118	87.86	64.58	69.59	64.58	87.86	74.01	10.00	14
F	Recycled	17858	69.65	39.32	100.00	39.32	100.00	69.66	24.77	36
G	Recycled	10205	61.80	23.73	55.32	23.73	61.80	46.95	16.63	35
H	Recycled	14173	63.35	33.92	83.81	33.92	83.81	60.36	20.48	34
I	Recycled	18520	42.01	26.93	29.94	26.93	42.01	32.96	6.52	20
J	As-received	19134	77.76	74.69	73.40	73.40	77.76	75.28	1.83	2
K	As-received	23622	99.42	99.62	95.81	95.81	99.62	98.28	1.75	2
L	As-received	29764	99.96	99.81	99.78	99.78	99.96	99.85	0.08	0
M	As-received	29764	78.62	84.32	87.19	78.62	87.19	83.38	3.56	4

H. Experimental Lap Shear Strength Curves

This appendix provides the complete set of experimental curves for Shear Strength (MPa) versus Displacement (mm). These plots complement the summarised results and statistical analyses presented in Section 5.2.

The raw data obtained from the universal testing machine were post-processed to ensure technical accuracy. The recorded force was converted into effective shear stress by dividing the load by the measured overlap area of each specific specimen. Additionally, the initial portion of the displacement data was trimmed to compensate for artefacts caused by grip slippage or mechanical play during the initial settling of the fixtures.

The data are organised by material group, featuring a side-by-side comparison between as-received and recycled specimens to allow for a detailed observation of individual specimen behaviour, failure modes, and experimental consistency.

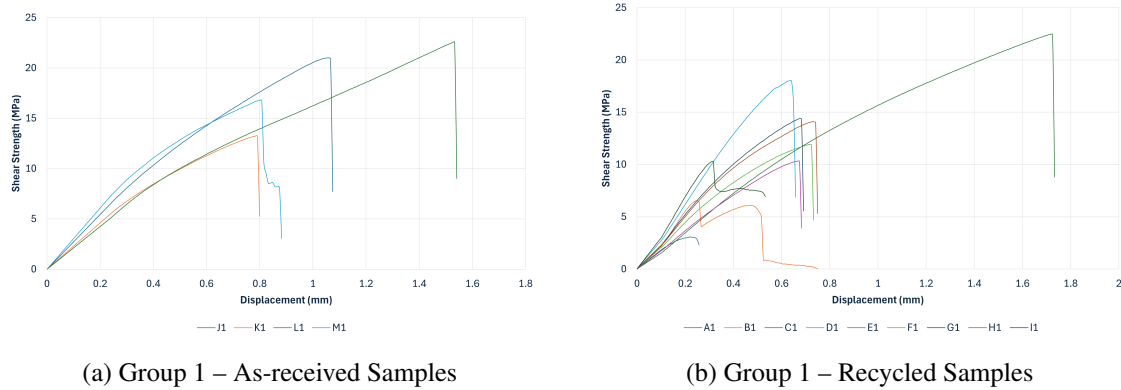


Figure H.1: LSS experimental curves for Group 1: Comparison between as-received and recycled states.

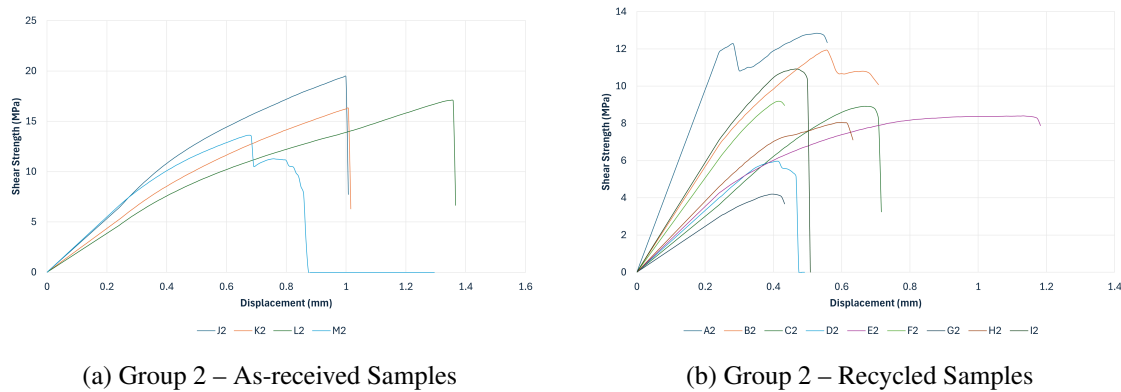
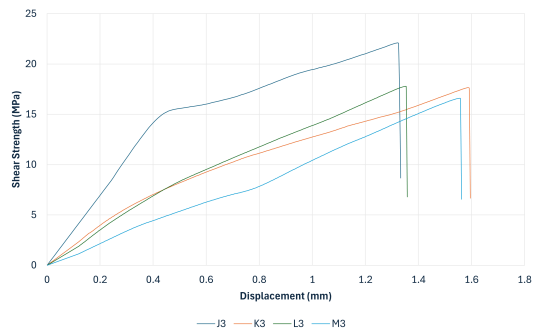
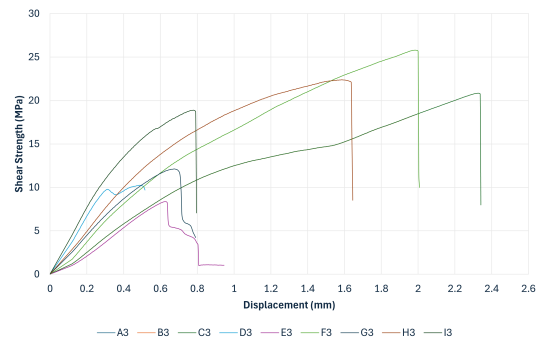


Figure H.2: LSS experimental curves for Group 2: Comparison between as-received and recycled states.



(a) Group 3 – As-received Samples



(b) Group 3 – Recycled Samples

Figure H.3: LSS experimental curves for Group 3: Comparison between as-received and recycled states.

I. Fracture Surface Macrographs

This appendix provides a comprehensive photographic record of the macroscopic fracture surfaces for all **CFRTP** joints tested in this study. The visual inspection of these surfaces allowed for the classification of the primary failure modes, which are strongly correlated with the mechanical performance discussed in Section 5.6.

The images are organised in a matrix format by experimental group (A to M) and their respective repetitions. The predominant failure mode is indicated below each macrograph. Although specimen A3 recorded a null **LSS** value, its fracture surface was preserved for visual characterisation.

Table I.1: Matrix of fracture surfaces and corresponding macroscopic failure modes for all tested specimens.

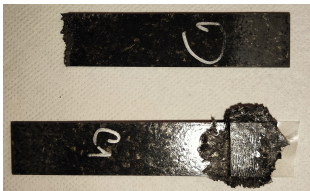
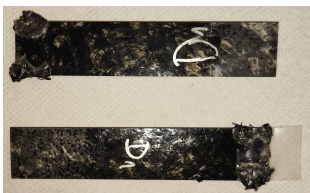
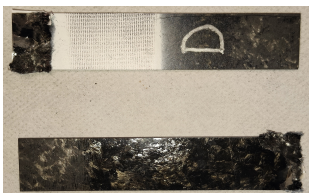
Group	Repetition 1	Repetition 2	Repetition 3
A			
	Adhesive	Mixed	Adhesive
B			
	Mixed/Adhesive	Mixed	Substrate
C			
	Substrate	Adhesive	Substrate
D			
	Mixed	Mixed/Adhesive	Mixed/Adhesive

Table I.1 continued from previous page

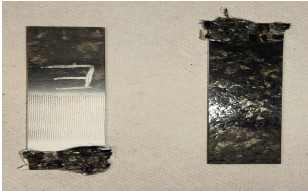
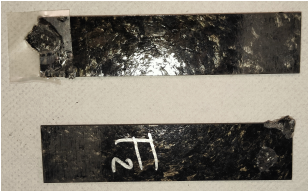
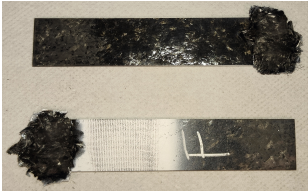
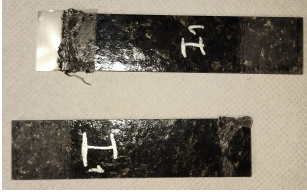
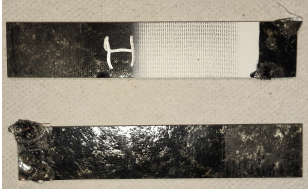
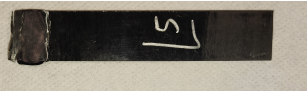
Group	Repetition 1	Repetition 2	Repetition 3
E			
	Substrate	Mixed	Mixed
F			
	Adhesive	Mixed/Adhesive	Substrate
G			
	Mixed	Adhesive	Mixed/Adhesive
H			
	Mixed	Adhesive	Substrate
I			
	Mixed/Adhesive	Adhesive	Mixed/Adhesive
J			
	Mixed/Adhesive	Mixed	Mixed/Adhesive

Table I.1 continued from previous page

Group	Repetition 1	Repetition 2	Repetition 3
K			
			
	Adhesive	Adhesive	Substrate
L			
			
	Adhesive	Adhesive	Substrate
M			
			
	Mixed/Adhesive	Mixed/Adhesive	Substrate

J. Response Optimisation Based on Taguchi and ANOVA Results

This appendix describes the multi-response optimisation procedure performed using the Minitab® Response Optimizer following the Taguchi and ANOVA analyses. The optimisation was carried out separately for as-received and recycled CF RTP materials, reflecting the differences in material structure and process sensitivity between the two systems.

For as-received CF RTP specimens, the optimisation considered the welding pressure, welding time, and vibration amplitude as control parameters. For recycled CF RTP specimens, an additional parameter related to the average fibre size (d_f) was included in the optimisation, in order to account for the increased material heterogeneity inherent to recycled composites.

J.1 Definition of Optimisation Objectives

The multi-response optimisation aimed to identify a compromise set of welding parameters that simultaneously maximises joint mechanical performance and joint quality while limiting excessive material flow. Accordingly, the following optimisation objectives were defined:

- **Maximise** lap shear strength (LSS);
- **Maximise** welded area;
- **Minimise** squeezing.

Variable	Constraint	Hold Value	Lower	Upper
p	Constrain to region	4	4	6
t	Constrain to region	4.5	4.5	5
A	Constrain to region	90	90	100

Confidence level for all intervals: 95

Type of confidence level: Two-sided

Buttons: Help, OK, Cancel

Figure J.1: Definition of optimisation objectives in the Minitab® Response Optimiser.

J.2 Optimisation Variables

The optimisation variables were defined according to the material system under analysis.

For the as-received **CFRTP** specimens, the optimisation variables were:

- Welding pressure (p);
- Welding time (t);
- Vibration amplitude (A).

For the recycled **CFRTP** specimens, the optimisation variables included an additional material-related parameter:

- Fibre size (d_f);
- Welding pressure (p);
- Welding time (t);
- Vibration amplitude (A).

The inclusion of fibre size in the optimisation of recycled materials reflects the influence of fibre length distribution on vibration transmission, polymer flow, and joint formation mechanisms in recycled thermoplastic composites.

J.3 Definition of Parameter Constraints

The optimisation was constrained to the experimental domain defined by the Taguchi designs. Lower and upper bounds were imposed on each parameter to ensure that the predicted optimal solutions remained within the tested ranges.

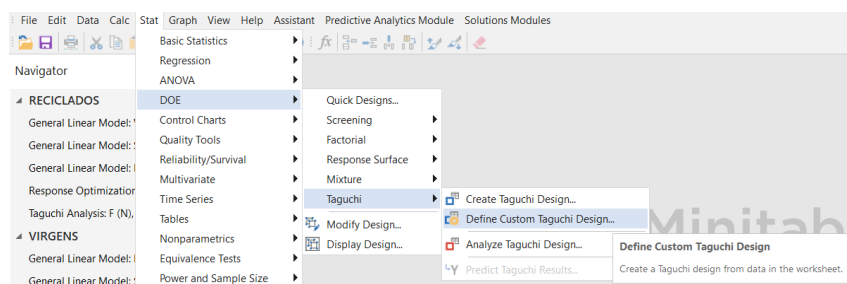


Figure J.2: Definition of parameter constraints for the multi-response optimisation in Minitab®.

J.4 Desirability-Based Optimisation

The Response Optimiser employs a desirability-based approach, where each response is converted into an individual desirability function ranging from zero to one. The composite desirability is then calculated as the geometric mean of the individual desirability, enabling the identification of a balanced solution that represents a compromise between competing objectives and control parameters.

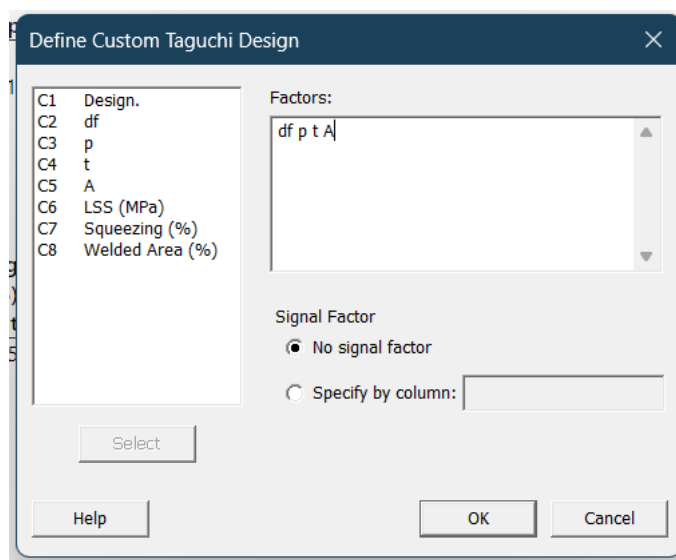


Figure J.3: Composite desirability setup for the multi-response optimisation.

J.5 Optimal Parameter Combinations

The optimisation results indicate distinct optimal parameter combinations for as-received and recycled **CFRTP** specimens. In the case of recycled materials, the predicted optimal solution includes a specific fibre size (d_f), highlighting the role of fibre length distribution in controlling joint performance and material flow during ultrasonic welding.

Figure J.4 presents the predicted optimal settings side-by-side for comparison.

J.6 Scope and Limitations

The optimisation results are based on linear models fitted to the experimental data obtained from the Taguchi designs. Consequently, the predicted optimal conditions represent trends within the explored parameter space rather than absolute global optima. Experimental validation of the predicted optimal parameter combinations is therefore required to confirm their practical relevance, as discussed in Chapter 5.

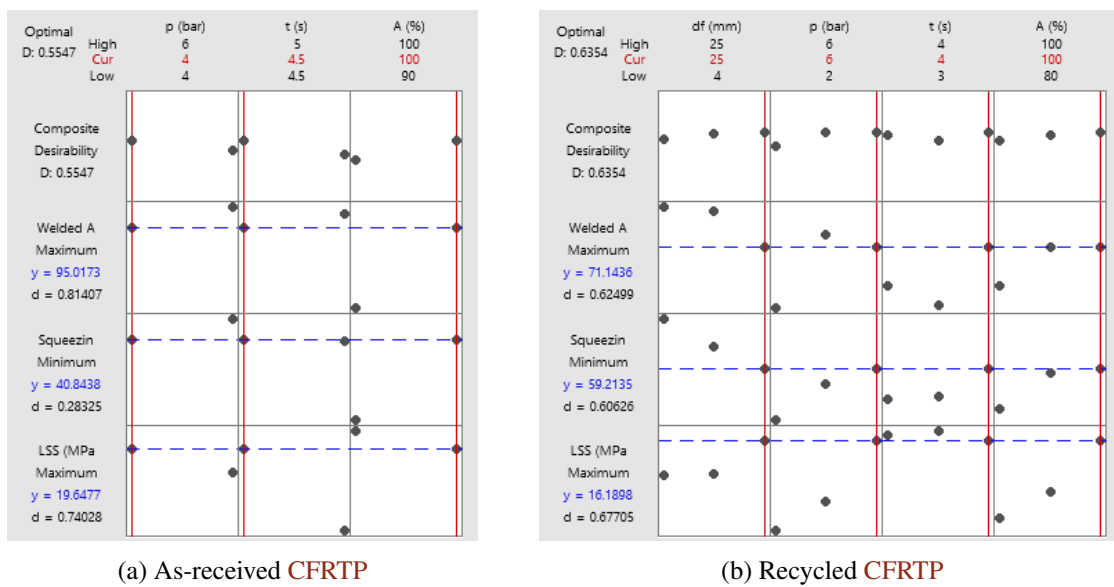


Figure J.4: Optimisation plots showing the predicted optimal welding parameters and composite desirability for both materials.