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Additive Manufacturing of Composites with Tailored Fibre Architectures in Fastened Joint Applications

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**THE UNIVERSITY
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Declaration

I hereby declare that this thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy is my original work and has not been presented for a degree in any other university or institution. This thesis is the result of my own research endeavours, undertaken under the supervision of Dr Dongmin Yang. The work contained within this thesis, unless otherwise stated, is solely my creation. Collaborative efforts and contributions have been clearly identified and appropriately acknowledged within the text. I confirm that any assistance received in preparing this thesis and all sources used have been duly cited.

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Abstract

This thesis investigates the enhancement of mechanical properties in carbon fibre reinforced polymer (CFRP) composites, with a specific focus on the bearing performance of fastened joints, by tailoring the fibre architectures using 3D printed continuous carbon fibre (CF) filaments. The research methodology integrates fibre steering techniques with finite element analysis (FEA) to improve the design and functionality of CFRP composites in fastened joint applications. It aims to explore the potential of tailored fibre architectures in reinforcing the mechanical robustness of these materials.

A comprehensive methodology is employed combining computational modelling with rigorous experimental validation. A novel multi-scale finite element modelling approach is developed, wherein continuous CF filaments are used as the fundamental modelling units, allowing for a detailed analysis of fibre path effects on laminate performance. The experimental outcomes, evaluating the bearing response of fastened joints under double-shear tensile loading, indicate significant enhancements in bearing strength and energy absorption through precise fibre steering and path design. The research also extends to the application of these methodologies in repairing deformed composite laminates, presenting the practical utility and environmental benefits of the developed techniques.

The conclusions of this study emphasise the revolutionary potential of integrating 3D printing with computational modelling in the field of composite materials. The developed methodologies not only provide insights into the mechanical behaviour of composites but also facilitate the development of novel approaches in material design and repair. This work significantly contributes to the advancement of composite material science, particularly in the context of mechanically fastened joints, offering a foundation for future innovations and applications in the industry.

Lay Summary

This research focuses on making materials stronger and more effective, specifically looking at materials made of carbon fibre and plastic (known as carbon fibre reinforced polymer composites). These materials are used in various applications, including parts where pieces are joined together with fasteners such as screws or bolts.

The study explores how to arrange the carbon fibres in these composites using 3D printing technology to make these joints stronger and more efficient. By carefully controlling the direction of the carbon fibres, the research aims to improve how well these materials can handle forces and stresses, particularly in the areas around those fasteners.

To test this idea, a combination of computational modelling and physical experiments was used. The computer models were very detailed, looking closely at how individual carbon fibres affect the mechanical performance of the whole material. Then, physical experiments were conducted to see how these materials behave under stress, particularly focusing on how much loading they can bear before breaking.

The results were promising. By changing the direction of the carbon fibres, the materials became stronger and could absorb more energy, especially in the areas with fasteners. The research also looked at how these techniques could be used to repair damaged materials, which is important for reducing waste and extending the service life of composite products.

Overall, this study shows that using 3D printing to precisely control carbon fibre placement can lead to stronger and more durable materials. This has big implications for the future of material design and repair, potentially leading to new and innovative ways to build and fix things, especially in industries, where joining materials together is crucial.

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Journal Papers

Li A, Zhang H, Yang D. Influence of fibre steering on the bearing performance of bolted joints in 3D printed pseudo-woven CFRP composites. *Composites Part A: Applied Science and Manufacturing*. 2024;108150. (Chapter 4 of thesis)

Zhang H, **Li A**, Wu J, Sun B, Wang C, Yang D. Effectiveness of fibre placement in 3D printed open-hole composites under uniaxial tension. *Composites Science and Technology*. 2022;220.

Zhang H, Zhang K, **Li A**, Wan L, Robert C, Ó Brádaigh CM, Yang D. 3D printing of continuous carbon fibre reinforced powder-based epoxy composites. *Composites Communications*. 2022;33.

Zhang H, Wang S, Zhang K, Wu J, **Li A**, Liu J, Yang D. 3D printing of continuous carbon fibre reinforced polymer composites with optimised structural topology and fibre orientation. *Composite Structures*. 2023;313.

Wang S, Zhang H, **Li A**, Ahmad Abdul Qayyum J, Wang Y, He Z, et al. A modified equally-spaced method (MEQS) for fibre placement in additive manufacturing of topology-optimised continuous carbon fibre-reinforced polymer composite structures. *Composite Structures*. 2024;335:117998.

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Li A, Yang D. Novel repair of bolted composite joints using 3D printed continuous fibre patch with custom fibre paths. (To be submitted to Composites Part B: Engineering; Chapter 7 of thesis)

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Chapter 1. Introduction

1.1. Project Motivation

The field of additive manufacturing (AM, also known as 3D printing) for composite materials is experiencing a significant rise, driven by its potential to revolutionise the fabrication of composite structures with complex geometries and tailored properties. This project is motivated by the growing interest in AM for composites, especially in the context of continuous carbon fibre-reinforced polymers (CFRPs), which are pivotal in industries like aerospace, automotive, and civil engineering due to their high strength-to-weight ratio and design versatility.

1.2. Problem Statements

Despite the advancements in AM, several critical issues persist and require continuing research efforts. Firstly, the development of 3D printed composites, especially continuous carbon fibre-tailored composite, remains an under-explored area, with significant room for improved mechanical performance. Secondly, the design and analysis of fastened joints in composite structures present complex challenges due to their anisotropic nature and failure modes. Additionally, the current finite element models for composite materials predominantly simulate the mechanical behaviours of homogenised equivalent conventional composites. There is a remarkable gap in simulating the mechanical behaviours of specially customised continuous fibre tailored composites, which are often manufactured through AM technologies. Lastly, the field urgently demands effective repair methods for damaged bolt holes in composite structures, which is crucial for promoting the sustainability of composite materials.

1.3. Aims and Objectives

The primary aim of this thesis is to explore the potential of AM techniques in enhancing the mechanical performance of fastened joints and providing innovative solutions for their repair.

To achieve this aim, the following four key objectives have been established:

1) To acquire a comprehensive understanding of the fastened joint, this study will review which conventional composite material systems offer the greatest potential for achieving this goal. It will examine common challenges encountered in the use of fastened joints, the advantages and disadvantages compared to other connection methods, strategies for designing and predicting the performance of a fastened joint prior to implementation, and approaches for repairing damaged joints.

2) Initially, a relatively simple case will be examined to address the common issues found in traditional fastened joints through experimental methods. This will be supplemented with a novel numerical model, specifically developed for AM, to assess how this new manufacturing method impacts the performance of bolted joints. The validity of the simulation results will be corroborated by comparing the damage in CFRP composite materials identified through experimental measurements such as digital image correlation (DIC) and X-ray micro-computed tomography (Micro-CT).

3) Building on these findings, a novel fastened joint will be designed using AM techniques and numerical analysis results, aiming to surpass the performance of conventional methods. The numerical model will guide the AM process of the composite, particularly in terms of fibre tailoring paths.

4) To further explore the potential of AM and the novel numerical method, an innovative repair technique will be developed. The method will be formulated based on the insights gained from previous manufacturing and simulation approaches.

1.4. Thesis Outline

The thesis is divided into 8 chapters including Introduction, Literature review, five chapters on related objectives, and one chapter of Conclusions.

Chapter 1 is the current chapter providing a brief introduction of the thesis.

Chapter 2 is a literature review which firstly presents the rationale for selecting continuous carbon fibre and powder epoxy as the material system for this thesis. Then, it commences with an exploration of the prevalent methods employed for joining composite materials. Concentrated attention is directed towards fastened joints, discussing existing challenges and potential opportunities for improvement. The chapter then progresses to a review of numerical models used in the study of composite material failure, detailing the specific cases each model addresses. Furthermore, it assesses various state-of-the-art composite repair techniques, explaining the original situations in which these techniques are utilised. Finally, the chapter ends with a thorough analysis of the various AM techniques developed for composites particularly the current design methodologies for tailoring continuous carbon fibre within the composite.

Chapter 3 investigates the use of carbon fibre tow and epoxy powder for fabricating continuous filament, exploring its curing processes and the mechanical properties through experimental tests.

Chapter 4 focuses on evaluating the bearing performance and understanding the failure mechanisms of continuous carbon fibre-tailored pseudo-woven CFRP fastened joint composites through experimental approaches. The chapter investigates three distinct cases of fibre tailoring and presents a comparative analysis and a benchmark against mechanically drilled composite counterparts.

Chapter 5 presents the development of a multi-scale modelling method for the 3D printed continuous carbon fibre-tailored pseudo-woven CFRP fastened joint composites that are tested in Chapter 4. The outcomes of this numerical method are corroborated through experimental results presented in the previous chapter, involving comparisons of load-displacement curves, failure modes in each case, as well as the quantification of strength and energy at various stages of the analysis.

Chapter 6 explores the improvement of bearing performance in fastened composite joints via the incorporation of 3D printed interlayers. It details three distinct fibre steering cases, discussing the design concepts derived from the numerical model developed in the preceding chapter. The chapter then provides comparative analyses of both the numerical outcomes and experimental tests, emphasising the effectiveness of these interlayers in enhancing joint performance. Additionally, it discusses the mechanisms responsible for this enhancement.

Chapter 7 evaluates a novel repair technique for fastened composite joints using 3D printed continuous fibre patches. This chapter illustrates the sequential process of the repair method and details the design of two distinct patches. It presents both experimental tests and numerical analyses to demonstrate the recovery capability of the repaired fastened joints and to explain the basic mechanisms of this repair method.

Chapter 8 summarises the findings and contributions of the thesis as well as outlines prospective routes for future research in this field.

Chapter 2. Literature Review

2.1. Composite Materials

Composite materials, by definition, combine two or more distinct materials to create a hybrid with superior properties as against the individual constituents. The reinforcing phase, typically fibres or particles, imparts strength and stiffness [1]. The matrix, often made of polymers, ceramics, or metals, binds the reinforcement and defines the component's geometry. Reinforcing fibres, which can be glass, aramids, or carbon, exhibit high length-to-diameter ratios, though this varies widely between types [2]. Reinforcements are classified as either discontinuous fibres, usually randomly oriented, or continuous fibres, often formed into woven fabrics, tows, or unidirectional sheets.

Carbon fibre reinforced polymer (CFRP) composite laminates have gained widespread use in various engineering applications due to their high strength- and stiffness-to-weight ratios [3-5]. The fabrication of CFRP composites, key in sectors like aerospace, sports, automotive, and civil engineering [6], involves diverse manufacturing methods influenced by factors like resin properties, component geometry, and cost. Techniques such as wet-layup, spray-up, and vacuum-bag layup are some examples [7]. The fibre-matrix interphase in these composites, crucial for stress transfer, is enhanced by applying a sizing agent, which improves resin-fibre adhesion and affects the composite's interfacial properties, as shown in studies like Guigon *et al.* [8]. The choice of sizing and resin, particularly epoxy, is vital to prevent issues like debonding. Epoxies, known for their mechanical, adhesive, thermal, and corrosion resistance, depend on the specific resin and curing agents used [1]. Curing conditions, especially temperature, significantly influence the mechanical properties and the glass transition temperature (T_g) of the final product [9].

In composite material fabrication, the wet layup method, involves manually placing fibre mats onto a mould and applying a resin-hardener mixture, ensuring optimal fibre-matrix mass ratio and desired mechanical properties [10]. The prepreg laying technique, prevalent in aerospace for high-performance parts, uses pre-impregnated fibres with a thickened resin, eliminating the need for on-site resin mixing and application after each reinforcement layer [11]. Both methods can utilise vacuum bagging to improve consolidation and remove excess materials, although limited to one-atmosphere pressure, leading to the use of autoclaves for highly consolidated parts [12]. Additionally, pneumatic presses with heated tooling surfaces are used for manufacturing plates and curved panels, applying greater lateral pressures during curing.

Since the 1950s, powdered thermosets have become crucial in the coating industry for their cost-effectiveness and environmental advantages, notably in reducing volatile organic compounds (VOCs) and allowing the reuse of excess powder [13]. The 1990s marked a significant increase in powder coating technology research, led by companies like DSM Resins and Dow Chemical Company [13-17]. These coatings, primarily based on epoxy or polyester resins, include agents like TiO₂ for pigmentation and latent curing agents to maintain storage stability and facilitate film levelling [15, 18]. Deposition techniques vary, ranging from fluidised beds for small objects to electrostatically charged spraying for larger substrates [13].

Since the 1970s, polymer powder has been used for impregnating fibre tows [19]. Significant developments in powder towpregging, involving thermoplastics and thermosets, were conducted by NASA and others in the late 1980s and early 1990s [20]. This process, including innovations like a towpregging apparatus for high-temperature polyimide, has shown economic and environmental benefits, such as reduced VOC emissions [21]. Subsequent research expanded into process modelling and the integration of towpregs in textile processes like weaving [22-25].

However, research into thermosetting towpregs, particularly using powder for towpreg production, has been limited. Commercial epoxy powder coatings and high-temperature thermoset powders were studied, revealing promising mechanical performance despite voids and extended 'out-time' [26]. Adherent Technologies Inc. reported on a low-exotherm epoxy powder for cost-effective towpreg production [27]. This historical progression shows the potential for further exploration in thermosetting towpregs.

The development of composite materials, particularly CFRPs, has advanced through techniques like wet layup and spray-up, enhanced by sizing agents and powdered thermosets for environmental and cost efficiency. Despite the progress, especially in powder towpregging for thermoplastics, research in thermosetting towpregs remains limited, opening avenues for future innovation. This thesis aims to combine carbon fibre tow and epoxy powder with the recent additive manufacturing (AM) technique to expand application possibilities. This subject will be thoroughly presented in the following sections.

2.2. Composite Fastened Joints

Although composites with complex shapes can be manufactured through a single process such as resin transfer moulding (RTM) and compression moulding, joining and assembly of composite parts are still required for large structures. Reliable applications of composite materials highly depend on using suitable choices for the joining technique as well as laminate lay-up, which are essential for providing safe load-transfer mechanisms and higher mechanical joint efficiencies [28, 29]. There are three main types of joints in thermoset composite structures: mechanically fastened, adhesively bonded, and hybrid bolted-bonded (HBB) joints [30].

Mechanical fasteners are frequently applied in structures (as shown in Fig. 2-1) and provide a removable means for facilitating the transfer of load between components [31, 32]. Their

design is crucial to the functionality of a structure since inter-part connections (of any type) often promote structural weakness and require additional material—ultimately manifesting as increased weight and expenditure [33].

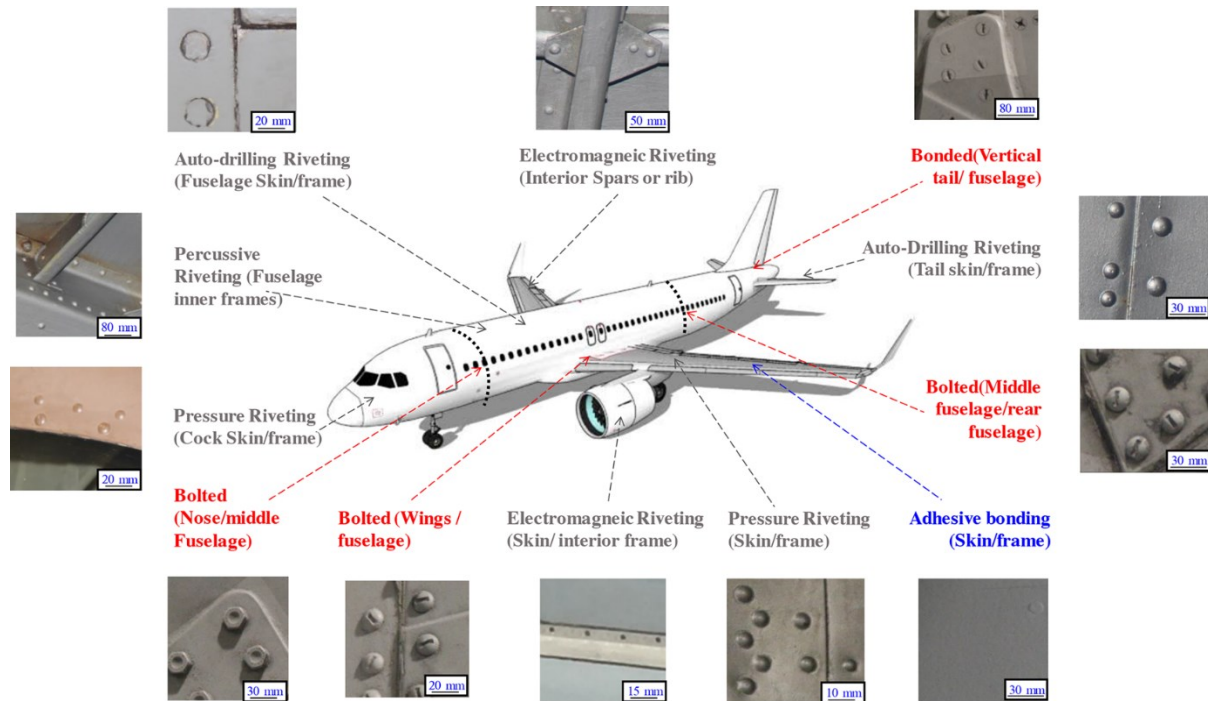


Fig. 2-1. Joining techniques frequently employed in aircraft [34].

Mechanical fastened joints using pins, rivets and bolts are the most trusted joining methods for composite structures and have commonly been used in the aerospace industry for decades [35-38], which can be formed by welds [39], rivets [40], [41], clinch joints [42], [43], or bolts [44], [45], [46]. Some examples of mechanical fastened joints are shown in Fig. 2-2. The key problem that arises from the use of mechanical fasteners is the high stress concentrations around the fastener holes which are more severe in composite laminates compared to metal plates [47]. The concentrations have the risk of causing early damage and decreasing the load carrying capacity of the joined composite structure. Adhesively bonded joints (shown in Fig. 2-3 (c)) are structurally more efficient than mechanically fastened joints as they perform better in distributing loads, eliminating a majority of the high stress concentration problems seen in bolted joints [48, 49]. Although glueing has been considered an effective alternative method,

in practical applications, adhesive bonds have quite a few defects, such as sensitivity to humidity together with peel stresses, and the lack of efficient methods for inspecting the joints [50]. Also, there is one more crucial weakness associated with bonded joints is its process control during repair applications. Improper processes would result in a weak bond that is not generally possible to be detected by means of non-destructive inspection (NDI) [51]. In order to further improve the joining performance, bolted joints and adhesive bonded joints were combined, which are called hybrid (bolted/bonded) joint [52] (shown in Fig. 2-3 (b)). However, the hybrid joint would essentially lose a big advantage of easily assembly and reassembly for bolted joint. Thus, bolted joint is an irreplaceable assembly method for thermoset composites when assembly and disassembly of the structure is essential.

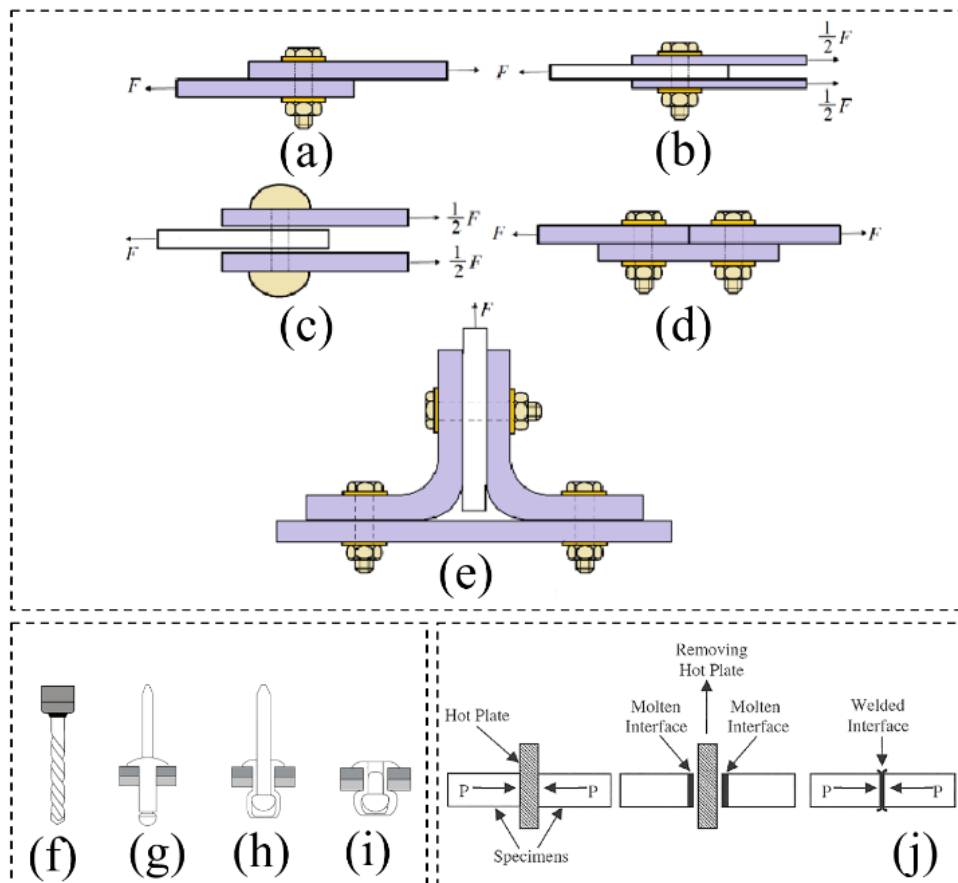


Fig. 2-2. Some basic bolted and pin joints((a) Single lap bolted joint; (b) Double lap bolted joint; (c) Pin (Riveted) loaded joint (d) Bolted butt joint (e) Bolted T- joint)[53]; Riveting mechanism (f) drill hole in joining components; (g) positioning of joining components, and

rivet insertion; (h) rivet tightening and joint consolidation through pressure; (i) a consolidated joint [54]; Schematic of the hot plate welding process (j) [55].

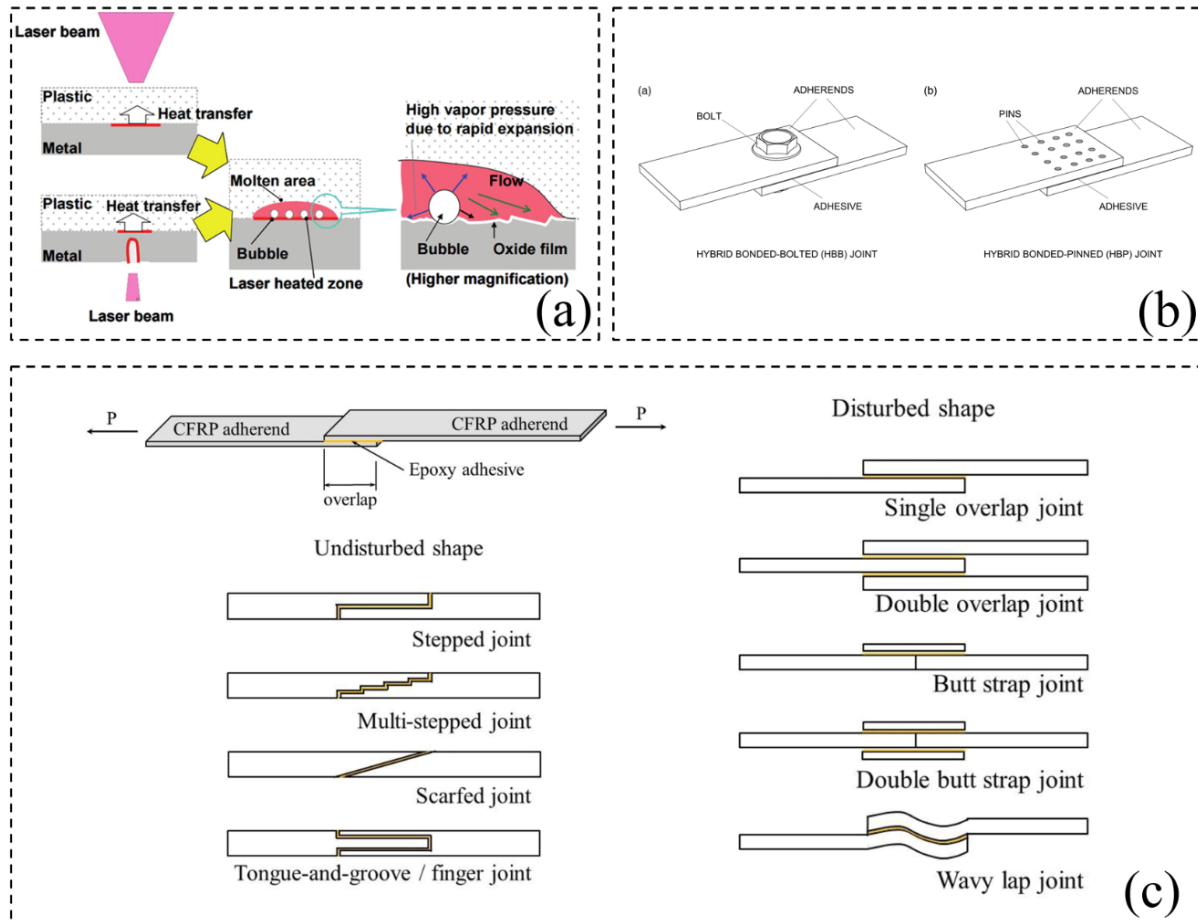


Fig. 2-3. Mechanism of (a) laser-assisted metal and plastic (LAMP) direct joining process [56]; (b) Main categories of Hybrid Bonded Fastened (HBF) joints [57]; (c) Various topologies for overlap-bonded joints [58].

The popular way to fabricate composite bolted joints is directly drilling a bolt hole in the composite laminate. However, this kind of mechanical drill leads to fibre disintegration and early failure. There is a still need to improve the components made of CFRP laminates to withstand high loads. Some researchers have achieved this by incorporating 3D printed layers into the laminate design [59-61]. Based on this concept, it is possible for the composite to have relatively higher stiffness, strength and better toughness. The stiffness and toughness of a CFRP composite can be tailored by adjusting the fibre orientation. It is important to note that optimising for both stiffness and toughness often requires a balance, as they are conflicting properties. To achieve maximum stiffness, the composite may be designed with a high fibre

volume fraction and fibres aligned in the direction of loading (principle trajectory) [62]. However, this type of design will likely result in reduced toughness (and increased brittleness), as the fibres are less able than the matrix to absorb energy and deform before breaking. On the other hand, to maximise toughness, the composite may be designed with a more random fibre orientation, which will reduce the overall stiffness of the composite.

Therefore, when designing a CFRP composite, it is necessary to strike a balance between stiffness and toughness to meet specific requirements and applications. Ultimately, the right balance between stiffness and toughness in a CFRP composite will depend on the specific requirement and goal of the application. It may take multiple design iterations and testing to find the optimal combination of fibre placement patterns that provides the desired balance of stiffness and toughness.

As mentioned above, designing bolted joints in composite structures is much more complicated than in metallic structures because of the anisotropic mechanical properties and complex failure modes of composites (shown in Fig. 2-4). Joints potentially act as weak links in structures, thus it is important to understand their strength and the mode in which they fail. During the last decades, structural design has mainly relied on experimental data using the building block approach [63], which induces extremely prohibitive costs due to a large number of experiments at each structural level. Thus, initiatives bridging the tests and analyses to reduce the design cost have become a common view in the aerospace industry [64]. Hence in recent years, the use of the finite element (FE) method to simulate the behaviour of composite joints has increased particularly due to the advancement of many FE software packages. However, most composite joint models reported so far are restricted to 3D models with homogeneous layers or 2D models [65-68]. In order to be used as a versatile design tool, especially to evaluate the joint manufactured with complex, tailored fibre placement, the FE

model needs to be able to accurately capture the three-dimensional stress states, material behaviour, load distribution, inter-laminar interactions as well as failure mode.

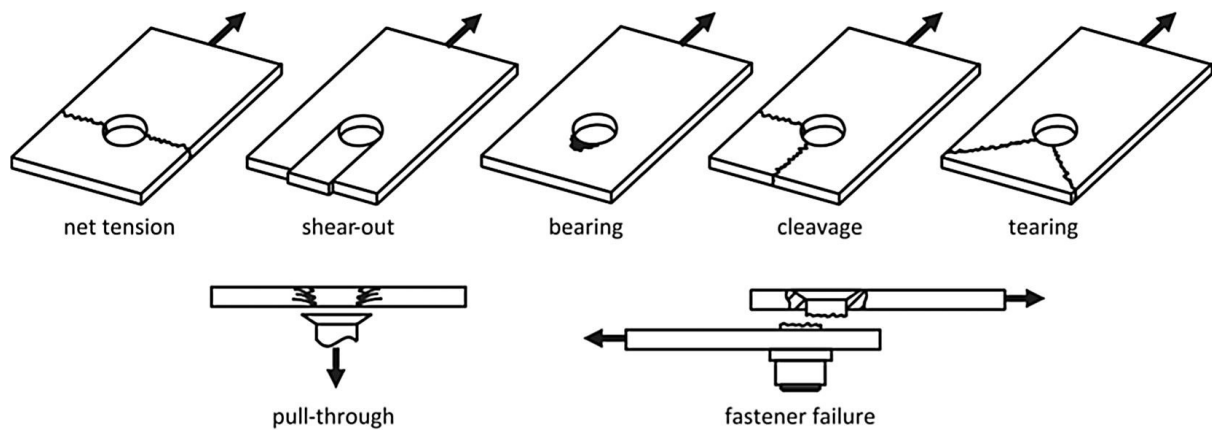


Fig. 2-4. Schematics of different failure modes of mechanically fastened CFRP joints [69].

2.3. Finite Element Modelling of Composite Failure

The research on damage and failure prediction in composite materials, especially fibre-reinforced polymer (FRP) composites, covers analytical, numerical, and experimental methods. The aim of it is to understand the failure mechanisms at different scales - micro, meso, and macro. Damage typically starts at the micro-level, progressing to catastrophic failure at the macro-level [70]. Analytical models, based on fracture mechanics and other theories, are good for initial damage prediction but lack depth in understanding damage propagation in heterogeneous materials. Numerical modelling, notably Finite Element Method (FEM), provides more detailed insights, particularly after validation with standard tests. Experimental methods, including advanced techniques like Synchrotron Radiation Computed Tomography (SRCT), complement these models but face challenges such as cost and limited testing conditions. This section reviews these approaches, focusing on FEM for virtual experimentation of damage in FRP composites across various scales, addressing the shortcomings of analytical models and enhancing understanding and prediction of composite behaviour under different loading conditions.

2.3.1. Fracture Mechanics and Continuum Damage Mechanics

Various studies have been performed on fracture mechanics and the failure of FRP composite materials, focusing on the analysis of fibre/matrix interactions and failure mechanisms. Aveston *et al.* [71] developed a shear-lag model considering matrix cracking leading to increased load on the fibres. Marshall and Cox [72] employed the stress intensity method to analyse the transition conditions between matrix and fibre failure. Budiansky *et al.* [73] focused on matrix cracking stress under different fibre conditions, incorporating energy balance considerations. Hutchinson and Jensen [74] examined fibre/matrix interface debonding, proposing an axisymmetric cylinder model and considering different friction conditions. Scheer and Nairn [75] also studied fibre/matrix interface debonding using a concentric cylinder specimen model to measure global strain energy. Liu and Nairn [76] introduced an analytical model to calculate the energy release rate from interface fracture toughness. Schuller *et al.* [77] proposed an analytical model focusing on interface friction, exploring crack extension criteria and its effects on failure processes. Kimura *et al.* [78] addressed interfacial debonding through an energy-based model, emphasizing the role of matrix plastic deformation on interfacial energy. Lastly, Bruno *et al.* [79] introduced a combined fracture and contact mechanics-based interface model to study mixed-mode delamination in composite materials, applying multilayer shear deformable plate modelling and the Lagrange multiplier method for interface displacement continuity.

These studies collectively investigate the mechanisms of fibre/matrix interactions and the failure processes within the composites. Central themes include matrix cracking, fibre/matrix interface debonding, and the energy release rate during failure. The research spans from developing analytical models to employing advanced mechanical concepts like stress intensity and multilayer shear deformable plate modelling, contributing significantly to the

understanding of composite material failure. However, these studies require further integration to achieve the prediction of damage propagation and stiffness reduction in composite structures.

Continuum Damage Mechanics (CDM) has been instrumental over the past decades in modelling the damage process in composite materials, primarily through various models [33–36] derived from limited experimental data. Chaboche [80–82] laid the groundwork for CDM, relating microstructure to mechanical behaviour and enabling analysis of deterioration in various materials under different conditions. Matzenmiller *et al.* [83], Chow and Wang [84], and Simo and Ju [85] further contributed by proposing models that explore damage mechanics in composite materials, addressing aspects like anisotropic damage, ductile fracture, and elastoplastic damage models. An example of CDM is shown with curves in Fig. 2-5.

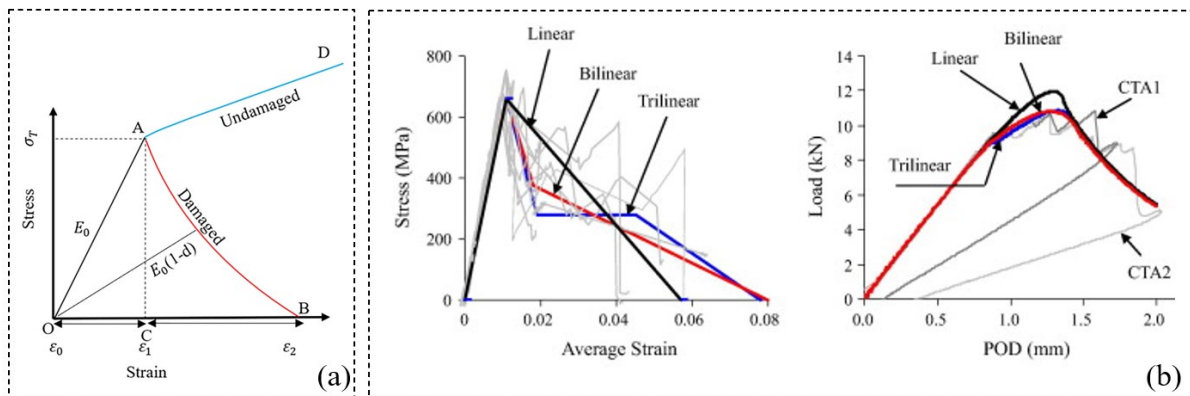


Fig. 2-5. (a) Schematic representation of stress-strain damage curve in CDM approach [86]; (b) Strain-softening curves and comparative analysis of experimental and predicted load- Pin Opening Displacement (POD) curves derived from strain-softening [87].

Maimí *et al.* [88], Hassan and Batra [89], and Okabe *et al.* [90] focused on predicting damage propagation and stiffness reduction in composite materials, employing different damage variables and models to address specific failure mechanisms. On the micromechanical front, models by Hild *et al.* [91, 92], Burr *et al.* [93, 94], Voyiadjis and Kattan [95], Bonora and Ruggiero [96, 97], Talreja [98], Varna *et al.* [99], and Raghavan and Ghosh [100] were significant. These models helped in understanding damage at a micro-scale, often overlooked

by phenomenological models, and were essential in identifying damage parameters and variables that are challenging to determine macroscopically.

These advancements in CDM, since its initial application by Kachanov [101] in metal creep rupture studies, have made it a vital method for analysing the progressive failure of composite laminates, providing insights into damage initiation and propagation under various loading conditions. Damage variables in these models are defined and measured through changes in material properties such as density, resistivity, fatigue limit, and acoustic emission [81, 102-104]. Thus, CDM has been a pivotal framework in understanding and modelling the damage processes in composite materials, with significant contributions from researchers. These models, both phenomenological and micromechanical, have advanced the ability to predict damage initiation, propagation, and stiffness reduction in composites. They integrate complex variables and parameters that are crucial in capturing the intricate failure mechanisms at both macroscopic and microscopic levels, significantly enhancing the field of composite material analysis. However, the predictive accuracy of these models is still far from sufficient for the diverse applications of composite materials, and more accurate predictive models need to be further developed based on the provisioning situation.

2.3.2. Failure Criteria for Composite Materials

The failure of fibre-reinforced polymer (FRP) composite materials is a multifaceted process, influenced by factors such as material properties, size, loading conditions, and manufacturing defects, necessitating accurate failure criteria for designing and ensuring safety [102, 105]. Various criteria exist, including strain-based [106], strain-energy-based [107], stress-based [108-111], and phenomenological approaches [112-116], yet their validation and prediction remain challenging, especially in the post-damage onset phase. The World-Wide Failure Exercises (WWFE-I, II, III) played a pivotal role in assessing these criteria under complex 3D stress states [117-124]. WWFE-I focused on strength and strain prediction in unidirectional

FRPs, highlighting limitations in addressing nonlinear deformations [119]. WWFE-II revised assessment methods for 3D stress states, indicating a lack of consensus on factors like hydrostatic pressure effects [117, 125]. WWFE-III in 2013 evaluated twelve criteria under multiaxial loading, revealing significant variability in predictions and challenges in consensus on damage propagation and the impact of lay-up and geometry [118, 123, 124]. These exercises demonstrated that no single model fully satisfies all requirements for a robust design tool, underscoring the importance of understanding various failure modes and their interactions for industrial application, despite challenges in experimental testing for data calibration. Notably, the maximum stress and strain, Tsai-Wu, Hashin, Puck, Mohr and LaRC05 failure criteria are discussed for their relative effectiveness in engineering applications, during continuous challenges in validating and predicting the strength of FRP composites.

Maximum stress and strain criteria is [126] critically evaluated for their simplicity and potential oversight of the complexities in composite materials (shown in Fig. 2-6(a)). These criteria assess failure based on the absolute maximum values of stress and strain in the material. However, a key criticism is that they may not adequately capture the multifaceted interactions in composites. This oversimplification can lead to inaccuracies in predicting material failure, as composite materials often exhibit complex behaviours under stress due to their heterogeneous nature. A more comprehensive approach is needed in failure analysis to accurately predict and understand the behaviour of composite materials under various loading conditions.

Tsai-Wu criterion [112] is a widely-used failure criterion in composite materials, that combines stress and strain factors to predict failure. Despite its popularity, this criterion is potentially not capturing all failure modes in composites. It implies that the Tsai-Wu Criterion, while effective in certain scenarios, may not fully account for the complex, multi-directional nature of stress and strain in heterogeneous composite materials. This limitation highlights the need for more

comprehensive criteria or the modification of existing ones to better understand and predict the behaviour of composites under various loading conditions.

Hashin criteria [114] is known for focusing on different failure modes in composites, considering various stress states and failure mechanisms. However, the heavy reliance on empirical data can limit its general applicability, as it may not be universally accurate for all types of composites or under all loading conditions. This reliance suggests that the Hashin criteria might be more suited for specific composite materials or scenarios where extensive empirical data is available, rather than being a universally applicable model for predicting failure in all composite material.

Puck criteria [115] is evaluated for their empirical nature, which can affect their objectivity. This criterion is designed to address different stress states in composite materials. However, the concern raised is that the Puck criteria's reliance on empirical data might lead to a lack of objectivity in its application. This means that while the criteria can be effective in specific scenarios where the empirical data closely matches the material and loading conditions, it may not be as reliable or accurate in situations where such data is not as closely aligned. This highlights a potential limitation in the universal applicability of the Puck criteria for predicting failure in diverse composite materials under varying conditions.

Mohr criterion [127] is acknowledged for considering different stress states in its formulation. However, the simplifications made in stress interactions according to this criterion can limit its applicability to composite materials. The Mohr criterion (shown in Fig. 2-6 (c)), traditionally used in metal and soil mechanics, may not fully capture the complex stress interactions and failure mechanisms inherent in composite materials. This limitation is particularly relevant because composites, unlike homogeneous materials, exhibit a wide range of behaviours due to their anisotropic and heterogeneous nature. Therefore, while the Mohr criterion provides a

fundamental understanding of stress states, its simplifications might not be sufficient for accurately predicting failure in the more complex realm of composite materials.

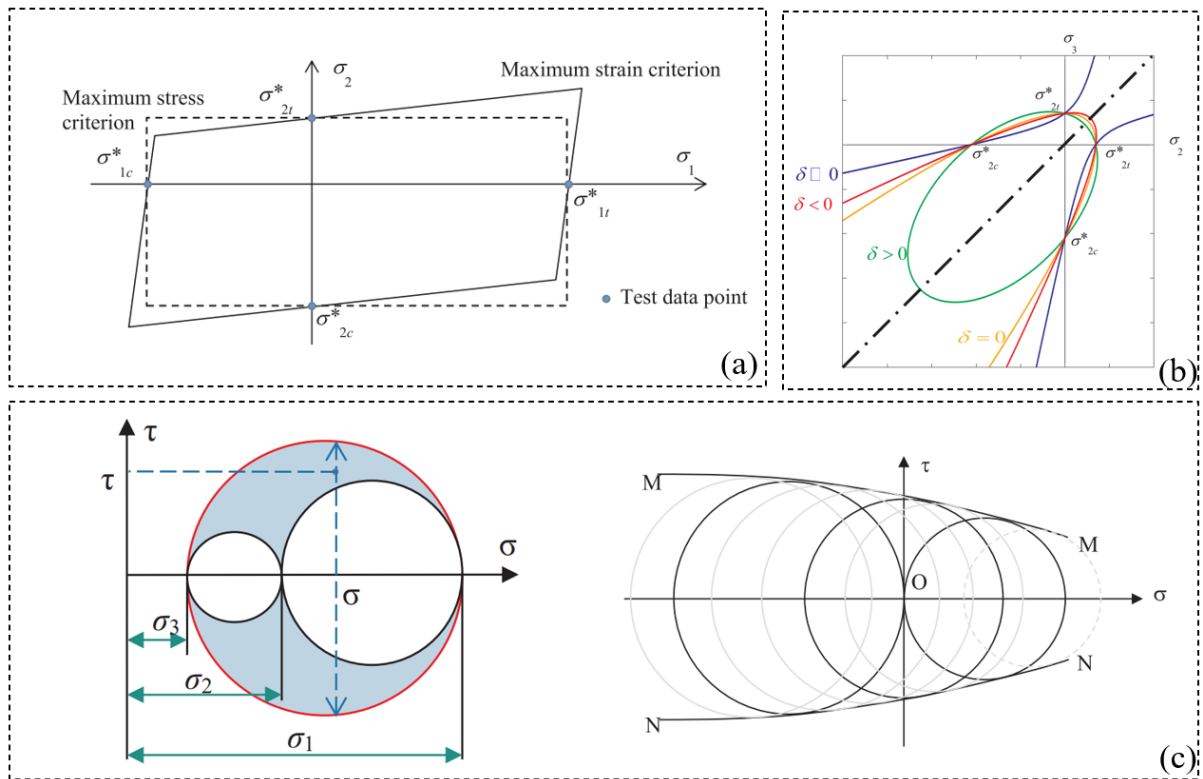


Fig. 2-6. (a) Failure envelopes in the stress plane: Comparison of maximum stress and maximum strain criteria; (b) Failure loci in plane direct stresses transverse to fibres; (c) Mohr's circles for 3D stress state and failure envelope of the Mohr criterion [128].

LaRC05 failure criterion [129], developed by NASA, is designed to integrate various factors in assessing the failure of composite materials (shown in Fig. 2-7). It focuses on a three-dimensional constitutive law predicting failure in laminated composites and integrates experimental data on non-linear constitutive response, particularly in shear, transverse, and through-thickness directions. The study employs secant stiffnesses dependent on hydrostatic pressure and general strain state. The failure criteria include matrix failure, fibre kinking, and fibre tensile failure, using in-situ strengths for matrix failure. This approach is significant for its comprehensive view of the failure mechanisms in composite materials, providing a more accurate prediction of the material response under various loading conditions. The model accounts for the fracture energy of each failure mode, considering crack accumulation in plies

for matrix failure. The study's significance lies in predicting triaxial failure envelopes and stress-strain curves in various test cases, contributing to understanding composite material behaviour under complex loading conditions. The research employs dimensional analysis and case studies for simulation, providing insights into the composite's mechanical response under varied conditions.

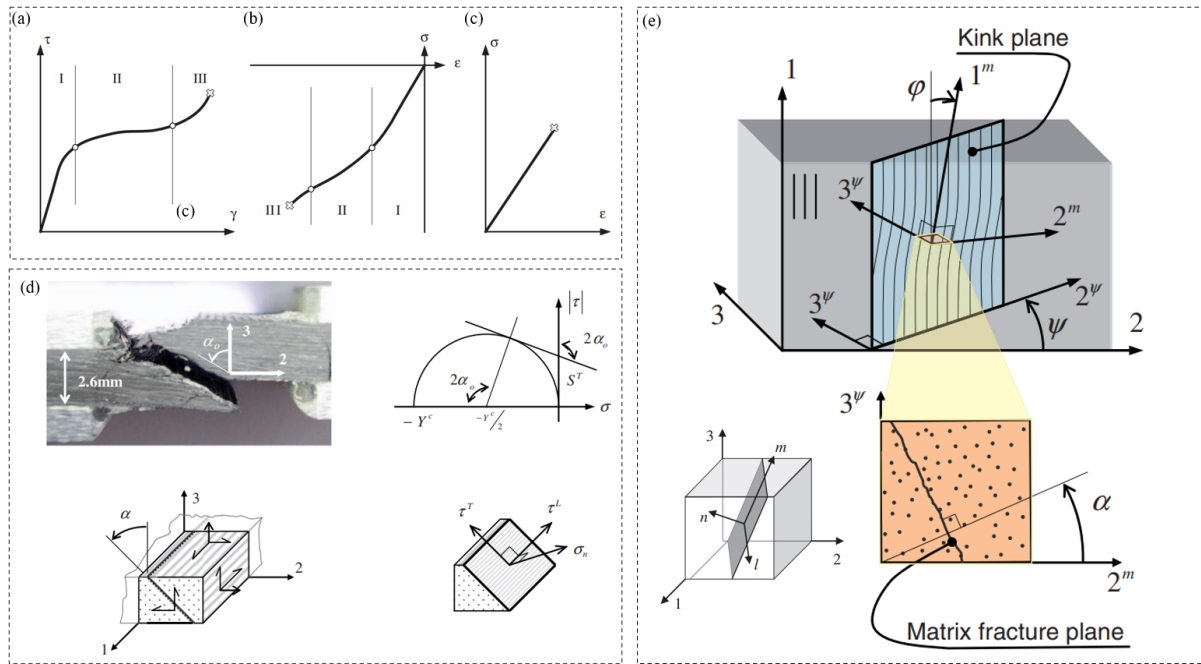


Fig. 2-7. The typical response of a polymer: (a) Three regions in a shear curve; (b) Compressive loading and (c) brittle response in tension; (d) Components of traction acting on the fracture plane in the matrix; (e) Physical modelling of kink-band formation [129].

2.3.3. Finite Element Models

Damage progression in fibre-reinforced polymer (FRP) composite materials is a complex, time and path-dependent process involving crack initiation and propagation. While analytical damage models and failure criteria can predict stress conditions for damage initiation and single damage mode propagation in homogeneous materials, they struggle to provide dynamic information on crack propagation in composites due to varying mechanical properties and internal microstructures. One of the numerical methods, the Finite Element Method (FEM),

has become increasingly important in damage analysis and modelling failure in composites. FEM, with its rigorous foundation, is widely used in academia and industry for damage and failure analysis of engineering materials, including polymers and FRP composites.

Bridging the gap between analytical models and real-world composite behaviours, FEM stands as a crucial tool in the comprehensive analysis of damage and failure mechanisms, specifically across the micro-, meso-, and macro-scale dimensions of composite materials. The micro-scale computational micromechanics, such as Representative Volume Element (RVE) modelling, delves into deformation and fracture mechanisms considering phase geometry and distribution, as highlighted in studies by Asp *et al.* [130], and Trias *et al.* [131]. At meso- and macro-scales, damage mechanics models focus on laminates as distinct damageable components [132, 133], employing techniques like cohesive models and the Virtual Crack Closure Technique (VCCT) to address delamination, as seen in the works of Camanho *et al.* [134, 135] and Liu *et al.* [136]. Further, studies by Liu *et al.* [137, 138] and Chen *et al.* [139] explore progressive failure and strain-softening in CFRP laminates. Underpinning these efforts, Llorca and colleagues [140, 141] propose a multiscale strategy, offering a holistic view of composite behaviour from microscale to macroscale, essential for understanding and predicting material performance in structural applications.

This section reviews recent research work (shown in Table 2-1) regarding the damage modelling and failure analysis of composites under various loading conditions using FEM, across micro-, meso-, and macro-scale levels.

Tan's study [142] provides a composite damage model that accounts for both intralaminar (matrix and fibre-dominated damage) and interlaminar (delamination) damage, demonstrating a high degree of capability in predicting impact damage and compression-after-impact (CAI) strength. The 3D model incorporates a modified maximum strain criterion for the fibre and modified Puck's criterion for the matrix. The research utilizes the surface-based cohesive

behaviour in ABAQUS/Explicit to capture delamination, employing a bilinear traction-separation relationship and a quadratic stress criterion for failure initiation. Delamination propagation follows the Benzeggagh-Kenane (B–K) criterion. The cohesive zone model is used to accurately represent tractions ahead of the crack tip, which is crucial for modelling the cohesive connections without the need for defining additional cohesive elements. The finite element model used in the simulations was validated against experimental data, with the damage model implemented as a VUMAT subroutine in ABAQUS. The simulations were executed in three steps: capturing the impact damage, stabilizing the specimen, and predicting the CAI strength.

Matrix cracking emerged as the dominant form of intralaminar failure for the range of impact energies investigated, with little evidence of fibre breakage. Delamination tended to propagate along the fibre orientation, and the predicted delamination areas showed good agreement with experimental results. The damage envelopes for intralaminar matrix damage developed parallel to the fibre orientation. It is found that the absorbed energy during impact is mainly dissipated in the form of intralaminar matrix damage, fibre-dominated damage, delamination, and impactor-laminate and ply–ply friction. The model captured the qualitative and quantitative aspects of intralaminar and interlaminar damage, as well as the permanent indentation of the laminates post-impact, which influences the CAI response. In summary, the study's composite damage model is a significant advancement in predicting and understanding the damage behaviour of composite materials under impact and post-impact conditions, providing insights into the mechanical performance improvements achievable through various damage criteria and evolution modes, executed at different dimensional levels, and applied to specified simulation cases.

The progressive failure simulation of 3D angle-interlock woven composites under uniaxial tension was conducted by Liu *et al.* [143]. The research focuses on developing a macro-scale

progressive damage model, based on a mesoscale representative volume cell (RVC) model, (example shown in Fig. 2-8 (a) (b)) using the inhomogeneous finite element method. A multi-scale modelling approach was developed, incorporating a modified Puck criterion for fibre yarn and a parabolic yield criterion for the matrix to simulate fibre breakage, inter-fibre fracture, and matrix cracking. The model's accuracy is validated through uniaxial tensile tests, comparing experimental and numerical results. This comparison shows a close correlation, affirming the model's predictive capability regarding the tensile effective elastic properties, failure strength, and damage evolution process. Additionally, the paper extensively discusses the damage initiation and development in 3D woven composites, highlighting the role of the matrix in initial damage and the subsequent fibre yarn breakage leading to overall failure. This research enriches the discipline by effectively combining experimental methods and finite element analysis, providing a more comprehensive understanding of the damage mechanisms in 3D woven composites.

The work from Chen *et al.* [144] examines the impact resistance and damage mechanisms of composite laminates composed of carbon, glass, and basalt fibres under low-velocity impacts. For the modelling part, the study employs finite element analysis (FEA) to investigate the effects of fibre hybridisation and fabric structures on deformation processes in composite laminates. Strain-based 3D Hashin damage criteria and linear damage evolution models were used to represent the components within the composites. The study distinguishes between intraply fibre and matrix failure, described by the CDM approach, and interply delamination, depicted by the cohesive zone model. The simulation covers various hybrid and non-hybrid laminate configurations. It analyses cases like carbon layers as the core or skin, and the incorporation of basalt or glass fibres. The FEA model is validated through comparisons with experimental results, focusing on force-displacement curves and damage patterns. The study

concludes that the stacking sequence and hybridisation significantly influence the impact resistance and damage development, with certain configurations offering superior performance.

A comprehensive multiscale progressive damage modelling methodology for 3D woven composites was presented by Shah *et al.* [145]. This methodology integrates various scales, from micro to macro, to accurately simulate damage response under different loading conditions. The study focuses on the behaviour of 3D woven composites made of thermoset and thermoplastic matrices. The model employs continuum damage mechanics, where the damage modelling framework incorporates damage initiation and evolution criteria for different components of the composite. For impregnated yarns, damage initiation is determined using modified three-dimensional quadratic failure criteria (Hashin 3D failure criteria), while the matrix follows a modified von Mises failure criteria. The damage evolution is modelled using linear and multilinear laws for yarns and matrices, respectively. The modelling is conducted on multiple scales - micro, meso, and macro. The micro-scale focuses on individual fibre and matrix properties, the mesoscale handles the composite unit cell, and the macro-scale deals with the overall composite structure. The methodology is validated through simulations of quasi-static tensile and compression tests, as well as dynamic low-velocity impact tests. Both thermoset (epoxy) and thermoplastic (Elium) 3D woven composites are considered. This study offers significant insights into the damage behaviour of 3D woven composites, enhancing the understanding of their mechanical properties under various loading conditions.

Kok *et al.*'s research [146] demonstrates an in-depth analysis of Advanced Placed Ply (AP-PLY) composites, focusing on their tensile behaviour. The study utilizes a multiscale numerical modelling framework to investigate the mechanical response of these composites, incorporating 3D Hashin failure criteria and parabolic yield criteria. The research is conducted both experimentally and numerically, providing a comprehensive knowledge of the behaviour of AP-PLY composites under tensile loads. The study's focus is on understanding the impact

of through-thickness fibre undulations on the composites' properties and optimizing the fibre placement pre-forming process for structural applications. The detailed numerical models developed in this study contribute meaningful observations to the design and application of AP-PLY composites in various engineering fields.

Wang, Qin [147] 's project explicates a detailed study on the failure mechanisms of composite bolted joints (shown in Fig. 2-8 (c)). The study employs Hashin's criteria for fibre fracture and a Mohr-Coulomb-based criterion for matrix cracking, providing a refined method for predicting the onset of different damage types in composite materials. The damage evolution follows a linear degradation law, enhancing the accuracy of the model. The research was conducted in a three-dimensional space, adding depth to the traditional two-dimensional analyses. This comprehensive approach allows for a more accurate representation of practical situations in composite bolted joints. The article simulates double-lap bolted joints under quasi-static tensile loading, an essential case in the structural integrity of composite materials. This simulation helps in understanding the behaviour of composite joints under real-world loading conditions. The study reveals the critical role of matrix cracking in initiating joint damage, which subsequently triggers fibre fracture and interface delamination. These insights are crucial for designing more resilient composite bolted joints.

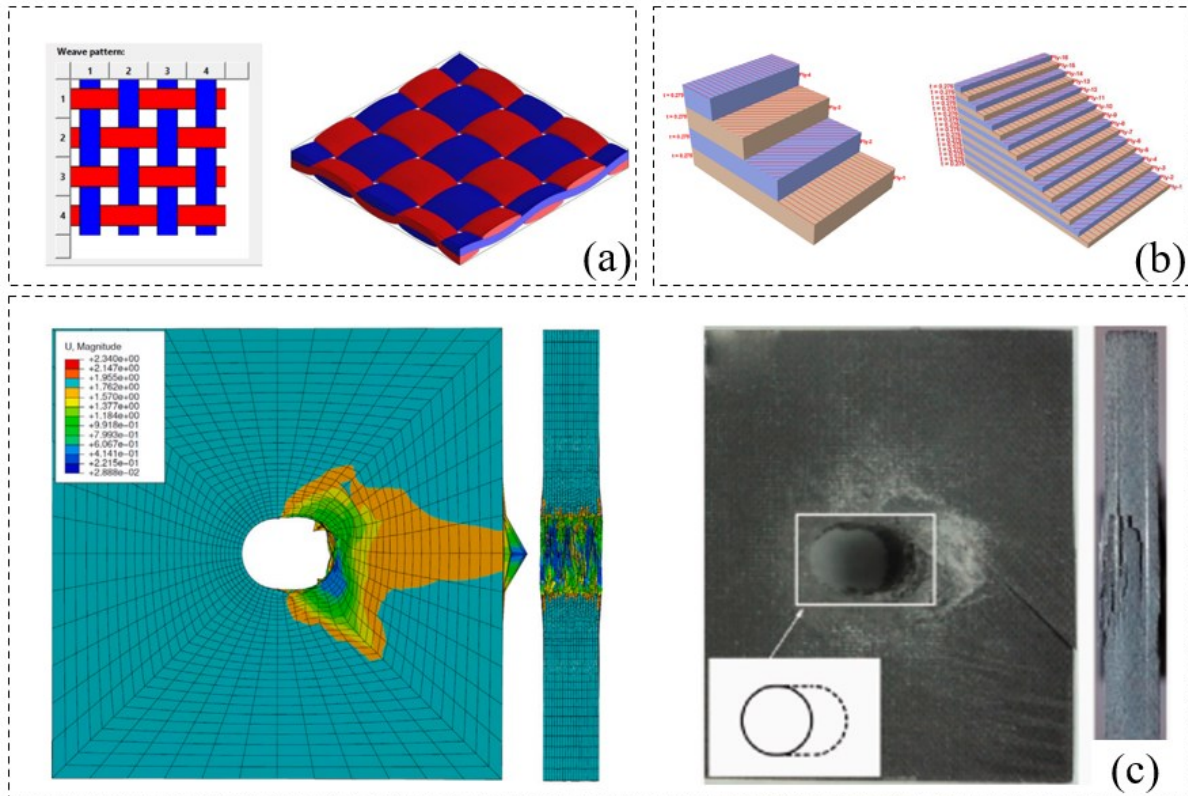


Fig. 2-8. (a) Pattern of weave and periodic geometry; (b) Laminated model in Abaqus displaying ply stack plot[148]; (c) Morphological analysis of failure in the double-lap joint: top and side views comparison between simulation and experimental results [147].

A 3D printed continuous carbon fibre composite was simulated by Avanzini *et al.* [149]. The work focuses on modelling using the Embedded Elements (EE) technique in Abaqus/CAE software (shown in Fig. 2-9 (a)). However, the study didn't enable damage criteria or evolution models for composite components and was unable to simulate damage. The model could only focus on the effective representation of fibre and matrix layout using the EE technique. The research is conducted in a three-dimensional space, considering complex geometries and fibre deposition patterns that are characteristic of 3D printed composites. The simulated cases were tensile tests on standard and multi-notch specimens. These cases were designed to assess the stiffness characteristics of the composites, focusing on different fibre layouts and complex specimen geometries. The study validates the EE modelling technique against experimental results, emphasising its effectiveness in replicating the mechanical behaviour of 3D printed composites. This approach allows for a more accurate representation of fibre-matrix

interactions in complex geometries, revealing aspects of the effective use of 3D printing technology in composite material fabrication.

The work from Hohe *et al.* [150] focuses on validating Puck's failure criterion for carbon fibre reinforced polymer (CFRP) laminates under various temperature conditions. The research applied Puck's criterion for failure analysis of CFRP laminates, considering multiaxial mechanical loading situations in both ambient and cryogenic thermal regimes. Experiments are performed on angle ply laminate specimens featuring holes and tapered sections at ambient temperature and in a cryogenic environment (4.2 K), using liquid helium. This study unveiled the details of the application of Puck's criterion under varying thermal conditions for CFRP laminates.

Zhao *et al.* [151] thoroughly investigates the mechanical characteristics of carbon fibre reinforced polymer (CFRP) composites under bending. The study integrates a micro-mechanical model for intralaminar damage and a cohesive zone model for interlaminar damage. It combines matrix cracking, fibre breakage, and delamination as key damage mechanisms. Both microscale and mesoscale models were employed in this research, enhancing the understanding of damage at different structural levels. This multiscale approach is crucial for accurately capturing the complex behaviour of woven CFRP under bending load. Simulations focus on three-point bending tests, a fundamental situation for assessing the flexural behaviour and strength of CFRP composites. The study contrasts quasi-static with dynamic loading conditions, revealing critical insights into the material's performance under different stress rates. This comprehensive modelling approach, combining different scales and damage mechanisms, provides a deeper understanding of the mechanical behaviour of CFRP composites, essential for applications where bending loads are prevalent.

In the work from Divse *et al.* [152], the damage of Fibre-Reinforced Polymer (FRP) laminates was simulated by using the LaRC05 failure criteria and a 3D progressive damage model (PDM),

the research addresses complex damage behaviours such as fibre kinking and pre-existing damage under open hole compression (OHC) tests. Various laminate layups and hole sizes were tested, revealing the impact of pre-existing damage on laminate strength. This model, validated through single-element tests, offers valuable insights into the failure mechanisms of FRP composites, particularly in terms of fibre kinking and matrix cracking, under different layup configurations and loading conditions.

An advanced method for simulating composite materials was introduced by Wang *et al.* [153]. The study used Artificial Neural Networks (ANNs) in conjunction with the LaRC05 failure criterion, a method known for its intensive computational requirements. By integrating ANNs with a Golden Section Search algorithm, the researchers significantly speeded up the failure initiation and fracture angle calculations. This novel approach is tested using ABAQUS software on various composite materials under shear load conditions. The results demonstrate the model's capability to accurately predict crack paths while substantially reducing calculation time. This technique represents a considerable advancement in composite material simulation, offering both efficiency and accuracy in failure prediction.

The study by Li *et al.* [154], focuses on modelling wrinkle defects in composite materials during the consolidation process. The research didn't manage to capture the failure behaviour of the composite. Instead, it concentrates on the simulation of wrinkle defects using an embedded digital element model (shown in Fig. 2-9 (b)). The research is conducted in a three-dimensional context, which is crucial for accurately representing the complex behaviour of composite materials during consolidation. The consolidation process of prepreg materials was simulated and the formation of wrinkles in flat plates and L-shaped structures was specifically focused. This helps in understanding the behaviour of composite materials under practical manufacturing conditions. The study's main contribution lies in its innovative approach to

simulating the complex process of wrinkle formation in composites, enhancing the understanding of manufacturing defects in these materials.

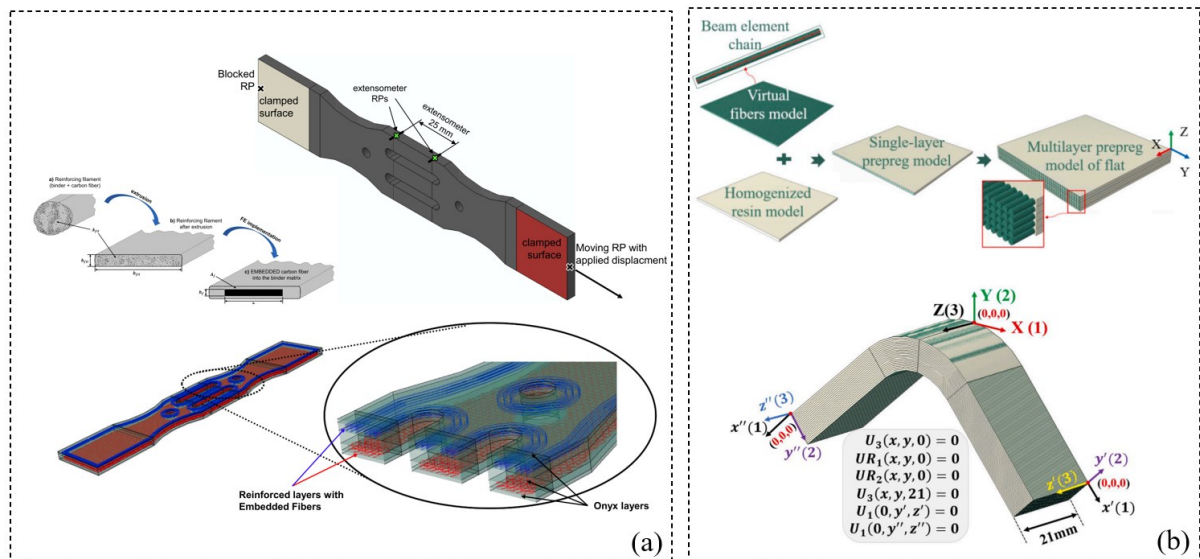


Fig. 2-9. (a) Continuous carbon fibre filament: comparison of raw 3D printed filament and idealised cross-section of embedded element representing extruded filament, continuous carbon fibre filament: comparison of raw 3D printed filament and idealised cross-section of embedded element representing extruded filament and illustration of specimen partitioning and fibre embedding strategy, featuring a mixed configuration of the multi-notch specimen [149]; (b) Schematic representation of the Embedded Virtual Fibre Model and the layer-by-layer modelling of UD prepreg in flat plate configuration, alongside the Virtual Fibre Multilayer Prepreg Model for L-shape with boundary conditions[154].

Table 2-1 Summary of multiscale damage models in existing literature

Fabric architecture	Scale-level	Fundamental unit	Damage initiation in fibre/yarn scale-level	Damage evolution	Damage initiation in matrix	Damage evolution	Case	Ref.	Year
3D woven composite	Macro	Laminate layer	Maximum strain criteria	Linear	Modified Puck's criterion	Linear	Impact	[142]	2015
3D woven composites	Multi-scale	Filament (RVE)	Modified Puck criterion	Exponential	Parabolic yield criterion	Exponential	Uniaxial tension	[143]	2019
Interlayer hybrid composite laminates	Macro	Laminate layer	Strain-based 3D Hashin criteria	Linear	Strain-based 3D Hashin criteria	Linear	Impact	[144]	2019
3D woven composites	Multi-scale	Filament (RVE)	Modified three-dimensional quadratic failure criteria (Hashin 3D failure criteria)	Linear	A modified von Mises failure criteria	Linear	Static tension and compression and impact loads	[145]	2021

AP-PLY composites	Multi-scale	Filament (RVE)	3D Hashin failure criteria	Linear	Parabolic yield criterion	Linear	Uniaxial tension	[146]	2022
QI laminate	Macro	Laminate layer	3D Hashin failure criteria	Linear	Mohr-Coulomb based criterion	Linear	Double-lap bolted joint	[147]	2022
3D printed continuous carbon fibre composites	Meso	Fibre	N/A	N/A	N/A	N/A	Tension	[149]	2022
CFRP laminates	Macro	Laminate layer	Puck's criterion	Linear	Puck's criterion	Linear	Multiaxial loads	[150]	2022
Woven CFRP composites	Multi-scale	Filament	3D Hashin	Linear	Maximum principal stress failure criteria	Linear	Three-point bending	[151]	2023
Laminates	Macro	Laminate layer	LaRC05	Linear	LaRC05	Linear	Double-lap bolted joint	[152]	2023
UD/QICFRP laminates	Macro	Laminate layer	LaRC05	N/A	LaRC05	N/A	Shear load	[153]	2023
CFRP laminates	Meso	Fibre	N/A	N/A	N/A	N/A	Wrinkle defects	[154]	2024

Based on the recent simulation studies reviewed, it is evident that few have focused on modelling composites with filaments as the fundamental unit. Those that have, typically rely on representative volume elements (RVEs) and eventually resort to homogenisation to study structures at the macro-scale. Additionally, methods in these studies that simulate the mechanical effects of individual filament orientations and distributions typically capture only the elastic mechanical properties of the composite structures, failing to model the subsequent damage and fracture evolution. Furthermore, there is a predominant focus on modelling tension failure, while comparatively fewer studies have addressed composite joints, often limiting their analyses to the macro-scale. This presents a significant gap, particularly for those aiming to simulate advanced composites manufactured through additive manufacturing methods. There is an urgent need for research in this area to better align with the current trends and demands in advanced composite fabrication. This calls for further investigation and highlights the importance of developing comprehensive models that can accurately represent the intricate

behaviours of filament-based composites, especially in the context of additive manufacturing techniques, which are becoming increasingly prevalent in the field.

2.4. Composite Repair

In conventional fabrication techniques, such as autoclave and resin transfer moulding, CFRPs are usually manufactured using a layered lamination technique [155, 156]. In this process, reinforcing fibres are layered to achieve the requisite thickness and are bonded together using a matrix material, typically an epoxy resin. This thermosetting resin requires meticulous curing to achieve a brittle yet robust bond. Nonetheless, the matrix material, typically a thermoset, offers superior heat resistance compared to thermoplastics but tends to be mechanically more brittle. This brittleness causes the thermoset composite to be more prone to cracking, which often propagates, leading to fractures[157]. Consequently, maintaining CFRP presents continuous challenges and special repair treatments are required [158]. Many researchers have developed particular repair methods aiming to meet various repair requirements.

The most commonly employed repair method involves removing a substantial portion of the damaged composite material and then directly joining it with a new as demonstrated in the industrial repair procedure illustrated in Fig. 2-10 (a). A typical joining repair features excision of the damaged area, followed by riveting and bolting (shown in Fig. 2-10 (b)). However, such repair creates holes in the composite and increases stress concentrations around the cracked area [159, 160].

Another method is bonded repairs, such as scarf and lap joint repairs. Bonded repairs are often preferred for primary (flight-critical) components as they are lighter and more aerodynamic, not requiring mechanical fasteners. However, bonded repairs are restricted to non-critical damage at limit/service load, adhering to conservative fail-safe requirements. This ensures that the structure retains sufficient reserve strength to complete a flight safely, even if the patch

bond fails [161, 162]. Consequently, there has been significant research focused on the behaviour and strength performance of stepped or ramped scarf repairs with small scarf angles [163-165]. Certified repair schemes are limited to a small range of joint designs, typically axisymmetric or plane-symmetric, supported by extensive experimental data and flight experience [163, 165, 166].

Most of the current studies, no matter which type of repair, are trying to reduce healthy material removal and the reason is that smaller repairs include less intrusion into the parent structure, reduced preparation and fabrication time, simpler lay-up and curing procedures, decreased inspection time, and lower likelihood of quality issues. Additionally, maintaining aerodynamic cleanliness and minimizing disturbance to the structure's original load path are crucial, especially to avoid unwanted failure modes due to load eccentricities. In the case of composite control surfaces like flaps and ailerons, which have critical mass balance limitations, the smaller, lighter weight flush scarf repair is often the only acceptable repair method [167].

In this section recent study of the repair method and their application are summarised in Table 2-2 and the details of them are following:

The work from Liao *et al.* [168] focuses on the numerical investigation of the load-bearing capacity and damage level of double scarf joints (DSJs) under combined tension and bending loadings. The study employs a FEM incorporating a mixed-mode cohesive zone model (CZM) with a bilinear shape, considering factors like scarf angle and adhesive type. It was found that the interface damage level in DSJs with ductile adhesive was higher and more uniform compared to those with brittle adhesive. The failure of DSJ was influenced by both the ultimate loading and the applied displacement until complete failure. The study introduces the concept of failure energy (integral of loading with respect to displacement) as a metric for joint performance. It was found that the failure energy of joints with ductile adhesive is higher. The parameters such as ultimate loading, von-Mises equivalent stress, and interface damage level

at ultimate loading, along with failure energy, were inversely proportional to the scarf angle. The paper validates the simulation method against existing experimental measurements, ensuring the reliability of the numerical approach. This numerical method provides a thorough comprehension of the performance of adhesive joints under complex loading conditions, contributing significantly to the field of adhesive joint analysis, particularly relevant for industries like aerospace and automotive where such joints are frequently applied. This study's insights into the behaviour of different adhesives under stress and the innovative use of failure energy as a performance measure are particularly noteworthy for practical applications and further research in adhesive joint technology.

The article from Wu *et al.* [169] presents a comprehensive study on the damage tolerance of composite scarf and stepped-lap joints using FEA. The research investigates various parameters influencing the damage tolerance of these joints, including flaw size, material anisotropy, adhesive properties, and environmental conditions. Scarf joints with composite laminates exhibit non-uniform stress distribution due to the orientation of 0° plies. Conversely, the stress distribution in stepped-lap joints is less affected by the anisotropy of adherents. In the study, both scarf and stepped-lap joints show a decrease in strength with increasing flaw size. Notably, the damage tolerance of these joints becomes similar with increasing nonlinearity of the adhesive. It was observed that damage tolerance can be enhanced by out-of-plane constraint or composite doubler reinforcement. The adhesive's plasticity contributes positively to damage tolerance. Additionally, the number of steps in stepped-lap joints is a critical factor affecting damage tolerance. Thus, optimal damage tolerance can be achieved by carefully considering the step number and adherend stacking sequence. While scarf joints have higher absolute strength, stepped-lap joints offer better damage tolerance, making them preferable in designs where damage tolerance is a primary concern. The study emphasises the importance of considering various parameters in the design of composite joints and repairs,

highlighting the potential for optimisation based on specific application requirements. The conclusions are based on FEA and suggest the need for experimental validation to further understand and confirm these behaviours in practical conditions.

A novel approach was developed by Kim *et al.* [157] to repair CFRPs by using a 3D printing technique. The study compares the effectiveness of this technique with traditional hand lay-up repairs by evaluating tensile strength. Key results show that for different lap lengths (50 mm, 25 mm, and 12.5 mm), the 3D printed repairs exhibit fracture loads that are similar or slightly higher than hand lay-up repairs. For instance, at a 50-mm lap length, the fracture loads for 3D printed and hand lay-up repairs were approximately 7737 N and 7695 N, respectively. These findings suggest that 3D printed repairs can restore about 80% of the undamaged CFRP's strength, demonstrating the potential of 3D printing for efficient and effective CFRP repairs.

The article by Emna Ghazali *et al.* [170] focuses on the mechanical performance of adhesively bonded repairs in sandwich panels, which are composed of carbon-epoxy composite skins and a Nomex core. The study examines the behaviour of both pristine and repaired panels under tensile loading at room temperature. The two material models for the adhesive joint (linear elastic and elastic-plastic with shear failure criterion) and an orthotropic linear elastic model for the composite skins were developed. The numerical model predictions align closely with experimental results, indicating a successful model validation. The strength recovery of the repaired structure increases as the scarf angle decreases. Detailed examination of the failure mode and pattern in sandwich panels, noting that the common failure mode for all tested repaired specimens was the failure of the adhesive joint. The paper's contribution lies in its comprehensive approach to understanding the performance of repaired sandwich panels and in developing effective models for predicting their behaviour. This is significant for applications in fields where the durability and repairability of composite sandwich structures are critical, such as aerospace.

The study performed by Psarras *et al.* [171] explores the effectiveness of various bonded repair procedures on CFRPs. It focuses on two types of bonded repairs: the soft/wet patch and the hard/dry patch approach, with material removal performed through conventional machining and laser ablation. The research investigates three repair configurations (laser ablation with a wet patch, milling with a wet patch, and laser ablation with a dry patch) and compares them to pristine specimens in terms of tensile strength and stiffness recovery. It reveals that the laser/dry repair method yields the highest recovered strength and stiffness, followed by milling/wet, with laser/wet repair having marginally lower recovery percentages. On average, 67% of ultimate tensile strength and over 95% of stiffness were recovered. The highest recovered strength was 69% in laser dry specimens, with milled wet repair specimens following at 68%. The laser wet specimens had a recovered strength of 65%. Finite Element (FE) models were developed and validated against experimental results to predict the mechanical behaviour of repaired elements and support the design and implementation of bonded repairs on composite aeronautical structures. The study concludes that both material removal methods can achieve the desired repair geometries and dimensions, with laser machining providing smoother surface quality. The findings suggest potential for further improvements in repair efficiency by modifying repair shape, scarf ratio, or adhesive type, indicating a promising avenue for future research and application in the field of composite material repair.

Focusing on advanced repair techniques for composite materials, specifically scarf repairs, the research by Pitanga *et al.* [171] addresses the challenges of conventional scarf repairs which require large repair sizes due to small taper angles, leading to significant stress concentrations and potential for further damage. The paper introduces an innovative approach to reduce the repair footprint by optimising the taper profile across the composite thickness. The authors proposed a method where the scarf angles vary according to the ply angle in the composite, allowing for a more efficient repair size. Experiments were performed with piece-wise linear

scarf joints, where 0° plies are tapered at different ratios compared to 45° and 90° plies. This method showed promising results in achieving significant tensile strength (up to 75% of a straight scarf) while reducing repair size by about 60%. The study also involves a detailed analysis of failure stress, fracture modes, and the adhesive's role in the repair strength. It demonstrates that optimised scarf joints, when compared to straight scarf joints, exhibit different failure mechanisms and stress distributions, leading to varied performance outcomes. The implications of this research are significant for the field of composite material repairs, particularly in aeronautics, where efficient and effective repair methods are critical. The findings suggest that by altering the scarf design, it is possible to achieve a more effective repair with a smaller footprint, which is essential for practical applications where space and material removal are constraints. This research contributes to the understanding of composite material repairs and presents a novel approach that could lead to more effective and efficient repair methods in various industrial applications.

Damghani *et al.* [172] explore a new repair method for CFRPs known as Variable Length Stepped Scarf (VLSS) repair (shown in Fig. 2-10(c)). This method aims to minimize the removal of healthy material while restoring the structural stiffness and strength of the damaged CFRP. The study involves experimental testing and FEA to evaluate the performance of the VLSS repair compared to traditional methods. Key findings include the VLSS repair's ability to restore approximately 95% of the stiffness of the pristine structure, with a strength repair efficiency of 64%. The research demonstrates that VLSS is a promising alternative for CFRP repairs, offering efficient material use and significant restoration of mechanical properties and it suggested a need for improved bonding between the repair patch and parent laminate.

In the work from Li *et al.* [173], the focus is on the innovative use of 3D printed patches to repair open holes in CFRP thermoplastic laminates (shown in Fig. 2-10(d)). This research is pivotal in the field of composite material repair, providing insights into the potential of 3D

printing technologies in enhancing the mechanical properties of damaged CFRP structures. The article employs experimental and simulation methodology to assess the efficiency of repairs. By investigating various scarf angles, the study aims to determine the most effective configuration for patch repair. The primary loading type utilised in the study is tensile loading, which is crucial for understanding the mechanical behaviour of the repaired laminates under operational conditions. One of the key outcomes of this research is the detailed analysis of repair efficiency, both in terms of stiffness and strength recovery. This aspect is crucial as it provides a quantitative measure of the effectiveness of the 3D printed patches in restoring the original mechanical properties of the CFRP laminates. The distinction between thermoset and thermoplastic materials in the context of CFRP laminates is also explored, offering valuable insights into the material-specific repair strategies. This study contributes significantly to the field of composite materials, particularly in understanding the role of 3D printing technology in repairing and enhancing the structural integrity of CFRP laminates. The findings have implications for the development of more efficient and reliable repair methods for composite materials based on 3D printing, which are increasingly used in various industries, including aerospace and automotive.

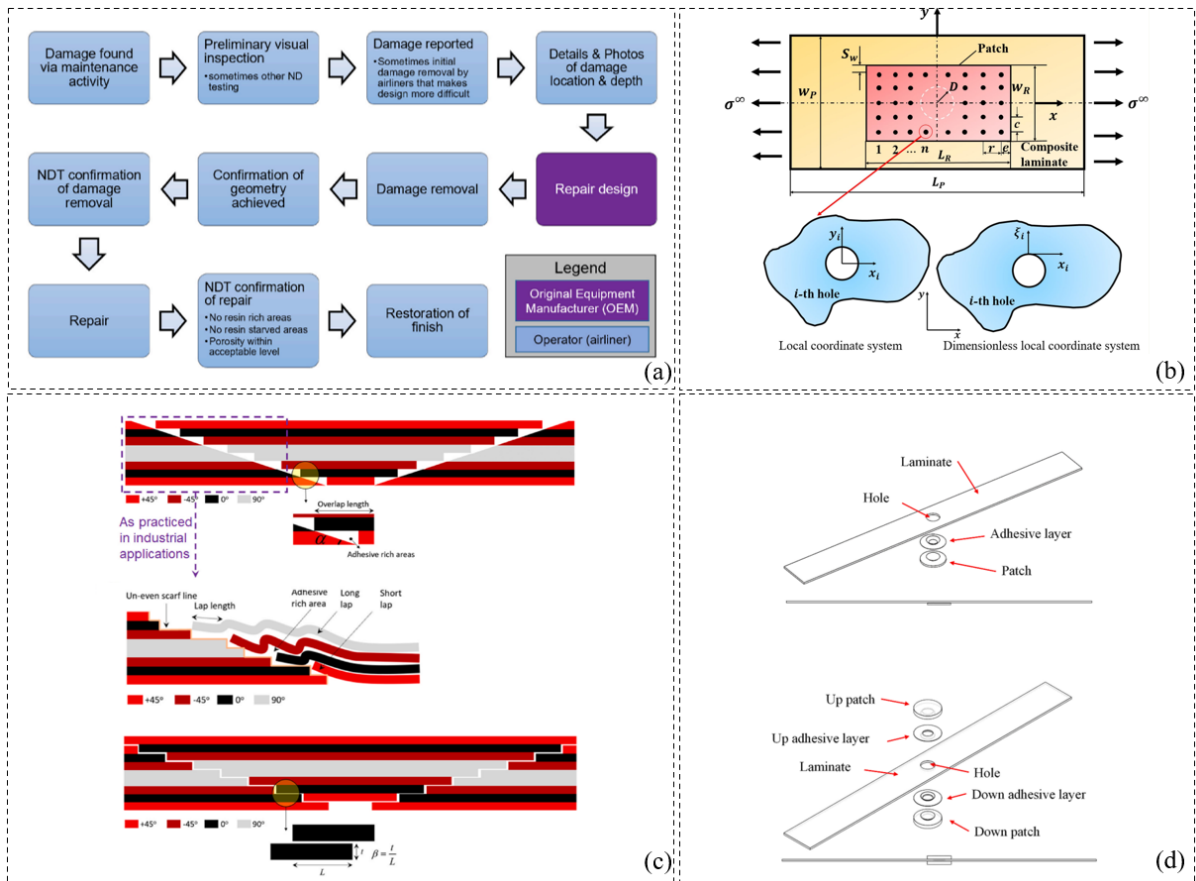


Fig. 2-10. (a) Overview of laminated composite repair process currently used in industry [172]; (b) Configuration of multi-bolt composite repair and local coordinate system for the i -th bolt[174]; (c) Examples of laminated composite repair methods: ideal ramped scarf repair, ramped scarf repair as implemented in industry and stepped scarf repair[172]; (d) 3D printing repair approaches: Single-bonded hybrid patch repair and Double bonded hybrid patch repair [173].

Table 2-2 Comparative overview of various repair techniques reported in the literature

Repair type	Research procedure	Parent material	Comparison object	Loading type	Ref.	Year
Double ramped scarf	Numerical	Laminate	Undamaged	Uni-axial tensile	[168]	2014
Stepped scarf	Simulation	Laminate	Undamaged	Uni-axial tensile	[169]	2018
3D printed patches	Experimental	QI laminate	Undamaged	Uni-axial tensile	[157]	2019
Stepped scarf	Experimental & Numerical	Sandwich panels	Undamaged	Uni-axial tensile	[170]	2019
Stepped scarf	Experimental & Numerical	Laminate	Undamaged	Uni-axial tensile	[171]	2020

Variable angle ramped scarf	Experimental	QI laminate	Undamaged	Uni-axial tensile	[175]	2021
Stepped scarf	Experimental & Numerical	QI CFRP laminate	Undamaged	Uni-axial tensile	[172]	2022
3D printed patches	Experimental	Open-hole angle-ply/QI laminates	Unrepaired	Uni-axial tensile	[173]	2023

Based on the referenced studies above, it could be concluded that existing repair methods for composite laminate primarily address impact damage/tensile damage that is already in place. To the best of the author's knowledge, there is no specific method for repairing bearing failure damage, which is the most common form of damage in CFRPs fastened joints and is characterised by deformation of the holes, resulting in them being unsuitable for assembly requirements. The method to restore damaged bolt holes in CFRP fastened joints will hold significant engineering implications. Repairing these bolt holes recovers the original strength and stiffness of the joint, extending the structure's lifespan and reducing material waste. Moreover, repairing rather than replacing parts reduces maintenance costs and downtime, particularly in large structures or hard-to-access areas. These benefits point out the method's significance in maintaining and improving the overall performance and economic efficiency of CFRP structures. Consequently, this identified gap emphasises the need for additional research and development in the area of composite repair.

As mentioned in section 2.2, in the field of composite materials, the integrity of joint structures is critical. These joints, serving as assembly components within larger composite structures, are often the most crucial yet vulnerable elements. Among the three primary joint types - mechanically fastened, adhesively bonded, and hybrid bolted-bonded (HBB) joints [30] - mechanically fastened joints, which employ pins, rivets, and bolts, are extensively used in industries like aerospace due to their reliability [35-38]. However, they exhibit a significant

drawback: high stress concentrations around fastener holes, leading to premature damage and reduced load capacity, especially in composite laminates compared to metal plates [47].

In composite structures, bearing failure is often the primary failure mode in effectively designed bolted joints, as indicated in reference [176]. This type of failure is characterised by crack development around the region of the through-hole, which bears the direct load from the bolt. When deformation takes place, it changes the bolt's dimensions, making it unfit for further use. This can lead to substantial material wastage, even from a single deformed bolt hole. Consequently, developing a new method for repairing deformed bolt holes in composite structures is of paramount importance.

2.5. Additive Manufacturing and Fibre Tailoring Techniques

2.5.1. Additive Manufacturing Methods for Fibre-Reinforced Polymer Composites

Over the past few years, Additive Manufacturing (AM) processes have revolutionised the fabrication of Fibre-Reinforced Polymer (FRP) composites, which are known for their high stiffness, strength, and excellent strength-to-weight ratio. These properties make FRP composites valuable in various academic and industrial applications. Traditional manufacturing methods of FRP composites faced limitations in design and production, especially in creating Variable Stiffness Composites (VSCs) that allow fibres to follow curvilinear paths, enhancing load distribution and structural performance. Conventional methods like hand layup struggled with precise fibre direction control. AM addresses these challenges by enabling automated and precise fibre layering, utilising either a 3D printer or a robotic arm equipped with various types of printing nozzles (shown in Fig. 2-11 (a)(b)), enabling the production of complex designs like VSCs. Techniques such as material jetting, vat photopolymerisation, and especially material extrusion (shown in Fig. 2-11 (c)(d)(e)) have

been successful in fabricating FRP composites, offering new avenues beyond traditional composite materials [177].

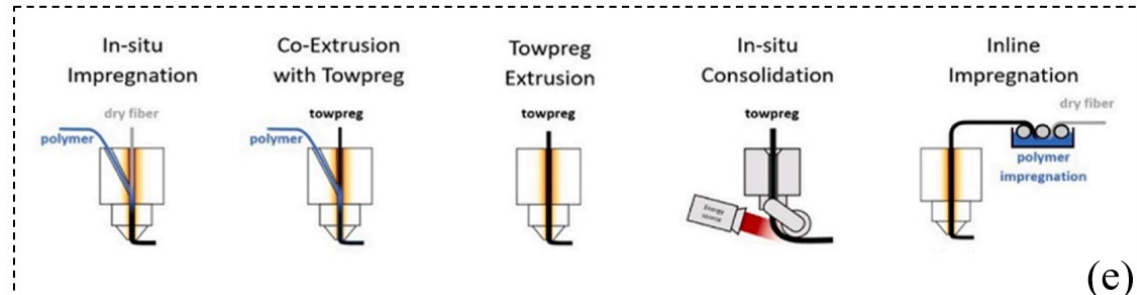
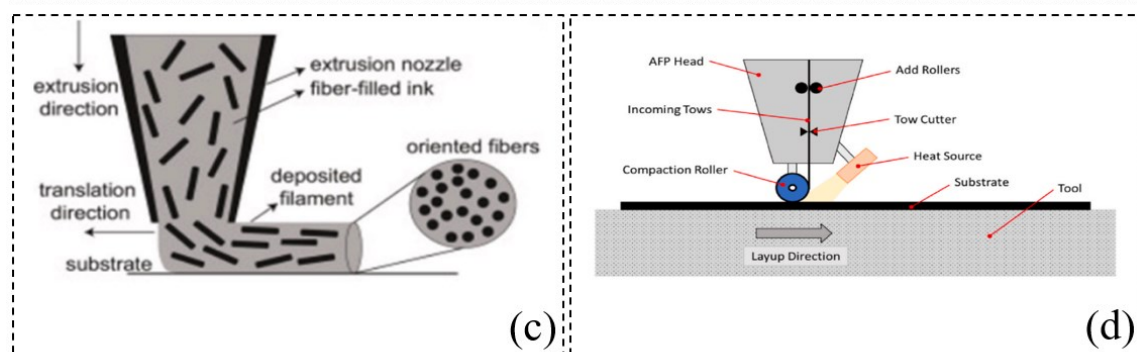
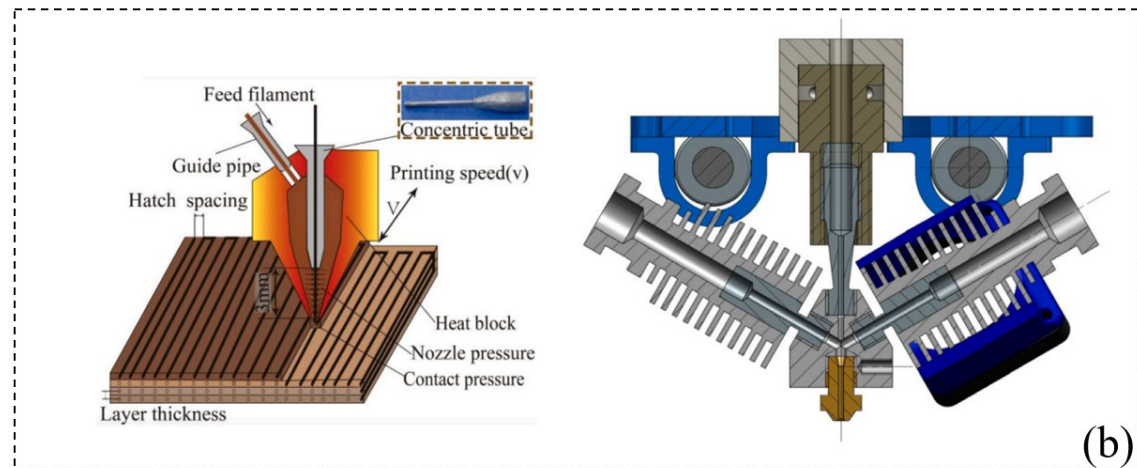
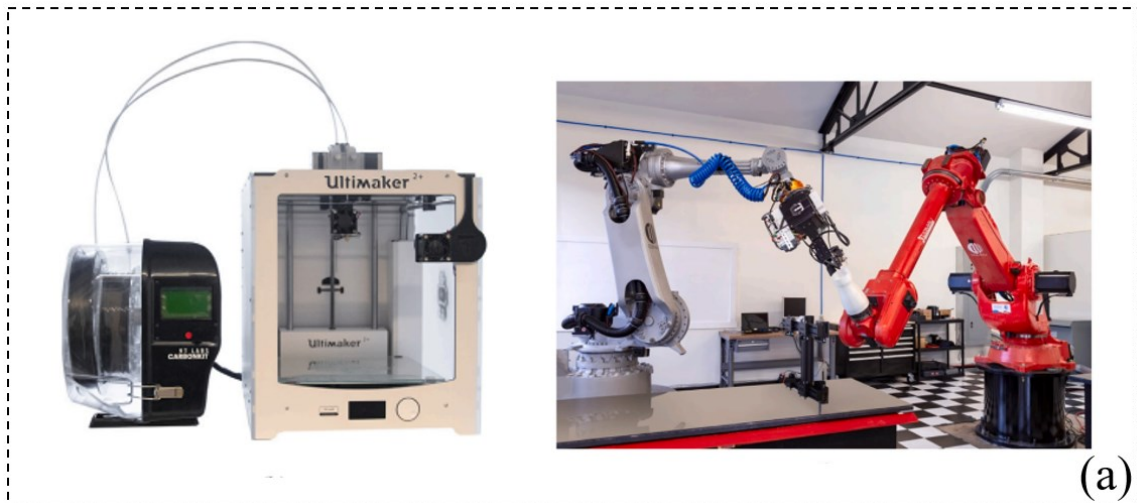


Fig. 2-11. (a) Commercial 3D printer and robotic arm printer [178]; (b) Schematic of print head designs for in-nozzle impregnation method as presented in various studies [179]; (c) Material extrusion of short fibre reinforced composites [180]; (d) Simplified representation of an AFP head [181]; (e) Comparison with material extrusion of continuous fibre reinforced composites [182].

An extensive review of recent advancements in the 3D printing of fibre-reinforced composite materials is presented. Table 2-3 summarises key literature in this domain, including a wide range of AM processes for both discontinuous and continuous fibre composites. The capacity of 3D printing for design freedom, customisation, waste minimisation, and manufacturing complex structures is a significant advantage highlighted across several studies [183-186]. These papers emphasise the use of rapid prototyping techniques in the mechanical and biomedical fields, where the applications are diverse, extending from polymer matrix composites to nanocomposites and bio-composites. Such a wide range of applications shows the versatility and adaptability of 3D printing technologies in various industrial domains. Concurrently, the focus of other papers [187, 188] is on optimising mechanical properties of AM products. This optimisation includes refining process parameters, such as infill speed, layer thickness, and nozzle temperature, enhancing fibre-to-matrix bonding, aligning fibres effectively, and reducing porosity for the production of high-quality composites. Additionally, the incorporation of various types of reinforcements to improve mechanical properties is also explored [4, 189, 190]. These reinforcements, including carbon nanotubes, fibres, and nanoparticles, are integrated into composite materials, thereby enhancing their physical attributes and broadening their industrial applications.

Subsequent papers specifically describe the application of continuous carbon fibre as a means to enhance a structure's stiffness and strength:

Brenken et al. [198] conducted a comprehensive analysis of the advancements in Fused Filament Fabrication (FFF) with a focus on fibre-reinforced polymers. The mechanical

properties of printed parts were focused on various composite material systems, emphasizing fibre orientation and the impact on mechanical behaviour. The paper includes a wide range of topics including the FFF process, the influence of physical phenomena like flow and fibre orientation, bond formation, and solidification behaviour on the printed parts. There is a strong emphasis on the importance of understanding and optimising the orientation of fibres during printing, as this greatly impacts the mechanical properties of the final product.

The article from Chapiro [191] provides a comprehensive overview of the current state and future potential of composite materials in the context of 3D printing. The article highlights that while metal 3D printing has seen significant developments and applications in industries like aerospace and high-performance automotive, composite 3D printing is still evolving. The main focus is on the challenges and potential of 3D printing with continuous carbon fibres, a crucial area for composite materials. Current technologies in composite 3D printing, such as those developed by Markforged and other startups, are analysed, emphasizing their limitations in terms of mechanical properties and cost-effectiveness compared to machined aluminium and 3D printed metals. The article critically evaluates the strength, stiffness, and performance gaps between metal and composite materials in 3D printing, considering aspects like material anisotropy, fibre orientation, and critical fibre length. Innovative approaches and potential methods for improving the performance of composite 3D printing are discussed. This includes the development of new filament types for FDM printing that could achieve longer fibre lengths and higher performance at a reasonable cost.

The work by Luca De Vivo [192] focuses on the advancements in AM of fibre-reinforced plastics, particularly using continuous fibre reinforcement. It examines various methods and materials used in AM, including different types of fibres (e.g., glass, carbon, Kevlar) and resins (thermosets and thermoplastics). The paper discusses technological advancements and challenges in designing and optimizing composite structures made through AM. It highlights

the significance of optimal fibre orientation in improving mechanical properties like stiffness, strength, and failure load in composite laminates. The research also revealed the need for developing new design and slicing software for AM and constitutive models to describe the mechanical behaviour of these new materials.

A significant section of the paper from Kabir *et al.* [193] is dedicated to continuous filament fabrication (CFF). It explained the mechanism of CFF, emphasising the process of integrating continuous fibres with thermoplastic polymers to enhance the mechanical properties of printed structures. The study addresses key factors that influence the quality of 3D printed structures, including preparatory, printing, and finishing factors. The materials used in CFF are extensively discussed, highlighting the synergy between matrix materials (such as thermoplastics) and reinforcing fibres (like carbon fibre, Kevlar, *etc.*) to improve the composites' tensile, elastic, and load-bearing capacities. The mechanical properties of these composites are another focus area. The paper examines various properties such as tensile, flexural, compression, shear, and impact properties, alongside predictive models to anticipate material behaviour. It also discusses the microstructural properties of these composites, analysing their meso and microstructures under different loading conditions to understand failure mechanisms. However, a significant portion of this data is relevant to products from a single commercial entity, Markforged [194].

A paper from Van de Werken [195] covers various aspects, including the benefits and challenges associated with AM of both short and continuous carbon fibre composites. The paper includes theoretical evaluations and experimental data on the tensile properties of these composites. Additionally, it discusses the applications of additively manufactured carbon fibre composites in both desktop 3D printing and large-scale AM. The focus of the paper is on the development of AM technologies that incorporate carbon fibres, highlighting their contribution to improved material properties such as thermal conductivity, reduced thermal expansion, and

enhanced strength and stiffness. These improvements expand the potential for end-use parts beyond prototyping.

Table 2-3 Comprehensive overview of recent literature on 3D printing techniques for fibre-reinforced composite materials: Including Material Extrusion (MEX), Powder Bed Fusion (PBF), Laminate Object Manufacturing (LOM), Stereolithography (SLA), Material Jetting (MJ), Vat Photo-polymerization (VP), Filament Winding (FW), Automated Tape Laying (ATL), Automated Fibre Placement (AFP), and Continuous Tow Shearing (CTS).

Additive manufacture method	Reinforcement type	Study purpose	Ref.	Year
MEX/PBF	Short and continuous fibre	Applications	[191]	2016
PBF/MJ/LOM/SLA/MEX	Particles and short fibre	Applications	[183]	2016
MEX/PBF/SLA/MJ	Particles/short and continuous fibre	Processes and applications	[196]	2017
MEX	Continuous fibre	Materials and process	[192]	2017
MEX/LOM/SLA/PBF	Particles/short and continuous fibre	Processes and performance modelling	[4]	2017
FW/ATL/AFP/Pick and place/CTS/SLA/MJ/MEX/LOM/PBF	Short and continuous fibre	Processes and properties	[184]	2017
MEX	Short and continuous fibre	Properties and physical phenomena of the process materials,	[197]	2018
MEX/LOM/SLA/PBF	Particles, short and continuous fibre	Processes, applications and challenges	[185]	2018
MEX/SLA/LOM/PBF	Short and continuous fibre	Processes, properties and outlook	[198]	2018
MEX/PBF/SLA	Particles, short and continuous fibre	Materials and properties	[188]	2019
PBF/LOM/SLA/MEX	Particles, short and continuous fibre	Materials, processes, properties	[186]	2019
MEX/MJ/SLA/PBF	Particles, short and continuous fibre	Processes, numerical and analytical modelling	[189]	2019
VP/MJ/PBF/MEX/BJ/	No reinforced polymer/particles short and continuous fibre	Processes and materials	[190]	2020
MEX	Continuous fibre	History, mechanism, materials, properties and limitations	[193]	2020

These recent studies on 3D printing techniques for fibre-reinforced composite materials collectively indicate a significant progression in the field. A particular focus is on the development of continuous carbon fibre composites, which present a promising avenue for achieving superior mechanical properties. The standout attribute of 3D-printed continuous fibre-reinforced composites is their markedly superior mechanical performance compared to their discontinuous counterparts, as evidenced in several reviews [191, 197, 198]. While the fabrication of discontinuous fibre-reinforced composites via AM is more straightforward, the mechanical benefits of continuous fibres, particularly in strength, are significantly more pronounced.

According to these references, the integration of continuous carbon fibres in 3D printing has been a significant topic, offering enhanced mechanical properties such as increased strength and stiffness, which are crucial for high-performance applications. And this is particularly advantageous for the design and fabrication of fastened joints. As mentioned in section 2.2, fastened joints are critical in many engineering applications, requiring high strength and durability while maintaining light weight. CFRPs, with their high strength-to-weight ratio and directional strength properties, are ideal for such applications. AM allows for precise control over fibre orientation and placement, which is critical in tailoring the mechanical properties of the joint to specific loading conditions. This capability is crucial in optimizing the performance of fastened joints, ensuring they can withstand the required loads and stresses. The following section explores in greater detail of continuous fibre tailoring techniques, providing a more thorough investigation.

2.5.2. Continuous Fibre Tailoring Techniques

This section focuses on the importance of printing path planning in manufacturing, particularly regarding the Design for Additive Manufacturing (DFAM) for continuous fibre-reinforced composites. It emphasizes the role of process planning in optimizing parameters and generating printing paths, essential for efficiently manufacturing parts. Crucially, this section shows that in most studies, the generation of printing paths for fibre tailoring, especially for continuous fibre-reinforced composites, is typically a post-processing activity succeeding topology optimisation (TO). The synergy of AM and multi-scale TO greatly expands the design space and maximises the potential of FRP composites.

In the field of additive manufacturing for continuous carbon fibre reinforced polymers (cCFRP), significant advancements have been made in the methods of toolpath generation, which are crucial for optimising mechanical performance. Traditional manufacturing often limits fibre placement to straight layers, but with additive manufacturing, more complex orientations are achievable. This leads to improvements in properties like stiffness and buckling load, as observed in computational simulations [199, 200]. Nonetheless, challenges persist in achieving precise, localised fibre orientations, with the printing path being a pivotal factor in determining the final mechanical properties due to the anisotropic nature of fibres.

Various toolpath strategies such as raster, zigzag, Hilbert-curves, and hybrid paths are common in slicing software [201], but these often lead to mechanical properties that are inferior to theoretical expectations. This shortfall is attributed to discontinuities during printing and restrictions in cured filaments due to fibre breakage and changes in thickness. Recent research has been critical in advancing toolpath generation strategies, especially in transitioning from academic to industrial applications. Innovative methods like offset by boundaries, equally-spaced method (EQS), or curves strategies have been developed, resulting in FRP composite parts with enhanced mechanical strength and performance compared to traditional infill

strategies [202-204]. For instance, printing paths designed based on stress maps from topological analysis have proven effective in reinforcing high-stress areas with carbon fibres [205]. Streamline-generated methods and stress-line methods align fibres with fluid flow streamlines and principal stress directions, respectively, improving the strength-to-weight ratio and avoiding fibre cut-off in unique geometries [206-208]. These advancements indicate a significant shift towards more efficient and effective methods of toolpath generation in the manufacturing of cCFRP composites.

Streamline algorithms, initially utilised in fluid flow analysis to visualize complex flows, have been adapted for toolpath generation in fibre-reinforced polymer composites (FRPCs). These algorithms generate streamlines from an initial seed point, filling the design domain, such as using streamline algorithms in Material Extrusion (MEX) with the von Mises stress field as the input [69] and stiffness-based optimisation and density-based topology optimisation methods are employed to design continuous fibre paths [202]. Despite their potential to improve stiffness, this can make FRPCs more brittle, thereby making them more prone to cracking and more likely to suffer catastrophic damage. Therefore, this algorithm still needs further refinement.

The authoritative studies concerning the literature on printing path generation methods in relation to manufacturing techniques are comprehensively compiled in Table 2-4. The following paragraphs provide a detailed explanation of each specific study:

Boddeti *et al.* [209] present an innovative approach to integrating digital design automation, material compilation, and digital fabrication into a unified workflow. This integration enables the simultaneous design and manufacture of both the macroscopic structural topology and the material microstructure. A methodology was designed for multiscale topology and microstructure design optimization. This approach involves the mathematical homogenization of a two-phase microstructure into a 3D design process. A distinct feature of this research is its

emphasis on optimal mechanical performance, guided by elasticity theory, but the approach is generalizable to other physical phenomena described by continuum field equations. The material compilation process projects the mathematical description of the optimal macro and microstructure into a physically realizable 3D material layout, generating machine code for fabrication. Digital fabrication is executed using voxel-based additive manufacturing with multi-material photopolymer material jetting, allowing for the precise placement of multiple materials. Experimental validation of this integrated design-manufacturing workflow is demonstrated through the design, fabrication, and testing of a series of structures. This novel approach significantly advances the field of product development. It disrupts traditional design and manufacturing paradigms by allowing for the simultaneous optimization of structure and material, leading to highly efficient and optimised products. The research has implications for numerous applications, providing a framework for developing products with enhanced performance and functionalities, previously unattainable with conventional methods.

A Path-designed 3D (PD-3D) printing concept was stated by Li *et al.* [205]. This method is designed to optimise the load transmission path and exploit the anisotropic properties of continuous carbon fibre reinforced filament (shown in Fig. 2-13). The PD-3D printing incorporates topological optimization for designing complex structures primarily into scaffold beams and branches, allowing the division of stresses within the parts into organised tensile and compression stresses. The study demonstrates that structures created using this method exhibit significantly improved mechanical properties. For instance, PD-3D printed specimens with holes and semicircles showed increases of 67.5% in tensile strength and 62.4% in flexural strength compared to specimens with drilled features. Additionally, the strength-to-weight ratio of these specimens also improved, highlighting the efficiency of PD-3D printing in producing lightweight yet strong structures. The research highlights how the application of topological optimization and anisotropic properties of the material can lead to innovative design

approaches in 3D printing, especially for composite materials. This includes the optimisation of the load transmission path and the printing path planning method. The use of continuous carbon fibre in 3D printing, guided by topological optimization, paves the way for innovative applications in various high-performance engineering sectors.

Boddeti *et al.* [210] provided a study of the design and manufacturing of composite materials with variable stiffness. This research is significant in the field of advanced manufacturing, particularly in the context of laminated continuous FRP composites. The authors have developed a design-to-manufacture workflow specifically for laminated FRP composites with spatially varying microstructures. This workflow consists of three main steps - design automation, material compilation, and digital manufacturing. Multiscale topology optimisation was employed, integrating microscale and macroscale designs. It is one of the first approaches to apply multiscale TO to 2.5D structures like laminated variable stiffness FRP composites, which possess a planar (2D) base but include out-of-plane features or properties. In this study, the concept of 2.5D specifically shows as materials where the layering process introduces a depth aspect to the structure, but without full three-dimensional complexity. The research leverages cutting-edge manufacturing methods like voxel-based multi material jetting for the fabrication of optimised structures. The developed approach allows for the design and fabrication of structures with complex geometries and varying material properties, enabling a high degree of design freedom. Also, experimental validation of the workflow was included, demonstrating the practical applicability of the research in practical applications.

The pioneering work by Sugiyama *et al.* [62] in the field of 3D printed composites provides an insightful analysis of Variable Volume Fraction of Short Composite (VVfSC) plates with bolted joints (shown in Fig. 2-12 (b)). Their study, which models and fabricates these composites using advanced 3D printing techniques, reveals that optimised fibre trajectory distances significantly enhance stiffness and load-bearing capacity. Tensile tests on these

VVfSC specimens showed a remarkable improvement in performance compared to Variable Stiffness Composites (VSC) and Constant Stiffness Composites (CSC), particularly in stiffness and maximum load metrics, with bearing failures indicative of the design's efficacy. This work not only emphasizes the importance of strategic fibre placement in areas of stress concentration but also highlights the potential for further mechanical property improvements through the integration of filament cutting mechanisms in the printing process.

Papapetrou *et al.* [202] explored the optimization of topology and fibre paths in continuous fibre composites. The study focuses on developing a framework to enhance the mechanical performance of composite structures through optimised material distribution (topology) and fibre infill pattern (morphology). The research introduces two methodologies for topology optimization: density-based and level-set methods. For fibre orientation optimization, energy-based and level-set based methods are employed. Additionally, three innovative techniques for designing fibre infill patterns are proposed, aiming to enforce fibre path continuity, ensure manufacturability, and minimize compliance. These include the Offset method, Equally-Spaced (EQS) method, and Streamline method. The study demonstrates the application of these methods in various case studies, such as cantilever beams and L-brackets, highlighting the advantages and limitations of each approach. Key findings indicate that different optimisation methods have varying effects on compliance and mechanical properties of the structures. The research shows that continuous fibre paths and topology optimisation significantly enhance stiffness and load distribution in composite materials. The methodologies developed in this study can be instrumental in designing more efficient and robust composite structures, particularly in aerospace and automotive industries where weight and strength are crucial factors.

Kubalak *et al.* [211] present a significant advancement in the field of AM. The focus of this research is on the development of a novel algorithm for generating deposition paths in material

extrusion processes. This algorithm is distinctive as it employs a streamline placement strategy, traditionally used in fluid flow visualisation, to guide the deposition paths in accordance with specified load paths. The main innovation of this work lies in its approach to aligning deposition paths with complex load paths for any arbitrary geometry. The authors successfully demonstrate that this algorithm can generate printing paths that effectively follow specified load paths while maintaining volumetric coverage comparable to standard methods. This is achieved by treating the load paths as a velocity field within which the deposition paths are planned. The paper emphasizes the importance of this method in improving the mechanical performance of printed parts. By aligning deposition paths with anticipated load paths, it is possible to enhance the strength and durability of AM parts, particularly in load-bearing applications. This aligns with the principles of Design for Additive Manufacturing (DfAM), which advocate for the optimization of part geometry and toolpath to leverage the unique capabilities of AM technologies. The validation of the algorithm is demonstrated through a comparative study with a standard toolpath planning technique, showing that the new method does not compromise on the coverage while providing the added advantage of alignment with load paths. This advancement opens new avenues for more efficient and effective use of AM in producing parts with optimised mechanical properties, catering to specific functional requirements.

The study of Murugan *et al.* [212] demonstrates the algorithm's ability to control various printing parameters, including extrusion width, layer height, filament spacing, and the number of layers. This research addresses the limitations of existing slicing software in 3D printing, particularly in controlling filament placement and orientation. The use of this algorithm in producing parts was combined with both partial and maximum infill, and with multi-oriented layer stacking sequences. This capability is a significant advancement in the field of FFF, as it allows for better control over the mechanical anisotropy in printed parts, potentially leading to

enhanced structural performance. Experimental tests were conducted to validate the algorithm's effectiveness. These tests involved printing different structural geometries, analysing filament trajectories, and verifying the inter-filament spacing. The results confirmed the algorithm's ability to accurately control filament orientation and density, providing better design solutions compared to traditional slicing software.

The paper also discusses potential applications of the algorithm in various fields, including the production of fibre-reinforced Variable Stiffness (VS) composites and customised lattice-type structures. The research represents a significant step forward in the additive manufacturing domain, offering an advanced method for controlling the filament deposition process in 3D printing, which opens up new possibilities for creating complex and customised parts with optimised mechanical properties.

Plocher *et al.* [213] explore the design and manufacturing of Fibre-Reinforced Additive Manufacturing (FRAM) components, focusing on design for AM and toolpath strategies. It compares the effectiveness of traditional infill patterns (grid and concentric) with custom strategies based on medial axis transformation (MAT) and principal stresses (MPS), evaluating stiffness, strength, CPU and print time, path undulation, and fibre utilisation. The study finds that MPS infill offers the highest stiffness and strength, highlighting the importance of tailored print paths. It also introduces a stiffness-alignment index to predict pattern performance, contributing valuable insights for FRAM design and processing.

A study by Fernandes *et al.* [214] studied three benchmark structures: a cantilevered beam, an MBB beam, and an L-shaped bracket. These structures were optimised for stiffness using topology optimization methods such as Solid Orthotropic Material with Penalization (SOMP) and level-set methods and then manufactured using an in-house modified 3D printer. Based on the results, the cantilever beam demonstrated a significant improvement in specific stiffness compared to non-optimised designs, with two different fibre layouts (EQS and offset)

examined. The same results came to the MBB beam, which was optimised using the level-set method. The L-bracket, optimised using the level-set/offset method, also exhibited considerable improvements in specific stiffness, demonstrating the effectiveness of the optimisation methods used. The study addressed the impact of manufacturing constraints like filament width, length, and the necessity for post-processing adjustments, as these constraints significantly influenced the final properties of the manufactured parts. Relative experimental testing and validation of the parts manufactured were also conducted, showing a close agreement between the computational and experimental results.

Chen and Ye [215] introduced a new technique for designing and manufacturing 3D-printed composite materials in their study. A two-stage topological design procedure that combines volume and stress-controlled algorithms for optimal structural topology was formulated. This method effectively minimizes compliance and confines maximum stress in isotropic materials. With the integration of fibre placement techniques with topological design, the study uses average load transmission trajectories to determine continuous carbon fibre placement paths, enhancing the load-bearing capacity of the structures. Experimental validation of the design methodology was conducted through the creation of cantilever and three-point-bending specimens. The specimens were fabricated using pure polyamide (PA), short carbon fibre reinforced polyamide (SCF/PA), and continuous carbon fibre reinforced polyamide (CCF/PA). The results show that the CCF/PA specimens exhibited a dramatic increase in stiffness and peak load compared to pure PA and SCF/PA specimens. Specifically, for cantilever specimens, the stiffness and peak load increased by 1198% and 1633% respectively with CCF/PA, and for three-point-bending specimens, these increases were 569% and 293% respectively.

Eckrich *et al.* [216] offered a new solution for advancing the design and manufacturing of FRPs through an integrated approach of topology optimisation and fibre placement path derivation. The study explores the optimization of FRP structures considering their anisotropic properties

as well as manufacturing constraints such as minimum feature width and the avoidance of undercuts transverse to the placement plane. A workflow was developed, combining topology optimization with fibre placement technologies, addressing the specific challenges of anisotropic materials and manufacturing constraints. A dilate sensitivity filter was presented in the anisotropic Bidirectional Evolutionary Structural Optimization (BESO) algorithm. This filter ensures that optimised structures do not have features narrower than the fibre tape width used in fibre placement, thereby enhancing manufacturability. A volume minimisation procedure was implemented within the BESO algorithm, driven by Puck's failure criteria, to achieve lightweight yet structurally robust designs. Then fibre placement paths were generated by a novel method that integrates clustering and streamline algorithms. This method improves the parallelism of adjacent placement paths, enhancing the manufacturability and efficiency of the fibre placement process. Experimental validation through 2D and 3D test cases was performed and the result demonstrates the algorithm's effectiveness in producing manufacturable, optimised structures with minimal material usage. This research addresses the complexities of designing and manufacturing composite materials by seamlessly integrating topology optimization and fibre placement technologies. It presents a significant step forward in the production of lightweight, high-performance composite structures.

In our previous work [217], the impact of fibre placement in 3D printed continuous carbon fibre reinforced polymer (CCFRP) composites was studied. Optimising fibre paths were generated for open-hole composites to enhance mechanical performance under uniaxial tension, combining 3D printing and post-processing with powder epoxy. The powder epoxy introduced successfully created low-porosity composites with customised continuous carbon fibre reinforcement. The main findings include the significant improvement in the mechanical performance of composites when fibres are aligned with maximum principal stress trajectories. This approach dramatically postpones crack initiation compared to traditional drilled samples.

Additional fibres along minimum principal stress trajectories or around holes further alter the failure mode and enhance mechanical properties. FEA is used alongside digital image correlation (DIC) measurements to understand stress distributions resulting from different fibre placements. The study demonstrates that custom fibre placement methods can effectively redistribute stress, improve the strength and stiffness of the composites, and maintain hole integrity under load. These findings offer valuable insights for designing 3D printed composites with complex shapes or geometric singularities, potentially impacting various engineering applications.

This manufacturing technique combining 3D printing and epoxy-infusion for creating curved continuous carbon fibre reinforced composites was further studied [218] in the case of a single notch composite under tension loading. This method was intended to address the challenges faced in material-extrusion based 3D printing, such as inadequate fibre impregnation and air voids, by first producing composite preforms using 3D printed continuous carbon fibre reinforced thermoplastic polyamide-6 (PA-6) filaments, and then treating these preforms with a thermosetting powder epoxy. The study demonstrates significant improvements in the mechanical properties of the composites. The stiffness and strength of the printed composites increased by 29.3% and 22.1%, respectively, compared to thermoplastic-only specimens. The innovative aspect of this technique lies in the ability to create composites with curved fibre alignment, leading to enhanced failure strength and fracture toughness. Specifically, the placement of continuous carbon fibres along principal stress trajectories in the composites resulted in an 81% increase in failure strength and a 157% increase in fracture toughness compared to traditional unidirectional and concentric placement methods. The combination of 3D printing and epoxy-infusion treatment enables the production of low-porosity composites with customised curved fibre paths while maintaining the anisotropic properties and structural integrity of the material. Additionally, the study suggests future automation possibilities for

[illegible]

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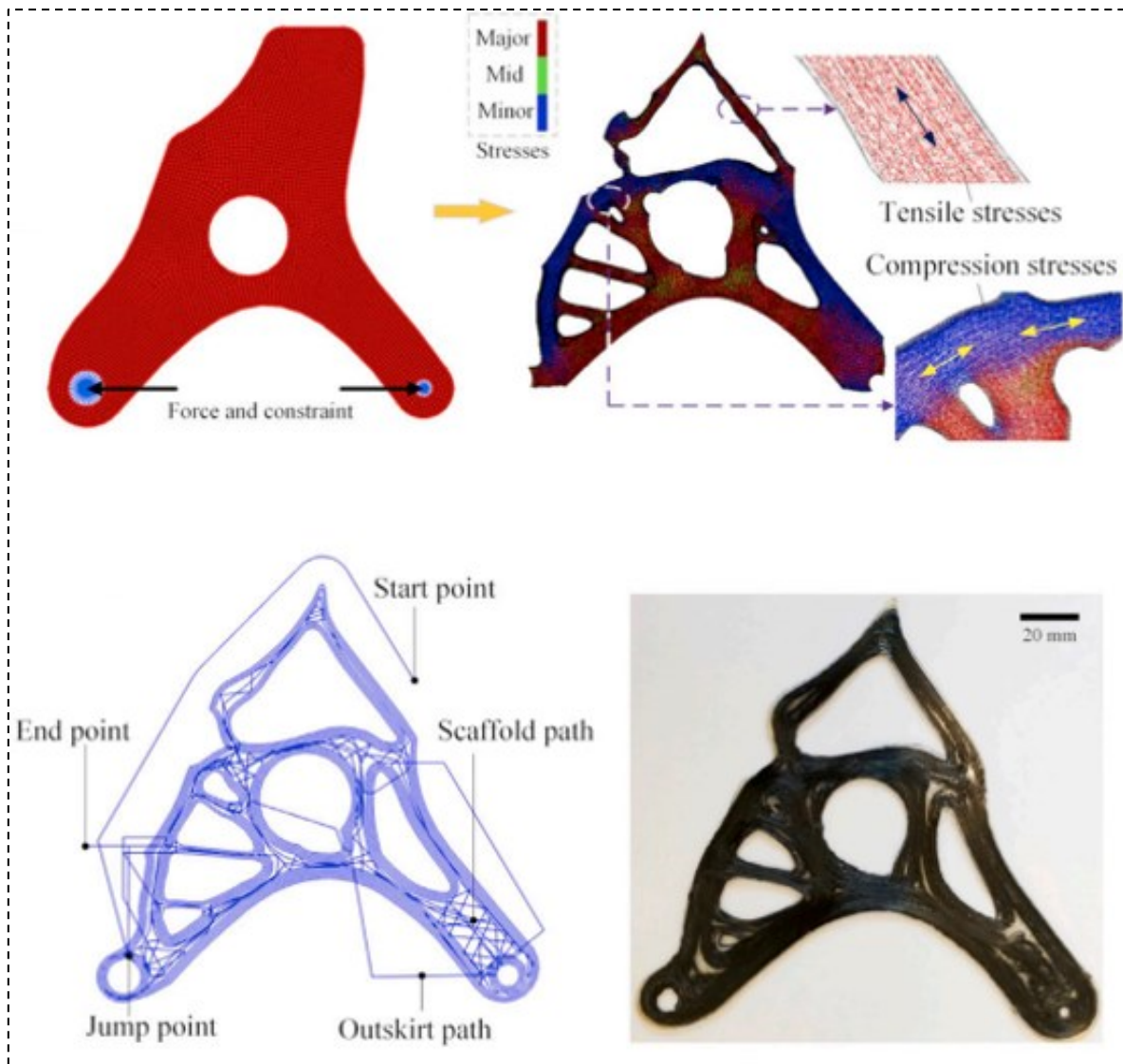


Fig. 2-13. Topological calculation and printing path design of the testing specimens and the suspension plate [205].

Table 2-4 Comprehensive overview of printing path generation methods in relation to manufacturing techniques, intended objectives, and problem types in composite fabrication;
Method: MJ-Material Jetting, MEX-Material Extrusion; Fibre type: SF-short fibre, CF-Continuous Fibre

Toolpath Generation Method	Manufacturing Method	Fibre type	Intended Objectives	Case	Ref.	Year
Voxelization	MJ	SF	Maximise stiffness	Macroscopic component	[209]	2018
Stripe Algorithm	SLA	CF	Minimizing compliance	Macroscopic component	[210]	2020
Streamline(von Mises stress), EOS, Offset	N/A	CF	Minimize compliance	Cantilever beams and L-brackets	[202]	2020

Streamline/Offset	MEX	CF	Maximise stiffness	Joint	[62]	2020
Principal stresses	MEX	SF, CF	Maximise stiffness	Scaffold beams and branches	[205]	2020
Streamline/Nodal Extraction	MEX	SF	Designing variables stiffness composites	Macroscopic component	[211]	2021
EOS and Offset	MEX	CF	Maximise stiffness	Cantilevered beam, MBB beam, and L-shaped bracket	[214]	2021
Streamline	AFP/ATP	CF	Minimizing compliance	Cantilever and three-point-bending	[215]	2021
LALI Method	N/A	SF	Maximise stiffness	Tension and bending	[212]	2022
Designed Path	MEX	CF	Maximise tensile strength and flexural strength	Macroscopic component	[213]	2022
Streamline	MEX	CF	Maximise stiffness	Truss	[216]	2022
Principal stresses	MEX	CF	Maximise stiffness	Open-hole	[217]	2022
Principal stresses	ME	CF	Maximise stiffness	Single-notch	[221]	2023

The current trend in printing path generation methods and associated manufacturing methods for composite materials, as illustrated by the reviewed articles, reflects a focus on integrating design and manufacturing processes. This integration aims to optimise both the macroscopic structural topology and the material microstructure. The main methods involve multiscale topology optimisation, using voxel-based additive manufacturing for precise material placement, and leveraging algorithms for filament path generation based on specified orientation fields. These methods enable the creation of structures with complex geometries and varying material properties, enhancing design freedom and mechanical performance.

However, the majority of printing path generation methods are based on topology optimisation during the elastic phase or principal stress lines, providing optimization mainly for stiffness

and initial strength. Yet, these path designs do not optimize for the damage evolution stage that follows initial damage onset. Additionally, these methods are predominantly applied in tension and scaffold beams and branches. As mentioned in Section 2.2, it's understood that composite fastened joints are crucial components within composite structures. Previous studies, such as [62], have focused solely on the elastic stage of these joints. In compliance with ASTM standards D5961/D5961M [176], the initial peak strength of a joint is only one criterion of assessment. The design requires a prolonged deformation phase for damage forewarning, making excessive stiffness undesirable for fastened joints. Therefore, a new path design method is necessary, considering both stress distribution in the elastic phase and the new stress distribution during the damage evolution stage to optimise for the entire mechanical phase experienced by composite components.

2.6. Literature Review Summary

Based on the literature provided in the above sections, the current research in additive manufacturing of composites primarily focuses on the development of composite materials with tailored fibre architectures for application in fastened joint structures. The research encompasses areas such as thermosetting towpregs, design complexities of bolted joints in composite structures, repair methods for damage in bolted joints, and advancements in printing path generation methods for composite materials. Further details are as follows:

1. Thermosetting Towpregs: There is a noted limitation in the research of thermosetting towpregs, especially those using powder for towpreg production
2. Studies have shown promising results, yet there is a need for further exploration in this area, particularly regarding commercial epoxy powder coatings and high-temperature thermoset powders.
3. Design Complexities in Bolted Joints: The complexity of designing bolted joints in composite structures due to their anisotropic properties and complex failure modes presents

a significant challenge. Existing models mostly rely on homogeneous layers or 2D models, indicating a gap in comprehensive 3D modelling that accurately captures stress states, material behaviour, and failure modes in composite joints.

4. **Printing Path Generation Methods:** While current trends show the integration of design and manufacturing processes for composite materials, there is a lack of optimisation for the damage evolution stage following initial damage onset in fastened joints. The need for new path design methods that consider both stress distribution in the elastic phase and during damage evolution is obvious, aiming to optimise the overall mechanical performance of composite components.
5. **Repair Methods for Bolted Joints:** There is a notable absence of specific methods for repairing damage in bolted joints of thermoset composites. The integrity of joint structures in composite materials is critical, this area demands significant research and development, particularly for mechanically fastened joints prone to bearing failures.

In summary, this thesis aims to address these gaps by exploring the additive manufacturing of composites with tailored fibre architectures, particularly in the application of fastened joints. The focus will be on studying the mechanical performance of composite manufactured by thermosetting towpregs; developing comprehensive 3D FE models for additive manufactured composites; innovating printing path generation methods that account for the entire mechanical phase of composite components and creating specific repair methods for fastened joints.

Chapter 3. Characterisation of Mechanical Properties in Custom Fabricated Composites

3.1. Chapter Introduction and Overview

Two composites were used in this thesis. The first type of composite was 3D printed continuous carbon fibre reinforced epoxy in the form of pseudo woven (using 1K carbon fibre tows for Chapters 4 and 5) and individual interlayer and repair patch (using 3K carbon fibre tows for Chapters 6 and 7). The second type of composite was plain woven carbon fibre reinforced epoxy laminate used in Chapters 6 and 7.

This Chapter 3 provides a detailed introduction to the sources of the intrinsic properties of the printed filaments as well as the plain woven laminates used in this thesis. These filaments were fabricated using 1K T300 carbon fibres (sourced from Toray) or 3K carbon fibres (sourced from Easy composites) on the in-house developed tapelines, as described in the previous work of our research group. For more details, please refer to the reference [218]. The filaments were utilised in a modified extrusion-based printer designed to melt and deposit them along predetermined printing paths to construct preforms with customised printing paths. In the case of the plain woven laminates, the 3K plain woven mat (sourced from Easy composites) was initially impregnated with PE6405 powder epoxy to form a prepreg. The final composite, comprising either exclusively filament, plain woven mat, or a hybrid of both, was then produced through a process involving vacuum bagging and oven curing. Because these materials are fundamental to this thesis, their comprehensive material properties such as elastic modulus, strength, and even fracture energy used in the FE modelling will be listed in this chapter by integrating findings from experiments, empirical formulas and relevant literature.

3.2. Sample Manufacturing and Testing

Owing to the inadequate experimental research presently available on individual filaments, the properties of the 1K and 3K continuous carbon fibre epoxy filaments were measured using unidirectional (UD) specimens. The filaments were printed into UD preforms with a modified Prusa 3D printer (shown in Fig. 3-1 (a)) and further vacuum bag curing was performed to manufacture the final printed specimen. For the plain woven laminate, eight layers of plain woven mat were cut and stacked in sequence in a stainless steel mould. Epoxy powder, in the target volume fraction, was sprinkled between the mats, and calculated based on the mass ratio of the mat and the powder. Finally, the piece was cured using vacuum bagging and ultimately cut into the corresponding sizes with a Hama A4 Guillotine wet saw according to ASTM standards.

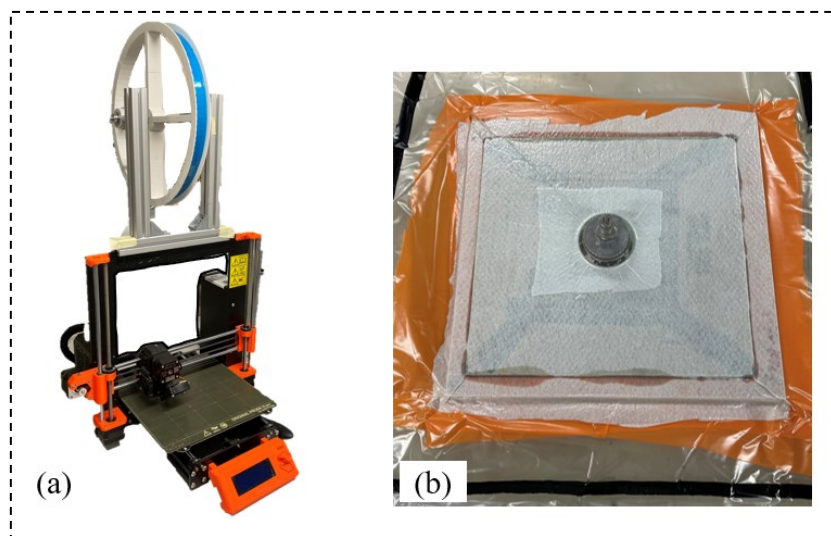


Fig. 3-1. (a) Modified Prusa 3D printer (b) Stainless steel mould with plain woven mat stacked for vacuum bag curing.

Experiments and characterisations were carried out on UD and plain woven laminate specimens in accordance with ASTM Standards D3039/D3039M and D6641/D6641M. Owing to the size constraints of the modified 3D printing bed, the dimensions of the tensile specimens manufactured using the impregnated filament were proportionally reduced to half of the dimension of the UD laminate required in ASTM standard D3039/D3039M. The specific

dimensions are detailed in Table 3-1. For the laminate made from plain woven mats, which in this study was solely used to determine the homogenised elastic properties of the 3K plain woven layer, only tensile tests were conducted to measure its longitudinal properties. The specific specimen dimensions for these tests are also listed in Table 3-1.

These specimens were respectively subjected to testing on an INSTRON 8802: 250kN Servo Hydraulic Test Machine and an MTS Criterion C45.305, 647 Hydraulic Wedge Grip (as shown in Fig. 3-2). A loading rate of 2 mm/min was applied, along with a 0.5 kN preload for each sample. Four specimens per case were examined, and the best three out of four data sets were selected for use. A high-speed camera served as a visual extensometer in all tests, capturing strain at gauge locations. Utilising data from the tests, the tensile stiffness, ultimate strength, and Poisson ratios were calculated and summarised in Table 3-2 to

Table 3-6.

Table 3-1 Specimen dimension for tensile and compressive tests

Tensile	Length (mm)	Width (mm)	Thickness (mm)	Tab length (mm)
Printed specimen (1K/3K UD)	150	9	0.6	33.6
Plain woven Laminate	250	15	2.4	50
Compressive	Length (mm)	Width (mm)	Thickness (mm)	Tab length (mm)
Printed specimen (1K/3K UD)	140	13	0.6	65



Fig. 3-2. Experimental setup in accordance with ASTM D3039/D3039M and D6641/D6641M for the UD and plain woven laminate.

For the other material properties, such as shear modulus, strength and fracture energy for certain cases, which are complicated to obtain from the experimental test, they were either calculated using the empirical approximate formula or directly cited the data presented in the literature. Based on the modulus and strength of the fibre and resin from others' research, the material properties of 1K&3K filaments were calculated using the equations from Eqs. (3-1) to (3-6). It should be noted that the fibre volume fraction used in the calculations is derived from previous research [221]. Additionally, since the same oven curing process, involving identical pressure and curing cycles was applied to all specimens, this fibre volume fraction was consistently used in the calculations of both 1K and 3K filament material properties.

The empirical formulas for calculating the transverse and shear modulus, transverse Poisson's ratio of the CF/Epoxy filament based on Chamis' model [222], are as follows:

$$E_{11} = V_f E_{11}^f + (1 - V_f) E_m \quad (3-1)$$

$$E_{22} = E_{33} = \frac{E_m}{1 - \sqrt{V_f} \left(1 - \frac{E_m}{E_{22}^f} \right)}, \quad (3-2)$$

$$G_{12} = G_{13} = \frac{G_m}{1 - \sqrt{V_f} \left(1 - \frac{G_m}{G_{12}^f} \right)} \quad (3-3)$$

$$G_{23} = \frac{G_m}{1 - \sqrt{V_f} \left(1 - \frac{G_m}{G_{23}^f} \right)} \quad (3-4)$$

$$v_{12} = v_{13} = V_f v_{12}^f + (1 - V_f) v_m \quad (3-5)$$

$$v_{23} = \frac{E_{22}}{2G_{23}} - 1 \quad (3-6)$$

where f and m stand for fibre and matrix respectively, t stands for tension and V_f is the fibre volume fractions.

The transverse and shear strengths of the printed filament are directly cited from the data in other studies published by Composites research group at Edinburgh [223], where the same PE6405 powder-epoxy was used for the UD CFRP composite.

3.3. Results and Discussion

The elastic properties are obtained through a combined approach of experimental testing and empirical calculation, employing 1K/3K fibre tow and epoxy material properties that are detailed in Table 3-2 and Table 3-4. It should be noted that the transverse and shear modulus values for Pyrofil TR30S carbon fibre are not available in existing literature. However, given

the similarity in the longitudinal modulus between Pyrofil TR30S (235 GPa) and Toray T300 fibre tow (230 GPa), the values for Toray T300 fibre tow can be utilised. The elastic modulus of the printed 3K filament can thus be calculated based on its fibre volume fraction. The strength parameters and fracture toughness of the material are presented in Table 3-3, Table 3-5 and

Table 3-6, where X_T, X_C, Y_T, Y_C are the tensile and compressive strengths along the longitudinal, transverse/through-thickness directions respectively. As the printed filament is assumed to be a transversely isotropic material, strength along the transverse and through-thickness directions is the same. And S_L, S_T are the shear strengths in the longitudinal, transverse/through-thickness directions, respectively. Additionally, the LaRC05 is used in this study, and it involves the critical energy release rates for fibre intra-laminar damage evolution, including fibre tensile failure G_{ft} and fibre kinking $G_{f_{kink}}$ are sourced from literature [129]. Also, the fracture toughness for matrix failure modes used for LaC05 is assumed to be the same as the inter-laminar fracture energies for Modes I and II (G_{IC} and G_{IIC}) also sourced from other research [129]. For the interface properties between each composite layer after curing are directly adopted from the epoxy values reported in other literature[224]. The normal and tangential stiffness values K_n, K_t , maximum contact stresses σ_{max}, τ_{max} and critical fracture energies G_{cn}, G_{ct} , are given in

Table 3-6.

The material parameters of 1K/3K filament and 3K plain woven laminate are shown below:

Table 3-2 Elastic properties of 1K fibre tow, epoxy and printed 1K filament			
Toray T300 1K fibre tow		PE6405 powder epoxy	
Longitudinal modulus E_{11} (GPa) [225]	230.00	Modulus of elasticity E (GPa) [217]	3.00
Transverse modulus $E_{22} = E_{33}$ (GPa) [225]	8.00	Poisson's ratio ν [217]	0.37

In-plane Poisson's ratio $\nu_{12} = \nu_{13}$ [225]	0.26	Shear modulus G (GPa) [217]	1.09
Transverse Poisson's ratio ν_{23} [225]	0.30		
Axial shear modulus $G_{12} = G_{13}$ (GPa) [225]	27.3		
Transverse shear modulus G_{23} (GPa) [225]	3.08		
Homogenised elastic properties of the printed 1K CF/Epoxy filament			
V_{fibre} [221]	E_{11} (GPa)	$E_{22} = E_{33}$ (GPa)	$\nu_{12} = \nu_{13}$ ν_{23} $G_{12} = G_{13}$ (GPa) G_{23} (GPa)
0.56	98.23	5.63	0.31 0.33 3.88 2.11

Table 3-3 Strength and fracture energy of printed 1K filament

X_T (MPa) [221]	X_C (MPa)	Y_T (MPa) [129]	Y_C (MPa) [129]	S_L (MPa) [129]
1372.00	411.73	73	185.0	90
S_T (MPa) [129]	G_{IC} (mJ/mm ²) [129]	G_{IIC} (mJ/mm ²) [129]	G_{ft} (mJ/mm ²) [129]	G_{fkink} (mJ/mm ²) [129]
48.98	0.21	0.80	92.0	80.0

Table 3-4 Elastic properties of printed 3K filament and 3K plain woven laminate

Homogenised elastic properties of printed 3K CF/epoxy filament						
V_{fibre}	E_{11} (GPa)	$E_{22} = E_{33}$ (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)
0.48	84.48	5.29	0.32	0.34	3.26	1.98

Homogenised elastic properties of 3K plain woven laminate

V_{fibre}	$E_{11} = E_{22}$ (GPa)	E_{33} (GPa)	ν_{12}	$\nu_{13} = \nu_{23}$	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)
0.48	28.19	5	0.05	0.3	1.5	1.5

Table 3-5 Strength and fracture energy of printed 3K filament

X_T (MPa)	X_C (MPa)	Y_T (MPa) [129]	Y_C (MPa) [129]	S_L (MPa) [129]
1350.00	580.10	73	185.0	90

S_T (MPa) [129]	G_{IC} (mJ/mm ²) [129]	G_{IIC} (mJ/mm ²) [129]	G_{ft} (mJ/mm ²) [129]	G_{fkin} (mJ/mm ²) [129]
48.98	0.21	0.80	92.0	80.0

Table 3-6 Interface properties for composite laminate [224]

K_n (N/mm ³)	K_t (N/mm ³)	σ_{max} (MPa)	τ_{max} (MPa)	G_{cn} (mJ/mm ²)	G_{ct} (mJ/mm ²)
1x10 ⁵	1x10 ⁵	30	30	0.26	1.002

3.4. Conclusions

In this Chapter, a series of mechanical tests were performed, focusing on self-manufactured 1K/3K continuous carbon fibre filaments and 3K plain woven laminates. These materials, representing a substantial advancement in the field of composite materials, were rigorously tested to explore their mechanical properties and potential applications. The experiments were conducted in accordance with the ASTM D3039/D3039M and D6641/D6641M standards, ensuring that the results are robust, reliable, and comparable with existing data in the field. The choice of 1K/3K continuous carbon fibre filaments was driven by their increasing relevance in the industry due to their high strength-to-weight ratio and exceptional durability. The 3K plain woven laminate, on the other hand, was selected for its structural integrity and potential in various engineering applications. The combination of these materials offers a unique insight into the capabilities of advanced composite structures.

The methodologies employed in this Chapter 3 were designed to extract detailed material parameters, such as modulus of elasticity, tensile strength and compressive properties. These parameters are crucial for understanding the behaviour of composite structures made from these materials under various load conditions. The data obtained serves as important, necessary inputs for the following FE modelling.

Chapter 4. 3D Printing of Pseudo-woven CFRP Composites with Bolted

Joints: Manufacturing and Testing

4.1. Chapter Introduction and Overview

CFRP is a composite material that exhibits superior specific strength and stiffness whilst maintaining a lightweight characteristic [193, 226-228]. It finds extensive use in industries such as aerospace, automotive and construction to fulfil the demand for a high strength-to-weight ratio and rigidity [3-5]. In traditional manufacturing methods like autoclave and resin transfer moulding, continuous carbon fibres are typically arranged in a straight manner in each layer [155, 156]. In the field of structural engineering, bolted joints represent a highly efficient method for securing composite structures and facilitating load transfer within these assemblies. However, when mechanical fastening is required, through-holes are introduced by punching and/or drilling processes, which result in the cutting of continuous carbon fibres, which leads to residual damage around the hole [229]. Consequently, the presence of holes in composites creates stress concentrations, posing a risk of early crack initiation and reducing the mechanical performance. The contact surface experiences micro-buckling when the fractured fibre is subjected to bearing loading, and delamination issues arise when through-thickness stress is applied to the surface. Therefore, composites with bolted joints tend to exhibit lower bearing stresses compared to their equivalent metal counterparts [230, 231].

To address the defects resulting from traditional machining processes, alternative manufacturing methods have emerged to produce composites with intricate geometries. Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) techniques, for instance, allow for the creation of variable angle tow (VAT) composites with customised fibre paths [232]. Furthermore, additive manufacturing (AM), also known as 3D printing, has recently

gained more attention. Compared to ATL and AFP, continuous fibre 3D printing offers greater design flexibility [184, 233]. This can be attributed to its higher printing system resolution and the narrower width of the printed fibre tows (approximately 1-2 mm). In 2014, Markforged® introduced the first commercial continuous fibre printing system, which, supported by its dedicated software Eiger, employs a concentric approach to place fibres around geometrical singularities. Other researchers have also developed their own printers for continuous carbon fibre composites [234, 235], as well as optimised methods for continuous fibre placement. For example, a novel concept involved placing curved fibres along principal stress trajectories generated through finite element analysis (FEA) based on the loading conditions [220]. Innovative techniques have also been developed and evaluated for the fabrication of pseudo-woven composites integrated with features like notches [236, 237]. These advancements in fibre placement methods offer the possibility of printing composites with holes, thereby avoiding the strength losses commonly associated with conventional composite machining. Numerous researchers have verified that the utilisation of continuous carbon fibre in the field of 3D printing significantly enhances the mechanical properties of the produced parts [238-242]. This improvement undoubtedly extends to the domain of composite joints. Considering the fibre path design concepts, strategies such as the tensile principal stress path [60] and load path design [59] were proposed for the fibre placement within the composite joint. Fibres were tailored into layers and replaced the 0° layer as a reinforcement in composite laminates, thereby enhancing pin-load bearing strength. Fujii *et al.* [219] developed more precise and intricate composite bolted joints using 3D printing technologies, employing radially aligned straight fibres to resist compressive loads and circumferentially steered curvilinear fibres to withstand tensile and shear loads. These studies focused on plates fabricated using fibre steering techniques to reinforce carbon fibre prepreps, although delamination occurred due to stiffness discontinuity and weak interlayer adhesion. The filament printing path, based on principal

stresses, often contained sparse print paths, resulting in weak adhesion and non-uniform stiffness. Dickson and Dowling [243] produced a pseudo-woven laminate with a 6 mm diameter notch using 3D printing, demonstrating improved bearing strength compared to the mechanically drilled specimens. However, further investigation of more intricate fibre steering paths to form notches, rather than simple routing, could be explored to achieve exceptional bearing performance.

This Chapter presents a comprehensive experimental investigation of the influence of steered fibre paths on the bearing performance of 3D printed pseudo-woven composites with bolted joints subjected to double-lap shear loading. The composite specimens were manufactured using 3D printing techniques to locally tailor the fibre paths, followed by vacuum bagging-only curing and consolidation. Experimental tests were conducted while digital image correlation (DIC) analysis and X-ray computed micro-tomography (micro-CT) scanning were employed to analyse microscale properties such as fibre volume fraction, void content and crack propagation paths. The research aims to propose a novel design approach to enhance the bearing capacity of composite materials through fibre steering while exploring the specific effects of this fibre steering method on the bearing performance of 3D-printed pseudo-woven composites.

4.2. Methodology

4.2.1. Design and Manufacturing

4.2.1.1. Fibre steering patterns in pseudo-woven composite

In previous work, 3D printing technique was applied to produce pseudo-woven laminates and the continuous fibres were diverted to leave the hole for bolted joints[243]. In this chapter, the method of fibre interlacing was further developed and pseudo-woven patterns were customised to investigate the effect of fibre orientation change for bearing load transfer mechanism within the bolted composite joint.

The design concept aimed to maintain filament continuity, thereby enabling load transfer over an expanded area beyond the hole's edge. Four cases were evaluated, including a mechanically drilled sample (case D) for comparison, where all fibre paths remained linear and a through-hole was drilled. The other three cases, referred to as cases C, L, and U respectively, employed unique fibre steering patterns: squeeze-apart, diverted-away, and loop-back, as depicted in Fig. 4-1. The figure illustrates the difference in how specific fibre tows (highlighted in black) were interlaced in the presented cases. In case C the filament path followed a similar approach to previous work [236] which was steered along the hole edge without altering the fibre orientation. Conversely, fibres were steered circularly around the edge in cases L and U, with orientation changes of 90 and 180 degrees respectively.

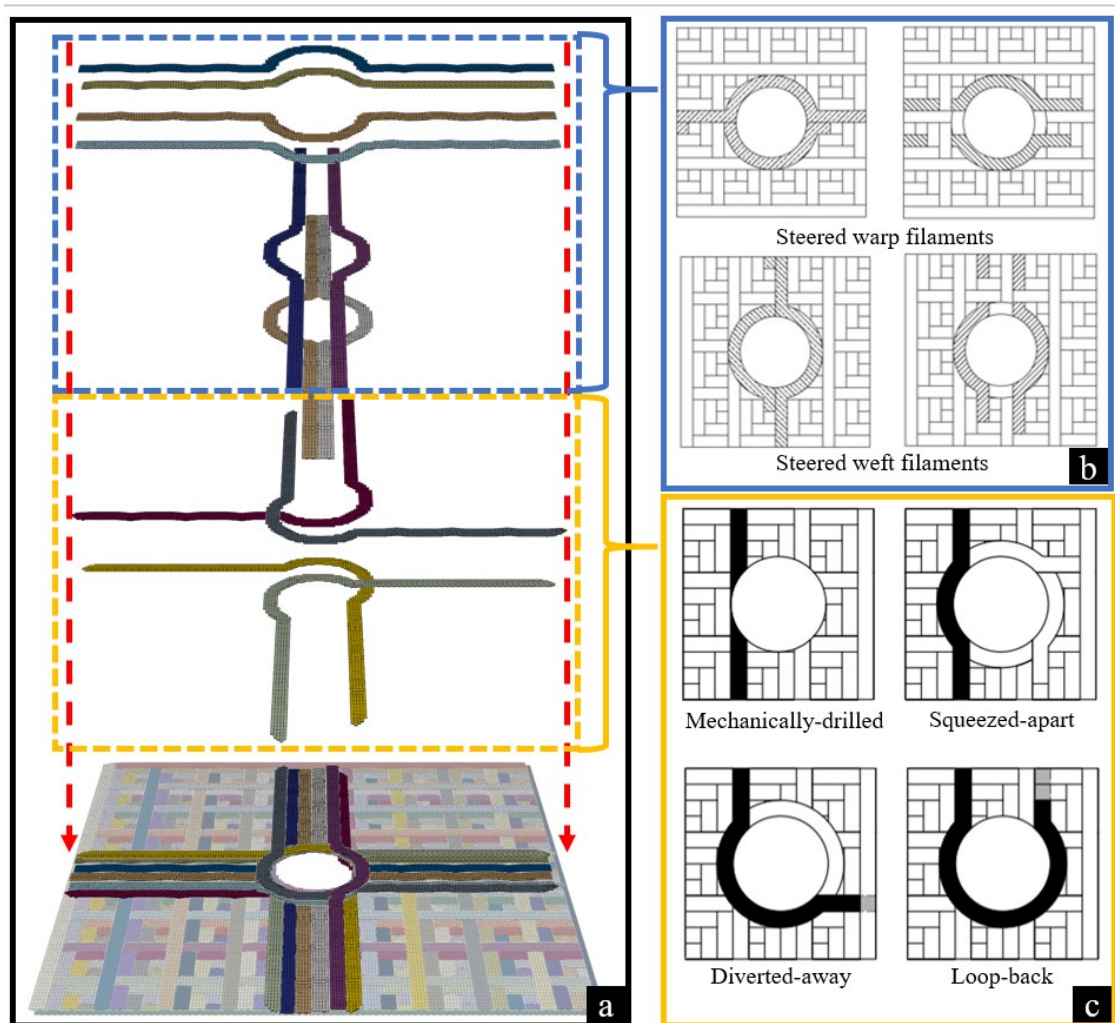


Fig. 4-1. Pseudo-woven pattern and fibre steering: (a) 3D model demonstration of steered filament distribution in the woven structure (case L); (b) Illustration of warp filaments in a

pseudo-woven pattern, showing their alteration due to a through hole, with infill pattern highlighted ; (c) Specific filaments unique to each case are marked in black, while interlaced parts are depicted in grey.

4.2.1.2. 3D printing and post-processing

In this study, a hybrid manufacturing process was employed, which involved 3D printing of composite preform layers followed by post-processing in the oven. The printing material stock was created using an in-house developed electrostatic powder deposition tapeline, similar to the method described in [218, 243]. Through this tapeline, 1K T300 carbon fibre tow sourced from Toray® was impregnated with powder-epoxy, resulting in the production of continuous filaments.

The composite filaments were 3D printed using a modified Prusa i3 MK3S printer, as illustrated in Fig. 4-2(a). The printer was interactively controlled via Pronterface, a comprehensive GUI host, connected through a USB interface. A passive continuous CF/epoxy filament feeding mechanism was employed, meaning that the feeding rate depended on the printing speed. The extruder and printing bed temperatures were set at 80 °C and room temperature, respectively. These temperature settings were chosen to ensure proper softening of the filaments within the nozzle and immediate cooling upon being printed on the bed, considering the weak adhesion between the printed tows and the bed. To prevent filament breakage caused by epoxy accumulation in the feeding channel, a polytetrafluoroethylene (PTFE) tube (Fig. 4-2 (b)) was inserted into the nozzle, creating a smooth filament delivery process. The nozzle-to-bed distance was set at 0.1 mm, resulting in a printed tow width of approximately 1 mm. Since the filament consisted of continuous carbon fibres, a continuous printing path was generated using a Python script to achieve the desired pseudo-woven pattern. Selvage regions (Fig. 4-2 (b)) were included in the print path for the purpose of path connection but were subsequently cut and removed, having no impact on the final specimen.

The connection design for the warp/weft filaments, as depicted in Fig. 4-2 (b), involved combining the steered filament pattern shown in Fig. 4-1 with the pseudo-woven units to form the bolt hole in each preform layer. Three types of connection patterns were designed and could be automatically selected and inserted into the G-code based on the filaments being connected. The first pattern, referred to as connection type I was a simple semi-circle used to connect adjacent same-direction filaments. The second pattern, identified as connection type II, was a three-quarter circle that enabled a smooth connection between warp and weft filaments. The connection methods for the third pattern varied based on the start and end points, as well as the layer dimensions. For the printing path in case L, for instance, the connection patterns were depicted as connection type III. The feed rate (also known as nozzle speed) was automatically determined by the Python program to achieve an efficient and stable printing process. Straight paths were assigned a rate of 400 mm/min, while curved paths were designated a slower rate of 200 mm/min to avoid filament detachment from the print bed. Following the 3D printing, post-processing and consolidation of the CF/epoxy was conducted. To achieve a final specimen thickness of 3mm, the number of layers was intentionally set at 13. These layers were printed individually and subsequently integrated using a compression mould, a technique that has also been applied in other studies [217, 244]. The temperature cycle curve for this process is illustrated in Fig. 4-2 (c). A temperature gap between the melting phase (around 40-60 °C) and the curing phase (above 150 °C) was present for the powder epoxy. As a result, excess epoxy and voids were squeezed out, leading to a high fibre volume fraction. To ensure easy removal of the cured sample from the mould, a non-stick PTFE sheet was applied around the mould, and the entire mould was coated with a release agent. The mould was then covered with a breathable fabric to absorb any excess melted epoxy, vacuum-packed, and placed in an oven. The heating process consisted of three stages: the oven temperature initially reached 40 °C and remained for 6 hours to eliminate moisture; it was then raised to 120 °C to melt the epoxy;

finally, the temperature was further increased to 180 °C and held for 2 hours to ensure proper consolidation of the printed composite. Manufacturing details can be seen in Fig. 4-3, including the details of the mould, post-processing set-up and final cured specimen. According to ASTM Standard D5961, for the test procedures A and C employed in this study, various requirements are specified for each variation during the experimental process. The standard test configuration for these procedures does not permit any variation of the major test parameters. These parameters are specified as follows: the loading condition must be double-shear for procedure A and single-shear for procedure C; the mating material should be a steel fixture; and the number of holes must be limited to one. However, variations in specimen and test fixture configuration are permissible, including fastener torque, laminate sequence, fastener diameter, edge distance ratio, and the ratio of width to hole diameter as well as the ratio of hole diameter to thickness. Changes can be considered compliant with this test method only as long as the values of all variant test parameters are prominently documented alongside the results. The dimensions of the specimen mentioned in this chapter were manufactured in strict accordance with the standard dimensional requirements.

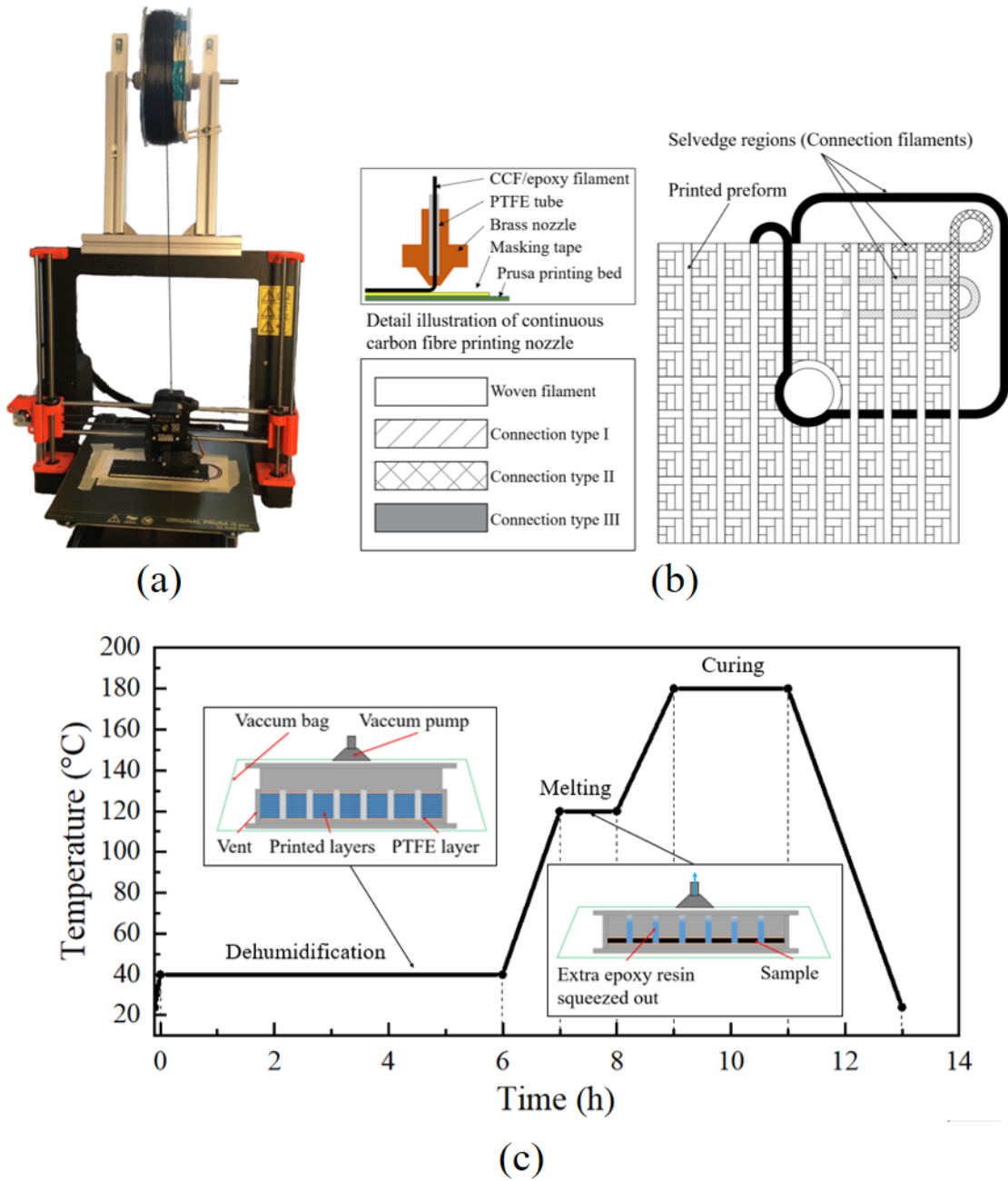


Fig. 4-2. Overview of the 3D Printing and post-processing: (a) Prusa i3 MK3S printer (b) connection of adjacent paths for continuous printing, and (c) heat cycling of oven curing.

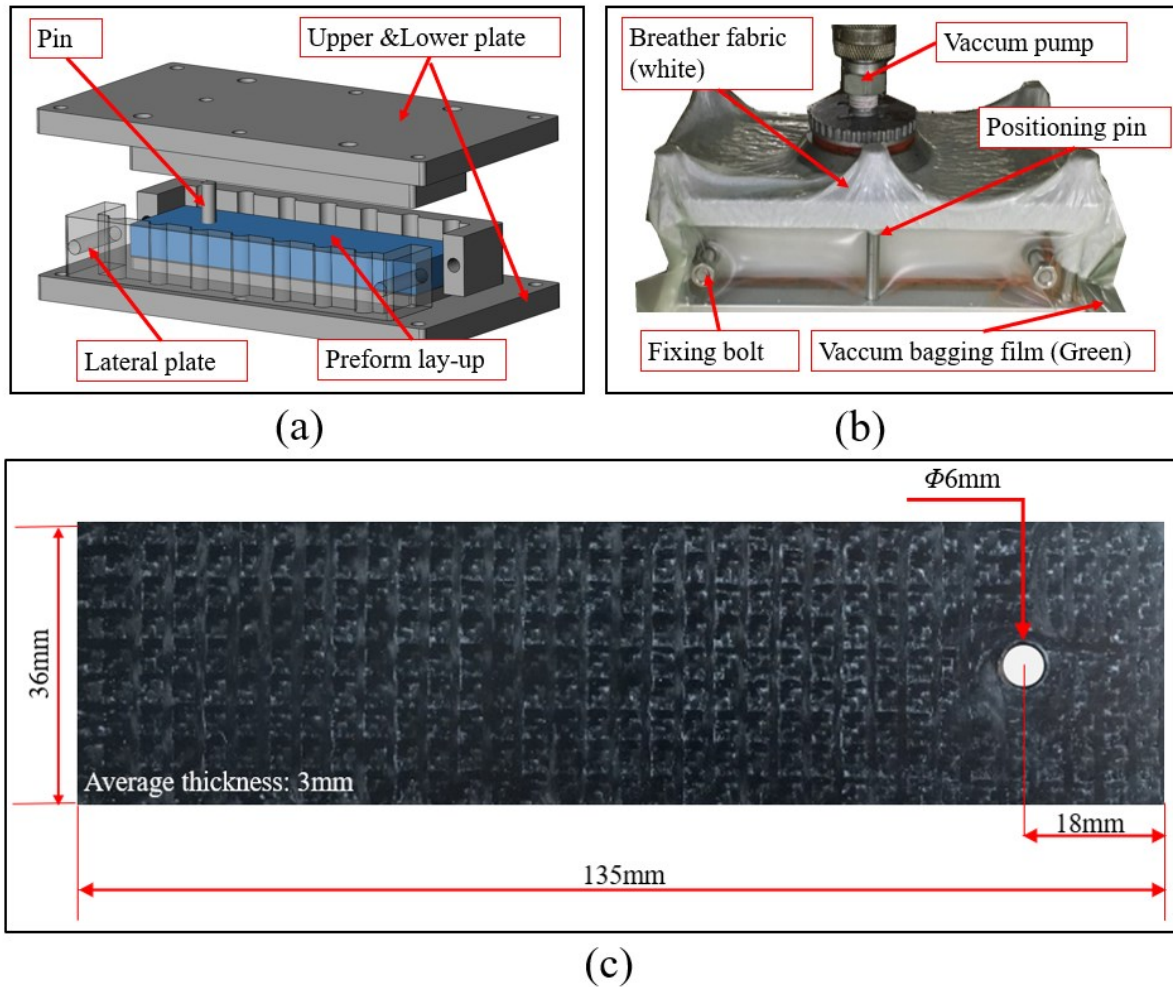


Fig. 4-3. Details of composite fabrication: (a) the dimension of the mould, (b) post-processing set-up and (c) final cured specimen corresponding to the ASTM D 5961.

4.2.2. Mechanical Testing and Micro-CT Characterisation

In this study, the ASTM D5961 standard was followed to conduct experimental tests focusing on the bearing response of fastened joints in multi-directional polymer matrix composite laminates reinforced by high-modulus fibres. The chosen testing method was the double lap joint configuration (Procedure A in the standard). The experimental work was performed using an MTS Criterion C45.305 electromechanical load frame equipped with a sturdy 300 kN load cell (as shown in Fig. 4-4). To ensure appropriate failure timing within the recommended range of 1 to 10 minutes, a loading rate of 0.5 mm/min was employed in all tests, in accordance with the ASTM standard. The specimens were securely positioned within a robust steel fixture fastened with an M6 steel nut and bolt (as depicted in Fig. 4-4). The nut was carefully tightened

to a torque of 3 N·m using a torque wrench. A 0.5 kN preload was applied to each sample prior to testing, and two specimens were tested for each fibre path pattern. To calculate the bearing strain, a high-speed camera was adopted for all the tests, functioning as a visual extensometer, recording the displacement at a specific location as depicted in Fig. 4-4. Additionally, to investigate the influence of fibre steering on strain propagation prior to initial failure, extra tests were conducted for each case using Procedure C, a test method demonstrated in the ASTM D5961 standard. Procedure C tests provide a more detailed understanding of deformation and strain distributions near the bolt hole through DIC analysis, which cannot be obtained in procedure A due to the obstructed view caused by the steel fixture. The focus was on the strain distribution before the initial failure as the loading conditions in both 'Procedure A' and 'Procedure C' were identical during the elastic stage. One specimen from each fibre steering case was subjected to procedure C tests, and the detailed experimental setup of procedure C can be seen in Fig. 4-5. The strain distribution was recorded precisely half a minute into the experiment, a stage where all four cases remained within the elastic phase and subjected to a longitudinal tensile deformation of 0.25 mm.

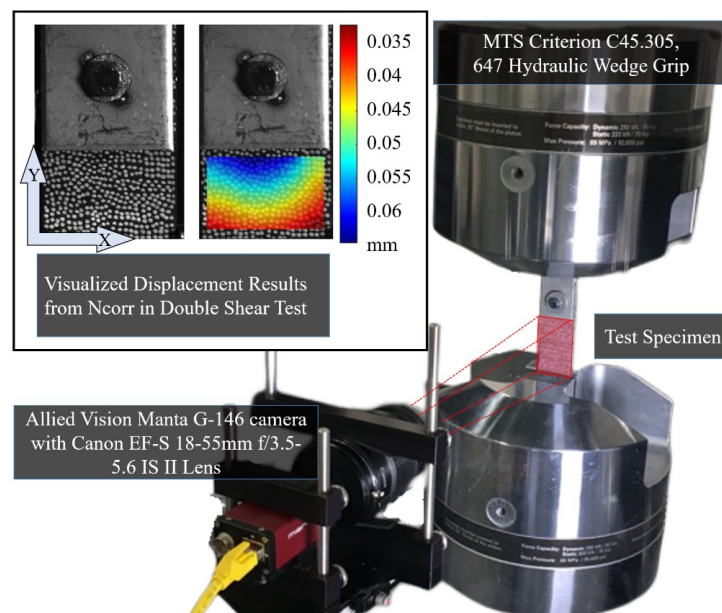


Fig. 4-4. The experimental set-up for double-lap shear bearing test.

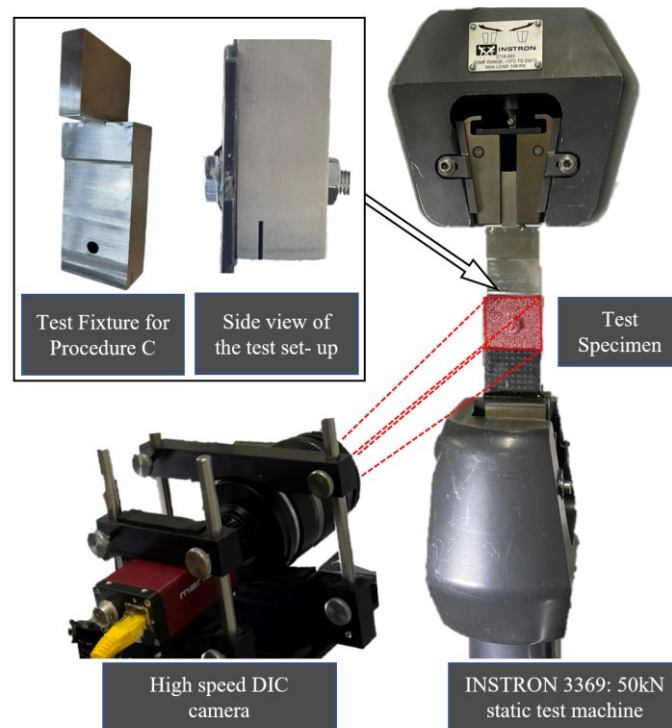


Fig. 4-5. The set-up for procedure C bearing test.

To gain a clearer view of the cracks within the composite, micro-CT scans were conducted at the in-house developed micro-CT facility in the Grant Institute, School of Geosciences, the University of Edinburgh (shown in Fig. 4-6). To achieve better resolution (around 10 μm pixel size), the tested specimens were cut into small pieces of approximately the same size with around 10 mm in width. The X-ray scans were performed with an accelerating voltage of 70 kV and a power of 24 W. The exposure time was set to 2 seconds to obtain high-quality images in terms of contrast and intensity. The raw scan data were reconstructed using Octopus 8.9 in LabView[®], and the threshold value for image analysis was determined based on expertise. Through micro-CT imaging, the crack propagation within the specimens caused by bearing load was successfully captured. The commercial software Avizo was utilised for 3D visualisation and analysis, particularly its volume rendering capabilities, which enabled the

identification of crack propagation and material deformation at any location within the scanned specimen.

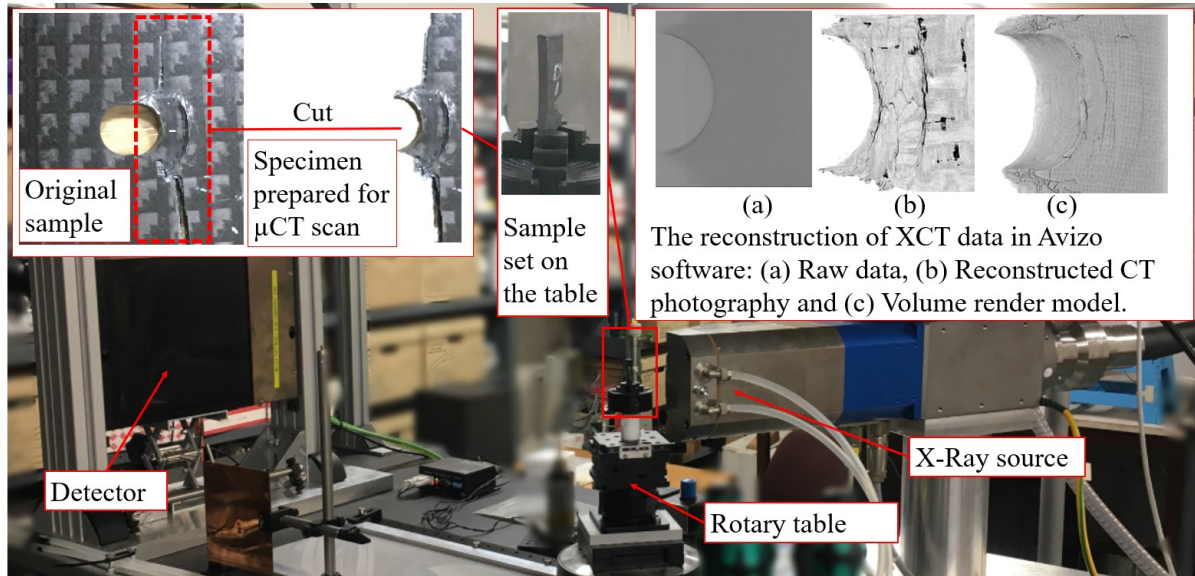


Fig. 4-6. Micro-CT scan set-up and the reconstruction of 3D images in Avizo software.

4.3. Results and Discussion

In this section, the bearing performance of 3D printed pseudo-woven composites under double lap shear loading was analysed, integrating the findings from both experimental and visual studies. Initially, the analytical results for each case are individually detailed in Fig. 5-8, including the elastic and plastic deformation, failure pattern and crack propagation identification. Subsequently, Fig. 4-12 summarises the experimental results to evaluate the capability of each pattern.

4.3.1. Analysis of Elastic Response, Failure Mode and Crack Propagation

Fig. 4-7 to Fig. 4-10 depict (a) the load-displacement curves for the four cases, which are annotated with numerical markers to represent different stages: from point ① to ② denoting the elastic stage, from point ② to ③ indicating plastic deformation, and point ③ representing the ultimate failure point. These curves are accompanied by DIC imagery and a post-failure macroscopic photograph, with damage types highlighted; (b) 3D reconstructed micro-CT

image with labelled crack propagation; sliced micro-CT images viewed in the (c) transverse direction and (d) thickness direction. Here only the necessary slices are shown and cracks are highlighted with colour associated with the labelled cracks in the 3D model. Together, these images offer further insights into the different failure modes observed during various loading periods.

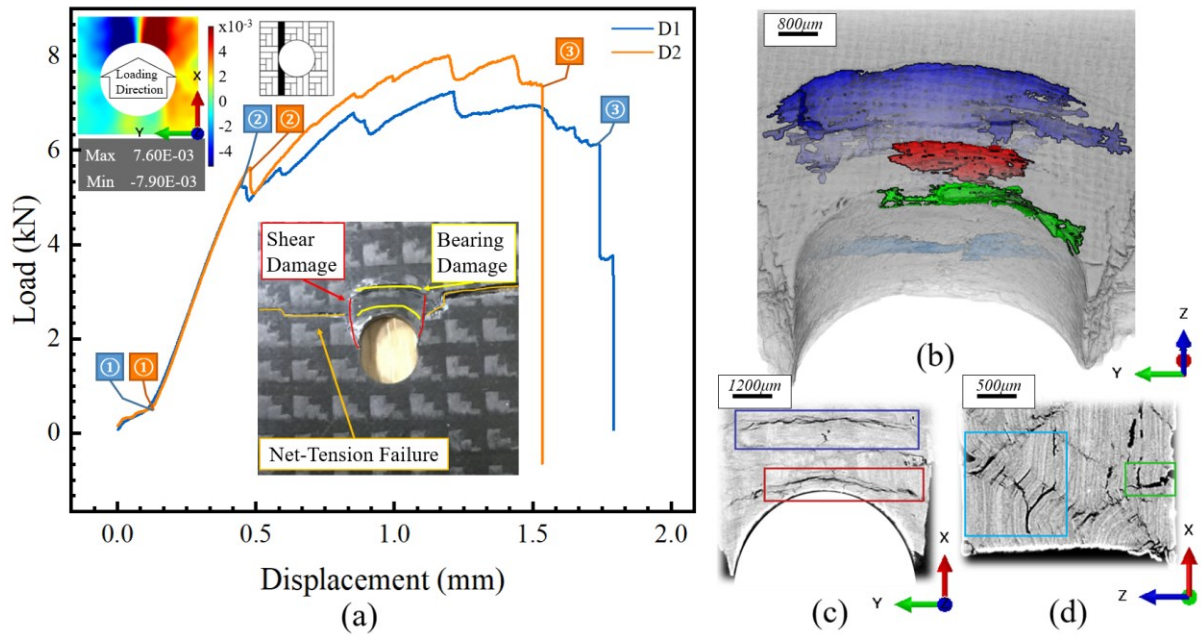


Fig. 4-7. Comprehensive analysis of case D: (a) Load-displacement curve, shear strain mapping and macroscopic visual analysis results; (b) 3D reconstructed model and micro-CT slice image captured in (c) the transverse direction and (d) thickness direction of the specimen's midsection.

As shown in the curve in Fig. 4-7, the joints exhibit structural nonlinearity with minor initial displacements until the bolt attains complete intimate contact with the hole at approximately 0.5 kN (point ①), subsequently followed by a linear correlation up to around 5.4 kN. From the DIC image, the distribution of shear strain in case D reveals the location of the highest concentration at the edge of the hole. This indicates a probable initiation point for shear deformation at this location. After a linear load increase during the elastic phase a sharp load drop (point ②) occurs. Beyond this drop, a combination of shear and bearing-induced progressive damage mechanisms was observed, extending from point ② to point ③,

characterised by alternating phases of load increase and sharp decline, a pattern that repeated until ultimate tension failure (point ③). This nonlinear behaviour is evidenced in the macroscopic photograph, which shows the shear cracks from the edge of the hole and subsequent bearing-induced crushing. Moreover, the CT image highlights cracks indicative of bearing load sustained solely by the direct contact area, leading to further kinking and crush failure as seen in the micro-CT slices (Fig. 4-7(b), (d)). in the context of case D, the initial load drop represents a significant disadvantage for the joint's overall load-bearing capacity. Despite the specimens' capability to continue carrying load, their stiffness gradually decreases. This is due to the propagation of the shear crack reducing the effective area bearing the load, leading to a weakened load transfer ability and worsened stress concentration. Overall, the above failure mechanism is considered to be particularly prevalent in mechanically drilled composite joints, because only the direct contact region bears the load without any load transfer.

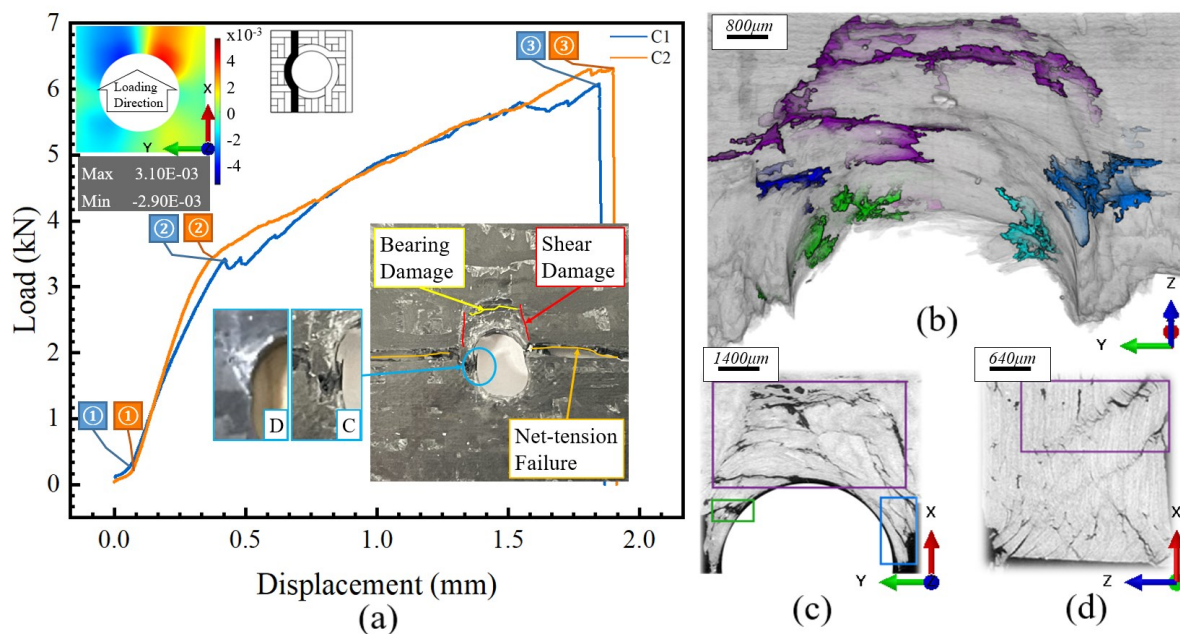


Fig. 4-8. Comprehensive analysis of case C: (a) Load-displacement curve, shear strain mapping and macroscopic visual analysis results; (b) 3D reconstructed model and micro-CT slice image captured in (c) the transverse direction and (d) thickness direction of the specimen's midsection.

From the photograph shown in Fig. 4-8 (a), a similar post-failure macroscopic photograph with case D could be seen in case C, but with differences in the specifics of the failure. Starting from the elastic phase (point ①), the strain distribution in case C indicates a reduced strain concentration, as evidenced by a lower value. Specifically, the maximum absolute strain in case D is $7.9\text{e-}03$, whereas in case C it is only $3.10\text{e-}03$. This suggests that the steered continuous fibres were successful in transferring load from the hole edge to a larger area. The consequential enhancement in shear resistance can be substantiated by the load-displacement curve, as C1 exhibits a less steep drop in load (from point ② to point ③) compared to case D, and C2 even demonstrates no initial sharp load drop at the inception of plastic deformation. By observing the fracture surface around the hole edge and cracks shown in the slices in Fig. 4-8 (b) and (c), although shear cracks were initiated, they did not trigger significant shear damage propagation in the first place until continuous fibres around the edge failed (highlighted with green and cyan).

In addition, the bearing resistance was also enhanced as the bolt movement induced a gradual increase in load with an obvious sharp drop. This signifies that not only was the region directly in contact with the bolt bearing the load, but the continuous fibres were also under tension to provide support. This observation is further validated by the macroscopic photography outlined, where the crack is seen at the neck of the hole instead of the corners, as observed in case D. Also from the micro-CT slices, instead of severe kinking, only minor crushing around the bearing region was identified.

Despite its contributions to bearing resistance, the steered fibre path C is not perceived as an efficient load transfer mechanism, because of the early initial deformation. The difference between the curves of specimens C1 and C2, suggests that the initial failure type is unpredictable, dependent on whether bearing or shear damage occurs first. This uncertainty

complicates its applicability. Also, the crack, attributed to this initial failure, reduced the bearing region capable of supporting the load from the bolt, as further confirmed by the crack marked with purple in the micro-CT scan image (Fig. 4-8 (c)), resulting in a significant stiffness loss.

Based on the results, while the steered fibre path in case C seems to enhance both shear and bearing resistance, it still fails to serve as an efficient load transfer mechanism. This inefficiency primarily stems from the early initial deformation and stiffness loss due to the subsequent cracking.

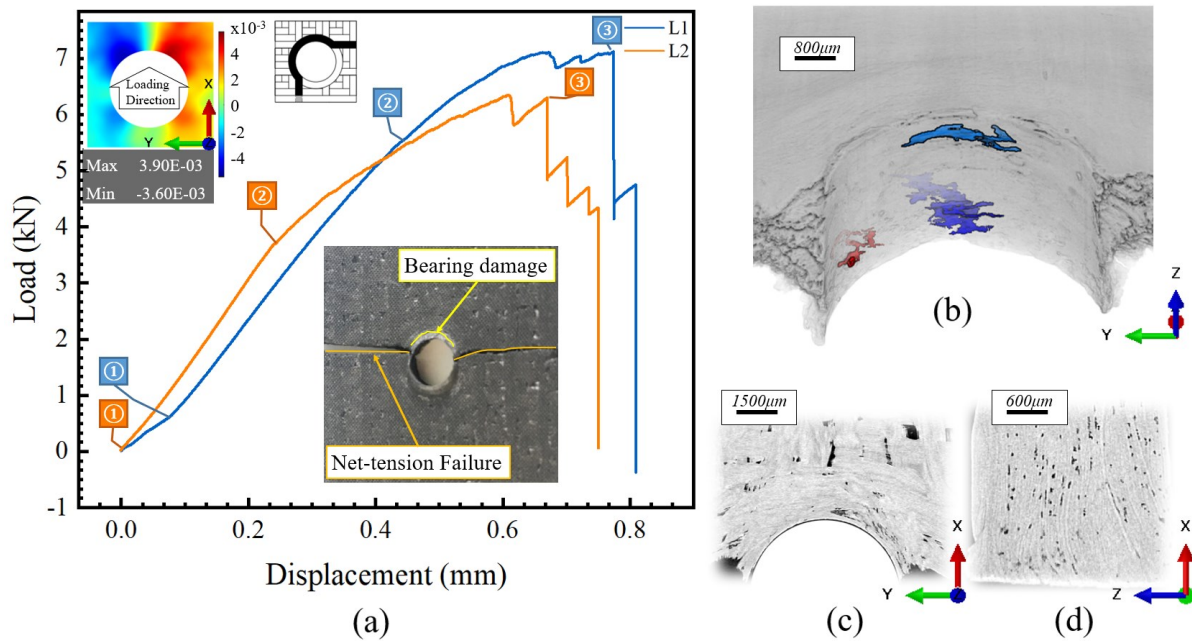


Fig. 4-9. Comprehensive analysis of case L: (a) Load-displacement curve, shear strain mapping and macroscopic visual analysis results; (b) 3D reconstructed model and micro-CT slice image captured in (c) the transverse direction and (d) thickness direction of the specimen's midsection.

In case L, the load transfer effect facilitated by the steered fibres becomes apparent from the shear strain distribution. The distribution of shear strain moved to a larger area beyond the hole edge, although some concentration remains. The load-displacement curves for case L (Fig. 4-9) display a linear behaviour until the stiffness degradation occurs at point ②. Subsequent bearing damage emerged at the edge of the hole, with the specimen's stiffness progressively decreasing

as the bolt moved. And no severe shear damage could be identified, neither from photography nor from the load-displacement curve. In this case, the specifically steered fibres were to be part of the warp and then transition into the weft. This fibre path design improved the shear resistance of the composite by altering the fibre orientation and providing a less direct path for the shear crack to initiate along the length of the fibres, potentially enhancing damage tolerance. However, a prolonged damage accumulation stage was absent before final tension failure, suggesting that while fibres steered in the L path ensured stable stiffness, they might also make the area around the hole more brittle. Upon reaching maximum load, the specimens failed abruptly in tension (point ③), accompanied by a series of sharp drops, and the load quickly decreased to zero. This implies that the orientation change potentially creates a weak point in the composite structure and the efficiency of tensile load transfer might be compromised at this junction, possibly leading to a decrease in the composite's tensile strength. The micro-CT result supports this assertion as it shows rarely bearing damage and from the photograph, the cracks initiated precisely at the fibre inflection point. In conclusion, the L pattern could enhance shear resistance and bearing resistance by transferring the load. However, the turning point of the path caused stress concentration and resulted in a weak point in terms of tension. This makes the joint to be more prone to brittle tensile failure.

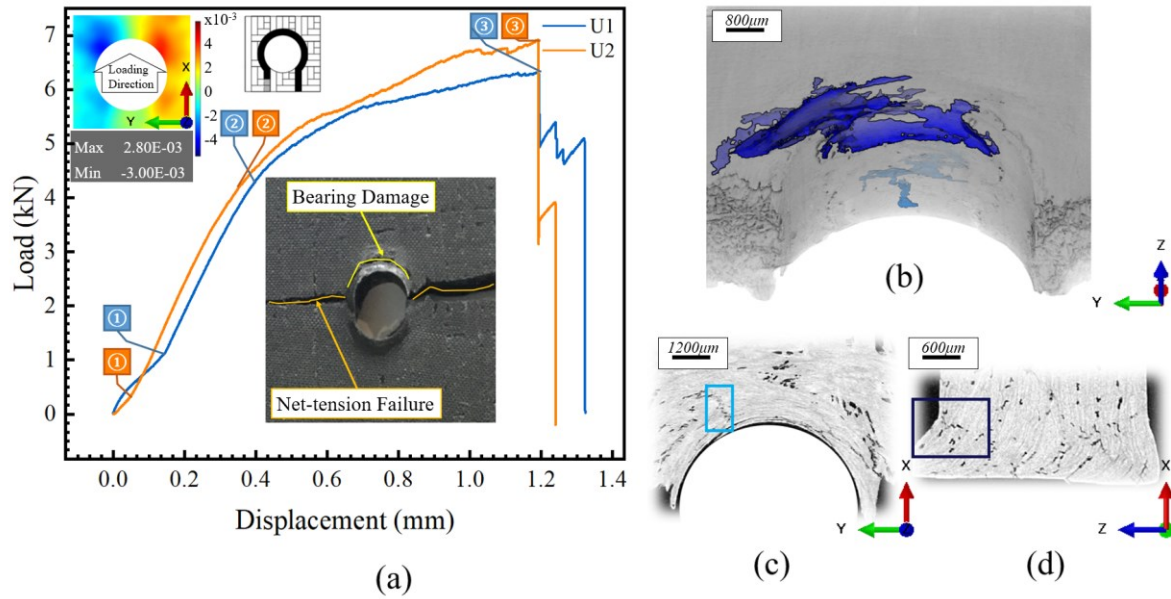


Fig. 4-10. Comprehensive analysis of case U: (a) Load-displacement curve, shear strain mapping and macroscopic visual analysis results; (b) 3D reconstructed model and micro-CT slice image captured in (c) the transverse direction and (d) thickness direction of the specimen's midsection.

For case U, the DIC image reveals that the fibre layout effectively minimised strain concentration around the hole edge and, therefore, helps resist the initiation and propagation of cracks. The load-displacement curves presented in Fig. 4-10 corroborate this improvement. Contrary to the sharp drops observed in other cases, case U displays a smoother, more gradual decline (from point ② to point ③), suggesting a more evenly distributed non-linear process within the composite rather than being localised in a few high-strain regions. The ability to alleviate shear strain concentration in a composite joint reflects the joint's resistance to localised deformation, which contributes to its overall mechanical performance with higher initial peak bearing strength and initial fracture energy. This could be obviously seen from the load-displacement curve without a sharp load drop during the bearing phase. Moreover, even though the bearing resistance in case U does not quite align with that in case L, as reflected by the reduction in stiffness, a prolonged damage accumulation stage appeared before the final tension failure. This can indicate an enhanced initial fracture toughness, with values of 22.98 mJ/mm²

in case U, compared to only 4.96 mJ/mm² in case D. Such differences are critical for the performance and longevity of composite structures across various applications.

The load transfer mechanism in this pattern is considered the reason for the toughness improvement. Unlike the L path, there was no inherent weakness prompting early brittle failure along the fibres. Also, the steered fibres in case U distribute the bolt's bearing force along their length, in conjunction with the direct contact region, providing a level of bearing resistance. Thus, a better balance was achieved between brittleness and energy absorption by this pattern, resulting in a structure that exhibits metal-like ductility. The post-failure photography and micro-CT results reveal that bearing damage mainly occurs at the direct contact surface. And the final catastrophic tension failure due to the breakage of the steered fibres happened at the neck of the hole which is reasonably the structurally weakest point.

In conclusion, the steered U fibre path provides the bolted joint with an improved better load transfer mechanism ensuring no significant shear strain concentration occurs and an ability to resist crack initiation and propagation. All these improvements lead to a uniform failure process, enhancing the composite's overall performance.

4.3.2. Comprehensive Evaluation of Mechanical Performance

This section begins with a comparative analysis of the performance of all four composite bolt joints, taking into account five mechanical properties. By comparing and contrasting these characteristics, the relative advantages and limitations of each fibre steering type are revealed. This analysis serves as a crucial step towards the selection and design of optimal composite joints, aligning with the specific demands and constraints of the intended application.

In the following discussion, a brief explanation of key parameters will be presented. In this study, the bearing chord (BC) stiffness was calculated between 50 MPa and 150 MPa. This property reflects the bearing resistance capacity during the elastic phase. It should be noted that

in this thesis, the bearing chord (BC) stiffness is not used as a precondition for determining the offset chord bearing strength, as traditionally done in ASTM standards[176]. Here, it is solely used for comparing the stiffness in various cases because this helps demonstrate the effect of fibre tailoring. As for the offset chord bearing strength, it is not considered as a comparable variable in this thesis. This decision is based on experimental results where, in some cases, the initial peak strength is the ultimate bearing strength and this is considered as an invalid condition for offset chord bearing strength according to standards[176].

Initial peak bearing (IPB) strength was selected to characterise the bolt's resilience against initial cracking and was identified by a sharp drop in the bearing stress. At this point, IPB strength and initial fracture (IF) energy were obtained for comparison. Upon reaching maximum force, ultimate bearing (UB) strength and ultimate fracture (UF) energy were recorded to demonstrate the maximum capability of a bearing specimen. The selection and computation of data were carried out utilising the Origin 2021b, a software for data analysis and graphing. A summary of these parameters is presented in Fig. 4-11 and their respective definitions and calculation equations are detailed in Eqs. (4-1)-(4-3).

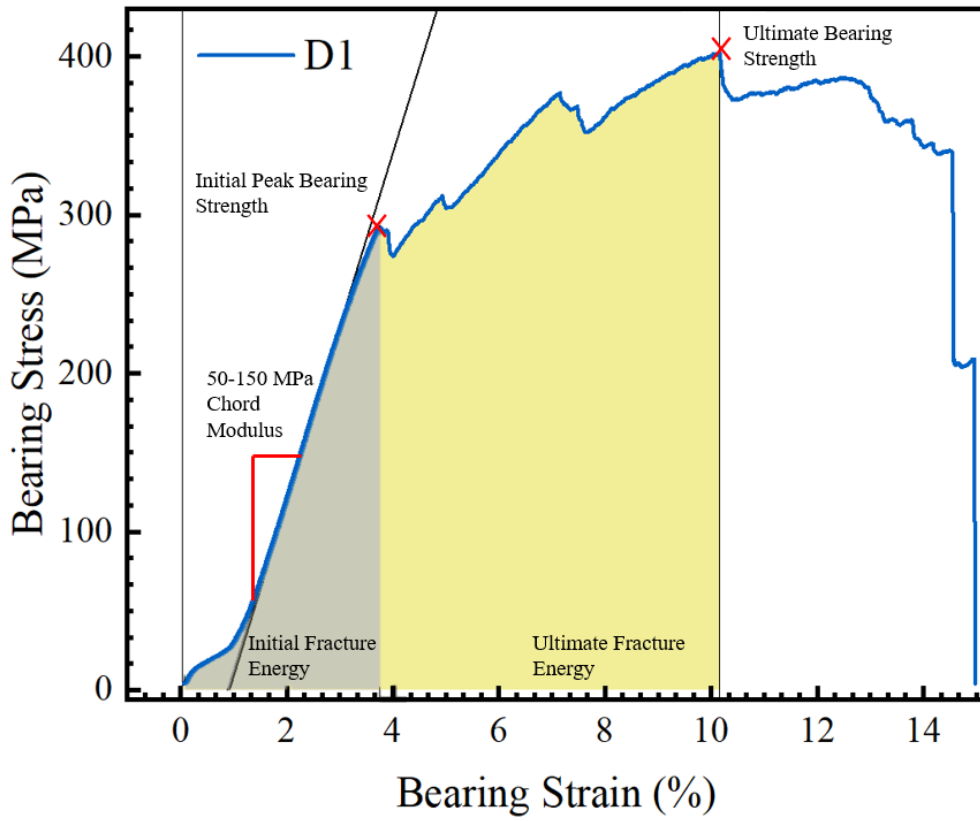


Fig. 4-11. Example (mechanically-drilled hole) of bearing stress/bearing strain curve.

The bearing strain, stress and stiffness were calculated according to ASTM-D5961 which is expressed as:

$$F^{br} = \frac{P}{(k * D * h)} \quad (4-1)$$

$$\varepsilon^{br} = \frac{(\delta_1 + \delta_2)/2}{K * D} \quad (4-2)$$

$$E^{br} = \Delta \sigma^{br} / \Delta \varepsilon^{br} \quad (4-3)$$

where *br* refers to bearing, F^{br} is the bearing strength (MPa), P is the load (kN); D is the hole diameter. h is the thickness of the specimen. k is the load per hole factor: 1 for a single fastener test. ε^{br} is bearing strain, and δ_1 and δ_2 are displacements of extensometers 1 and 2. In this study, they refer to the displacement of the load cell and the one deduced from DIC by the

method mentioned above. K is the factor and 1.0 for double shear. E^{br} is bearing stiffness (GPa), calculated between two specific points in the essentially linear portion of the load-displacement curve. $\Delta \sigma^{br}$ is the change in bearing stress and $\Delta \varepsilon^{br}$ is the change in bearing strain.

The initial and ultimate fracture energies were determined by the amount of energy absorbed until the respective points of initial and ultimate failure and were calculated through the integration of the stress-strain curve, as shown in Fig. 4-11 with grey and yellow infill, by using the integrate function in Origin software.

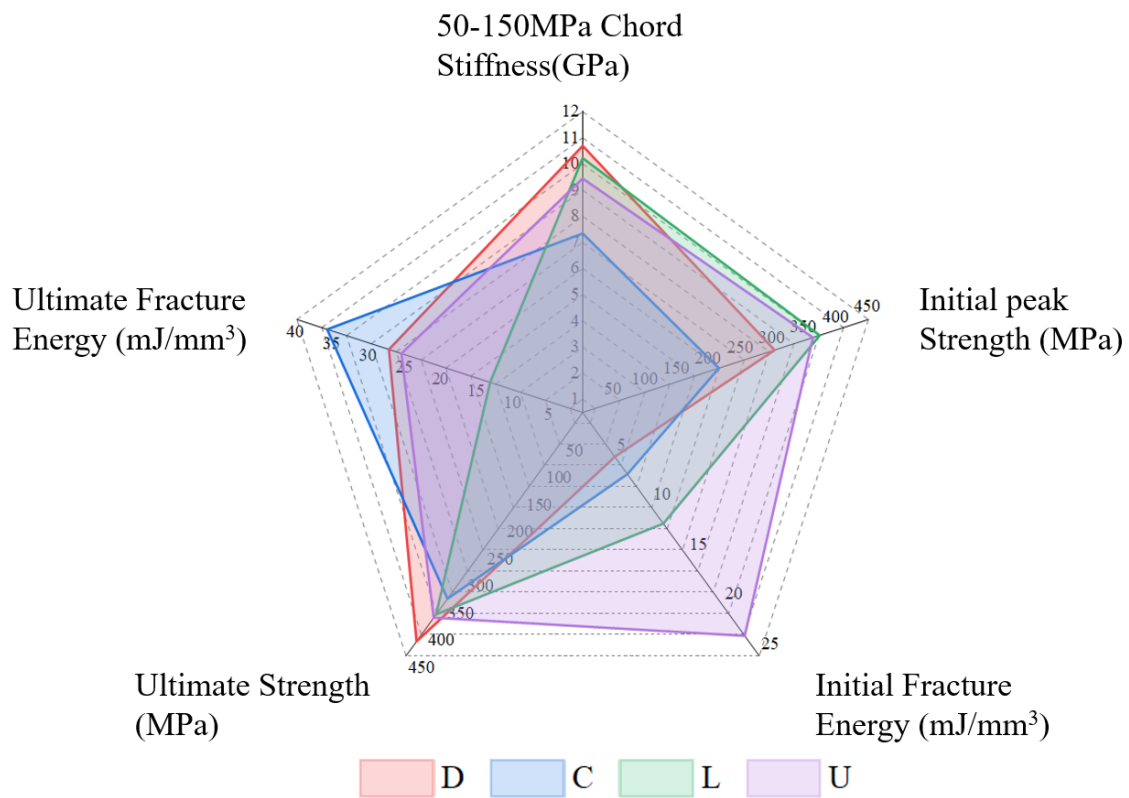


Fig. 4-12. Comparative analysis of four cases based on mechanical properties.

For the elastic phase, in terms of 50-150 MPa BC stiffness, all the fibre-steered cases exhibited a reduction except for case D. This was primarily attributed to the higher porosity within the fibre steering patterns cases caused by the defect of manufacture mentioned above. For these cases, a pin was required to form a hole during the consolidation process, thereby providing an

exit for air during compression. Consequently, voids were more likely to form around the bolt hole in fibre-steered cases as opposed to drilled cases where no pin was needed. This assertion was substantiated by porosity calculations carried out using Avizo with results presented in Table 4-1 indicating that the porosity in fibre-steered cases is nearly double that of drilled ones. Thus, the failure will be much easier to occur as the void will converge into cracks during crack propagation in tests. However, the observed stiffness behaviour contrasts with earlier work by Dickson [243], where drilled cases exhibited lower stiffness. This difference could be attributed to the manufacturing-induced damage in the drilled case in the previous study, which was minimised in the current study by utilising a carbon fibre epoxy composite. The curing process created a robust fibre/matrix interface, and the drilling process had minimal impact on stiffness. Also, due to the printing precision, fibres meant to resist the compressive load from the bolt might not be as well aligned as those in drilled cases, where the bearing load is resisted along the fibre direction. However, even among the fibre-steered cases, different steering patterns contributed variably to deformation resistance. With the lowest BC stiffness in case C, the squeezed-apart pattern is relatively weaker than diverted-away and loop-back, of which the stiffness increased by 39.25% and 28.60% separately. As discussed earlier, the deformation resistance ability depends on how well it reduces strain concentration caused by the bolt and this relies on the effectiveness of the load transfer mechanism.

Table 4-1 Void content calculated in Avizo

Case	Specimen 1	Specimen 2	Average void content (%)
Mechanically drilled (D)	1.04	1.76	1.40
Squeezed apart (C)	2.47	1.91	2.19
Diverted away (L)	2.79	2.00	2.40
Loop back (U)	2.94	2.48	2.71

Compared with case D, in terms of the IPB strengths, an improvement (23.5% and 20.0% increase respectively in cases L and U) was observed in the fibre-steered cases, with the notable exception of case C. As previously discussed, the shear damage will cause a sharp load drop, and this type of initial failure was exclusively observed in case D and case C, leading to a low IPB strength. This difference is mainly attributed to the fact that, in case L and case U, altering the fibre direction around the bolt-hole edge prevents the shear crack from initiating and propagating along the length of the fibres, potentially enhancing shear damage tolerance. This reduces the risk of shear failure at the very beginning. However, in situations like case C where the fibre direction remains unchanged, the steered continuous fibre only mitigates the plastic deformation caused by shear stresses without completely preventing it.

In addition, the early onset of shear damage in both cases C and D compromises their ability to absorb IF energy. In comparison with case D, case L exhibits an increase in energy absorption by 135.8%, attributed to its high IPB strength. However, an abrupt failure was observed in case L, leading to an energy absorption lower than that of case U. The joint in case U is considered superior among other cases, absorbing about 363.7% higher energy, achieved through a more progressive, less catastrophic deformation process.

Up to this point in the discussion, it can be asserted that the U pattern could achieve a decent initial failure tolerance in the composite bolt joint. The steered fibre not only provides high resistance to shear cracking but also ensures there are no induced weaknesses that could compromise tension resistance. As conventional CFRP composites are not widely utilised as energy absorption components due to their complex energy absorption mechanisms [245-247], the improvement of IPB strength and IF energy could significantly broaden the potential applications for CFRP composites.

In order to gain a deeper insight, the UB strength and UF energy of each case were also compared. This comparison primarily aims to provide valuable insights for future studies that

focus on reinforcing areas beyond the hole edge using fibre steering. From Fig. 4-12, none of the fibre-steering cases outperformed the UB strength achieved by the drilled case. For case D, after the initial load drop, the initial shear damage did not lead to final brittle shear out failure and the bearing damage occurred due to the high edge distance ratio of the sample, which helped case D to reach a better ultimate ability. However, compared to case D, case C exhibited a 29.6% increase in UF energy. With substantial stiffness loss following the initial damage, the joint in case C experienced gradual bearing damage, allowing it to absorb more damage before ultimate failure. For the other two steered fibre cases, they mitigated the strain and stress concentrations at the edge of the bolt hole, but the region beyond the hole was unchanged leading to low UB strength and UF energy. Although the improvements presented here are specific to the initial failure stage, the ultimate goal is to optimise all stages of joint behaviour to ensure structural integrity during the entire bearing period. These findings are instrumental in directing future research towards achieving this goal.

After evaluating all the properties, it is found that reinforcing the edge of the hole with steered fibre significantly enhanced the initial stages of failure for the bolted composite joint. Even though the steered fibre pattern implemented in this study did not significantly increase the ultimate capacity, a comprehensive analysis of the radar chart in Fig. 4-12, indicates that case U exhibited the most balanced bearing performance throughout the entire bolt bearing process.

4.4. Conclusions

The effect of fibre steering on the crack initiation and propagation was examined through double-lap bearing tests performed on four distinct cases and various damage mechanisms were studied in all the cases. The possibility of enhancing the joint's bearing performance by fibre steering was explored. Based on the results, the following conclusions can be drawn:

- Fibre steering can address the issue of shear strain concentration at the edge of the bolt hole by maintaining the continuity of the carbon fibre. It transfers the bearing load into a larger volume of material. Furthermore, altering the fibre orientation enhances the load transfer mechanism's effectiveness. For pseudo-woven composites, an orientation change of 180 degrees has been proven to distribute strain evenly and reduce the maximum absolute strain value by approximately half.
- Regarding the enhancement of initial damage toughness, merely maintaining carbon fibre continuity is insufficient. This is because both shear and bearing damage will still commence. By adjusting the orientation of the steered fibre around the hole edge, the initiation and propagation of shear cracks along the fibre direction become less likely. This finding is clearly demonstrated in case U, where notable enhancements of IBP strength and IF energy were observed, with improvements approximating 23.5% and 363.7% respectively.
- The steered fibre provides different bearing ductility for the composite joint, depending on the degree of fibre orientation change. According to this study, a change of 90 degrees induces brittleness, while 180 degrees enhances ductility. Therefore, fibre steering emerges as a potential solution for meeting specific bearing requirements by manipulating the fibre path.
- Steering fibres only around the hole edge may not improve ultimate toughness and might even weaken it. Future studies should focus on optimising load transfer with steered fibres considering the entire structure.

A limitation of the current study lies in the absence of comprehensive data regarding the progressive failure process and the exact mechanisms by which the specific steered fibres transfer the load. Further simulation studies will be conducted in the next Chapter to investigate these aspects.

Chapter 5. 3D Printing of Pseudo-woven CFRP Composites with Bolted

Joints: Multiscale FE Modelling

5.1. Chapter Introduction and Overview

This Chapter investigates the bearing failure process of 3D printed pseudo-woven carbon fibre reinforced polymer (CFRP) composites that were manufactured and tested in Chapter 4, with a particular focus on the damage mechanisms influenced by steered fibres. A multiscale finite element model employing LaRC05 failure criteria is developed and validated against the experimental load-displacement curves and Micro-CT images of four distinct cases.

Manufacturing and testing experiments of CFRP composites are expensive and time consuming, thus theoretical and computational analysis has been sought to support and compliment the physical experiments [64]. Specifically, several methodologies have been developed to study the mechanical behaviour of composite bolted joints and bridge the analysis with experimental results [248] such as analytical methods [64, 249], and progressive damage methods [147, 250-252]. These methods are useful for the traditional composite joint where the fibre orientation is either unidirectional or displays periodicity, which can be modelled by RVE and then homogenised to the macroscopic scale. However, for the macro composite structure with a locally customised fibre tailor pattern, it is not feasible to directly use RVE to homogenise the entire structure. The simulation approach for composites with curved continuous fibres has also been developed [149]. However, the fibre placement was defined within the ply level, which cannot address the woven cases where fibres interweave in the thickness direction. In Chapter 4, pseudo-woven composite joints are 3D printed, where the fibres in each filament are steered around the joint, thus a mesoscale filament-level numerical model based on a three-dimensional real printing paths needs to be developed so as to predict the mechanical response of the printed composite joint.

From the mechanical tests under shear loading in Chapter 4, it was found that different initial failure behaviours were achieved by altering the fibre steering pattern, therefore in this Chapter, more detailed characterisation was performed to better understand the failure mechanism. Scanning Electron Microscope (SEM) and Micro-CT scans were conducted to obtain the material and damage characteristics including fibre volume fraction, void content and crack propagation. In addition, a novel finite element model integrated with Texgen software was then built using real fibre paths within the 3D printed pseudo-woven composites.

5.2. Methodology

5.2.1. Modelling Strategy

The model described in this section aims to provide a comprehensive understanding of the mechanical behaviour of 3D printed filament based composites, with specific application to pseudo woven composites. The orientation of fibres in both out-of-plane and in-plane directions is crucial for accurately predicting deformation, failure and damage progression in 3D models of composites [253, 254]. Explicitly modelling steered filaments as uninterrupted models presents significant challenges due to the intricate internal architecture at tow crossovers. It also suffers from issues related to tow interpenetration, requiring manual involvement for resolution [255]. To avoid these limitations, a novel multiscale modelling approach is introduced in this study, which is capable of capturing the macroscale variations in strength and stiffness induced by steered filaments.

The multiscale modelling process, shown in the flowchart in Fig. 5-1, integrates the microstructure and mesoscale geometry into the macroscale response of the composite structure. Initially, material constituents of fibre tows and epoxy resin are characterised to establish a stiffness matrix for both the filament and the resin-rich regions at the microscale. This initial phase uses the volume fraction data mentioned in section 3.3, setting the stage for

a detailed mesoscale analysis. At the macroscopic scale, the first step in finite element analysis involves achieving equilibrium through parameters initially defined within the macro-model, which include boundary conditions, constraints, and contact relationships, among others. Subsequently, in combination with the stiffness matrix calculated at the micro-level, the initial strain at each integration point within the mesoscale model is computed. At the mesoscale, critical input parameters such as the initial stiffness matrix, global strain vector, state variables and time step, alongside the filament orientation field, are read into the model and assigned to the elements in each component based on their relative contributions. Specifically, the orientation of filament elements is defined by a discrete field based on fibre directions, while resin-rich regions are considered isotropic. Consequently, the model consists of two distinct parts: one part representing the filament embedded within the resin and the other part representing the resin-rich region or the host material surrounding the filament. The LaRC05 damage criterion is employed for both pathways to evaluate the onset of damage.

Upon the onset of damage, the stiffness tensor begins degradation. The degradation process is controlled by distinct parameters across each part. Specifically, the damage of the filament part includes three damage variables, d_f , d_m and d_s , which correspond to damage in the fibre, matrix and shear modes, respectively. Conversely, the matrix part is influenced solely by the matrix damage variable d_m , reflecting the specific damage within the matrix. This demonstrates a customised strategy for modelling the damage behaviours of each constituent individually. Subsequently, a linear damage evolution law is applied, resulting in the calculation of new stress states. Returning to the macroscale model, the new the constitutive tensor from the mesoscale are homogenised by an embedded element (EE) technique to determine the next step deformation within the entire composite structure. This process is repeated at each time increment throughout the entire multiscale simulation. The following sections will offer a

comprehensive mathematical and physical explanation of all the components at multiple scales comprising the proposed modelling approach.

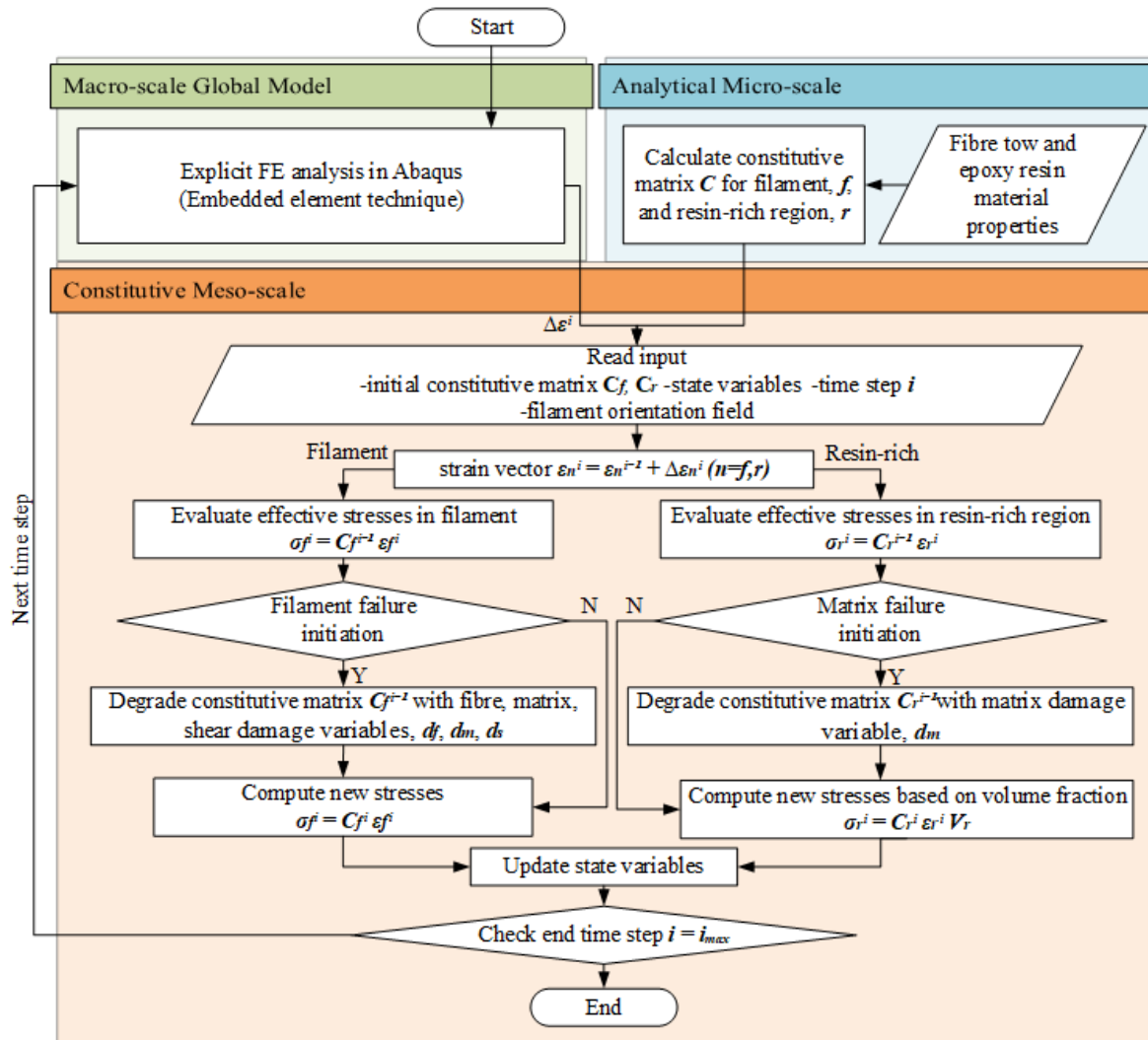


Fig. 5-1. Flowchart of the multiscale modelling strategy.

5.2.2. Microscale Model of Material Properties and Mesoscale Unit-cell Model

As outlined in Section 3.3, the elastic properties are determined using a hybrid approach that incorporates reference data, experimental testing, and empirical calculations, employing 1K fibre tow and epoxy material properties that are detailed in Table 3-2 and Table 3-4. The strength parameters and fracture toughness of the material are presented in Table 3-3, Table 3-5 and

Table 3-6, which are obtained from experiment tests and literature. Through these material parameters, the model advances from the micro-scale model of fibre and epoxy resin to the meso-scale of filament and resin-rich region.

5.2.2.1. Assumptions and idealisation at the meso-scale level

In the multiscale modelling approach, the macroscale behaviour of the 3D pseudo-woven composite is linked to a mesoscale idealised unit-cell model which evolves with the printed filament paths. Thus, the mesoscale model is essential for characterising both the elastic behaviours and damage evolution of the composite. It is applied by the macro-level explicit finite element solver at each material integration point to update the state of the macro model.

The mesoscale unit-cell model includes a few specific considerations: a) the fibre-matrix interface is not explicitly modelled but assumed to be perfectly bonded; b) to simplify computations, the filaments are represented using voxels and the waviness of the filaments is approximated by applying a finer voxel mesh in the thickness direction; c) the cross-sectional area of each printed filament (in parallel with a yarn in the traditional woven composites) is approximated as elliptical and constant along its length; d) voids are not included but accounted for through material properties; e) each filament is independently generated based on ideal printing paths, neglecting potential intersections; f) the resin-rich region properties are assumed to be identical to the transverse properties of a unidirectional tow and the properties of this region are assumed to be identical to the transverse properties of a unidirectional tow and only the matrix damage is considered; g) only a single layer is simulated under the double-shear condition; h) as mentioned in section 3.2, due to the current lack of sufficient experimental studies on individual filaments, each printed filament was treated as a impregnated UD laminate concerning aspects of failure initiation and damage evolution with uniformly distributed fibres and no fibre misalignment.

The idealised unit-cell model is representative of the real internal architecture of the 3D pseudo-woven composite, capturing the geometric details of each steered filament. This is achieved by using actual printing paths and post-curing thickness to construct the ideal geometric model, thereby facilitating the study of the mechanical behaviour and failure modes of individual fibres within the overall structure. In order to consider the impact of voids, according to the literature [256], the filament's transverse elastic and shear modulus, along with the elastic and shear modulus of the resin-rich region, reductions of 12.19% and 11.64% are applied respectively for each 1% increase in porosity. Detailed porosity in each case is listed in Table 4-1. To simplify calculations, the embedded element technique (EET) is employed to model the fibre-matrix relationship. This is deemed acceptable based on prior research [217], particularly as the study involves a thermosetting matrix that generally exhibits good wettability, thus allowing for the assumption that the filaments (impregnated yarns) are perfectly bonded within the matrix. The filament intersection issue is resolved each printed filament is independently embedded into the host elements of the matrix. Although it is possible to model these intersections by adjusting cross-sectional shapes along the paths in Texgen, such a method would significantly increase the time required for model generation and computation. Therefore, the adopted approach efficiently addresses these challenges without compromising the effectiveness of the model. Also, when using the EET, additional mass and stiffness due to the embedded elements are added to the model [257]. This issue is resolved by calculating the global stress contribution components based on the volume fractions of the resin-rich region and filament, which will be explained in section 5.2.3. Further information about EET can be found in the upcoming section 5.2.4. Lastly, the absence of delamination and out-of-plane failure is justified since the laminate has identical layers subjected to a double shear loading, thus a single layer model is sufficient for investigating how fibre steering around the hole affects the overall mechanical performance of the laminate.

5.2.2.2. Constitutive relationship

As mentioned above each printed filament is treated as an orthotropic material. The local coordinate system for the filament is defined as 1-2-3, where 1-axis is the fibre direction (and also the print direction). Meanwhile, the 2 and 3 axes, perpendicular to the fibre direction, display isotropic behaviour in the 2-3 plane within this filament. The constitutive behaviour of an undamaged filament in compliance form is described as:

$$\varepsilon = S\sigma \quad (5-1)$$

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{12} \\ \gamma_{23} \\ \gamma_{13} \end{pmatrix} = \begin{pmatrix} 1/E_1 & -\nu_{12}/E_1 & -\nu_{12}/E_1 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & -\nu_{23}/E_2 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & -\nu_{23}/E_2 & 1/E_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1 + \nu_{23})/E_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{pmatrix} \times \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{12} \\ \tau_{23} \\ \tau_{13} \end{pmatrix} \quad (5-2)$$

Damage in the filament follows a CDM framework mentioned in section 2.3.1 that modulates the material stiffness as the damage occurs to account for the damaged material response. In this context, a damage tensor, denoted as M , serves to relate the effective stress $\tilde{\sigma}$ to the nominal stress σ as per Eq. (5-3). M is a diagonal matrix composed of damage parameters, represented using the diag () notation.

$$\tilde{\sigma} = M\sigma ; M = \text{diag} \left(\frac{1}{1-d_f}, \frac{1}{1-d_m}, \frac{1}{1-d_m}, \frac{1}{1-d_s}, \frac{1}{1-d_s}, \frac{1}{1-d_s} \right) \quad (5-3)$$

Prior to any damage onset, the material behaviour is linear-elastic. Once damage initiates, stress decreasing linearly with the increase of the strain in the filament is modelled according to the linear damage evolution laws, which are functions of three damage variables, *i.e.* d_f , d_m and d_s , which represent damage in fibre, matrix and filament shear modes, respectively. These variables account for the effects of loading directions, specifically tension (t) and compression (c), as described in Eq. (5-4).

$$\begin{aligned}
d_f &= 1 - (1 - d_{ft})(1 - d_{fc}); \quad d_m = 1 - (1 - d_{mt})(1 - d_{mc}); \\
d_s &= 1 - (1 - d_f)(1 - d_m)
\end{aligned} \tag{5-4}$$

These damage variables are initialised at zero and evolve toward unity as strains reach the levels corresponding to failure. The computational methodology for determining the damage variables d_{ft} , d_{fc} , d_{mt} , and d_{mc} will be elaborated in Section 5.2.2.4. Additionally, the constitutive relationship for the damaged filaments can be assessed through the integration of Eqs. (5-1) and (5-3), as expressed in Eq. (5-5).

$$\varepsilon = S\tilde{\sigma} = SM\sigma = S_d \sigma \tag{5-5}$$

Here, S_d denotes the compliance matrix that incorporates damage effects and can be formulated as a function of these damage variables and the material's inherent elastic constants as Eq. (5-6)

$$S_d = \begin{pmatrix} 1/(1-d_f)E_1 & -\nu_{12}/E_1 & -\nu_{12}/E_1 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/(1-d_m)E_2 & -\nu_{23}/E_2 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & -\nu_{23}/E_2 & 1/(1-d_m)E_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/(1-d_s)G_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu_{23})/(1-d_s)E_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/(1-d_s)G_{12} \end{pmatrix} \tag{5-6}$$

Additionally, the stiffness matrix that incorporates damage, denoted as C_d , is computed by inverting S_d , such that $C_d = S_d^{-1}$. As a result, the constitutive relationship for the damaged filament, expressed in terms of the stiffness matrix C_d , is articulated in Eq. (5-7) and is integrated into a VUMAT subroutine in Abaqus/Explicit.

$$\sigma = C_d \varepsilon \tag{5-7}$$

The components C_{ij} of the C_d matrix are expressed in terms of material properties and damage variables, as specified in Eq. (5-8).

$$C_{11} = (1 - d_f)E_1[1 - (1 - d_m)(1 - d_m)\nu_{23}\nu_{32}]/\Delta$$

$$C_{22} = (1 - d_m)E_2[1 - (1 - d_f)(1 - d_m)\nu_{13}\nu_{31}]/\Delta$$

$$C_{33} = (1 - d_m)E_2[(1 - d_f)(1 - d_m)(1 - \nu_{12}\nu_{21})]/\Delta$$

$$C_{12} = (1 - d_f)(1 - d_m)E_1[(1 - d_m)\nu_{31}\nu_{23} + \nu_{21}]/\Delta$$

$$C_{13} = (1 - d_f)(1 - d_m)E_1[(1 - d_m)\nu_{21}\nu_{32} + \nu_{31}]/\Delta$$

$$C_{23} = (1 - d_m)(1 - d_m)E_2[(1 - d_f)\nu_{12}\nu_{31} + \nu_{32}]/\Delta$$

$$C_{44} = (1 - d_s)G_{12};$$

$$C_{55} = (1 - d_s)G_{23};$$

$$C_{66} = (1 - d_s)G_{12}$$

with

$$\begin{aligned} \Delta = & 1 - (1 - d_m)(1 - d_m)\nu_{32}\nu_{23} - (1 - d_f)(1 - d_m)\nu_{31}\nu_{13} \\ & - (1 - d_f)(1 - d_m)\nu_{21}\nu_{12} - 2(1 - d_f)(1 - d_m)(1 - d_m)\nu_{13}\nu_{21}\nu_{32} \end{aligned} \quad (5-8)$$

As mentioned in section 5.2.2.1, the resin-rich regions are assumed to be linearly elastic and isotropic. As such, their modulus is degraded using a single scalar damage variable d_m . The compliance matrix, which is a function of the damage state, is:

$$\begin{aligned} H &= \frac{1}{E_m} \begin{pmatrix} 1/(1 - d_m) & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1/(1 - d_m) & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1/(1 - d_m) & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 + \nu/(1 - d_m) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 + \nu/(1 - d_m) & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 + \nu/(1 - d_m) \end{pmatrix} \end{aligned} \quad (5-9)$$

Damage onset in resin-rich regions is also predicted using the same LaRC05 criteria, but only matrix failure onset and evolution are considered. This method of calculating constitutive behaviour separately has been applied in other studies [146, 258]. Specifically, in the resin rich region, it is assumed to be equal to the transverse strengths of the unidirectional tows. Therefore,

a single damage variable, d_m , is used to degrade the stiffness in all directions of the resin-rich region, indicating matrix damage.

5.2.2.3. Failure criteria and damage initiation

For the onset of CF/epoxy filament damage, the 3D LaRC05 failure criterion [129] is used. Generally, it can be applied to polymer-matrix fibre-reinforced composites and it considers four different damage initiation modes, *i.e.*, matrix cracking, fibre kinking, fibre splitting and fibre tension, using corresponding failure index FI . For the fibre tensile failure, as maximum stress failure criterion has been shown to well related with existing experimental data regarding fibre tensile failure [259], it is used to predict this failure mode in LaRC05:

$$FI_{FT} = \frac{\sigma_1}{X_T} \quad (5-10)$$

For fibre kinking and splitting failure in LaRC05, it is assumed that they are triggered by localised shear-dominated matrix failure next to misaligned fibres. In multi-layer composite, matrix splitting between fibres may occur as the consequence of high shear stress brought by failure in the adjacent layer or manufacturing defects like fibre misalignment. In this study, such damage predominantly results from the substantial variability caused by fibre steering, similar to fibre misalignment. Additionally, if the absolute value of longitudinal compression load is greater than $X_C/2$, fibre breakage occurs due to the combination of bending and compressive stresses and the failure will be fibre kinking instead. Thus, the LaRC05 criteria for fibre splitting and kinking use the same failure index (Eq. (5-11)) and these two failure modes are differentiated by the magnitude of longitudinal compression.

$$FI_{KINK} = FI_{SPLIT} = \left(\frac{\tau_{23}^m}{S_T^{is} - \eta_T \sigma_2^m} \right)^2 + \left(\frac{\tau_{12}^m}{S_L^{is} - \eta_L \sigma_2^m} \right)^2 + \left(\frac{\langle \sigma_2^m \rangle_+}{Y_T^{is}} \right)^2 \quad (5-11)$$

where σ_2^m , τ_{12}^m and τ_{23}^m are the normal and shear traction components on kink-band plane with subsequent rotation to the misalignment frame. Y_T^{is} , S_T^{is} and S_L^{is} are the transverse tensile

strength, longitudinal shear strength and in-situ transverse shear strength, respectively; η_T and η_L are the friction coefficients under longitudinal shear stress and transverse shear stress.

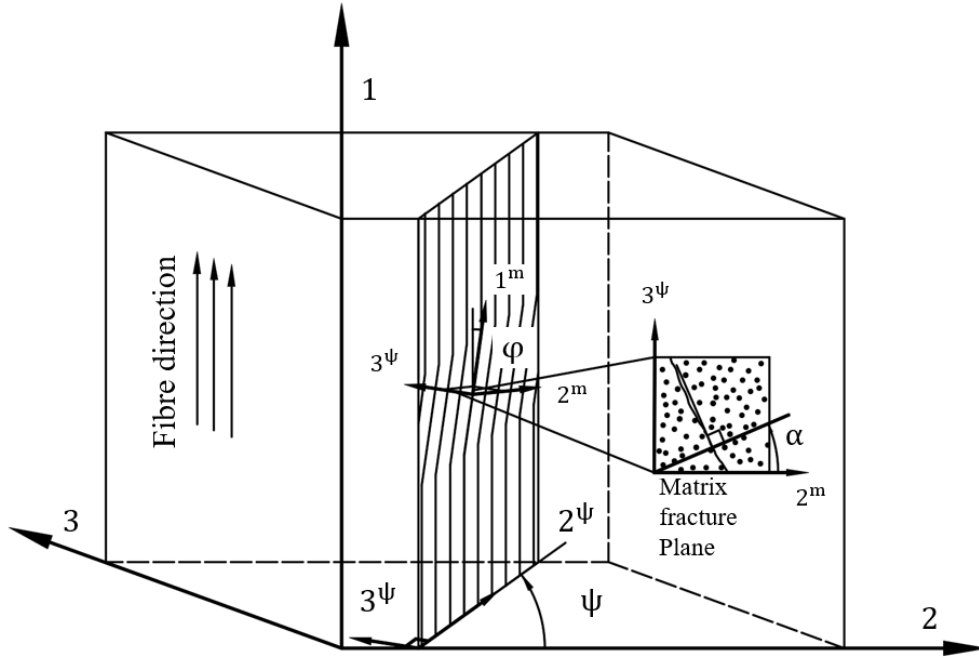


Fig. 5-2. Schematic representation of kink-band and fracture plane along with associated coordinate systems.

The assessment of failure indices for fibre kinking and matrix failure is conducted based on the effective stresses acting on the respective planes of kinking and fracture, as depicted in Fig. 5-2. The relevant rotation of stress to the kink-band plane, denoted by ψ , is described in Eq. (5-12).

$$\begin{cases} \tilde{\sigma}_2^\psi = & \tilde{\sigma}_2 \cos^2 \psi + \tilde{\sigma}_3 \sin^2 \psi + 2\tilde{\tau}_{23} \sin \psi \cos \psi \\ \tilde{\tau}_{12}^\psi = & \tilde{\tau}_{12} \cos \psi + \tilde{\tau}_{13} \sin \psi \\ \tilde{\tau}_{13}^\psi = & \tilde{\tau}_{13} \cos \psi - \tilde{\tau}_{12} \sin \psi \\ \tilde{\tau}_{23}^\psi = & (\tilde{\sigma}_3 - \tilde{\sigma}_2) \sin \psi \cos \psi + \tilde{\tau}_{23} (\cos^2 \psi - \sin^2 \psi) \end{cases} \quad (5-12)$$

where the angle of the kink-band plane, ψ , is determined within the subroutine using a numerical search algorithm. This algorithm searches within the interval $[0^\circ, 180^\circ]$ in increments of 1° to find the angle that maximises the fibre splitting/kinking failure index.

$$\begin{cases} \tilde{\sigma}_2^m = & \tilde{\sigma}_1 \sin^2 \varphi + \tilde{\sigma}_2^\psi \cos^2 \varphi - 2\tilde{\tau}_{12}^\psi \sin \varphi \cos \varphi \\ \tilde{\tau}_{12}^m = & (\tilde{\sigma}_2^\psi - \tilde{\sigma}_1) \sin \varphi \cos \varphi + \tilde{\tau}_{12} (\cos^2 \varphi - \sin^2 \varphi) \\ \tilde{\tau}_{23}^m = & \tilde{\tau}_{23}^\psi \cos \varphi - \tilde{\tau}_{31}^\psi \sin \varphi \end{cases} \quad (5-13)$$

Eq. (5-13) is for the subsequent rotation to the misalignment frame. As the simulation is based on the fundamental units of individual filaments, it is assumed that there is no misalignment of the fibre. Consequently, the intrinsic misalignment angle φ is considered to be zero (mentioned in section 5.2.2.1), eliminating the need for any subsequent rotation to the misalignment frame.

The failure index for matrix cracking is defined as:

$$FI_M = \begin{cases} \left(\frac{\tau_T}{S_T^{is} - \eta_T \sigma_N} \right)^2 + \left(\frac{\tau_L}{S_L^{is} - \eta_L \sigma_N} \right)^2 + \left(\frac{\sigma_N}{Y_T^{is}} \right)^2, & \sigma_N(\alpha_0) \geq 0 \\ \left(\frac{\tau_T}{S_T^{is} - \eta_T \sigma_N} \right)^2 + \left(\frac{\tau_L}{S_L^{is} - \eta_L \sigma_N} \right)^2, & \sigma_N(\alpha_0) < 0 \end{cases} \quad (5-14)$$

where σ_N , τ_T and τ_L are the normal and shear traction components. Other variables are mentioned above.

The traction components σ_N , τ_T and τ_L on the fracture plane are obtained by stress transformation:

$$\begin{cases} \sigma_N(\alpha) = & \frac{\sigma_2 + \sigma_3}{2} + \frac{\sigma_2 - \sigma_3}{2} \cos(2\alpha) + \tau_{23} \sin(2\alpha) \\ \tau_T(\alpha) = & -\frac{\sigma_2 - \sigma_3}{2} \sin(2\alpha) + \tau_{23} \cos(2\alpha) \\ \tau_L(\alpha) = & \tau_{13} \sin(\alpha) + \tau_{12} \cos(\alpha) \end{cases} \quad (5-15)$$

where the σ_2 , σ_3 and the τ_{23} , τ_{12} , τ_{13} are the normal stresses and shear stresses in the material coordinate system. This criterion is aimed to be suitable for both tensile and compressive matrix

failure, depending on the value of normal traction σ_N . If the value of σ_N is positive, the traction is considered to contribute to the matrix failure in opening cracks. This failure criterion assumes that the failure may appear on an arbitrary plane parallel to the fibre direction depending on the combination of shear (τ_T, τ_L) and normal (σ_n) tractions on the corresponding plane. When the failure index of traction components on a certain plane reaches the failure criterion, the composites fail on this plane. In the composite material, the plane of fracture is identified as the plane that maximises the indices of failure for matrix failure modes, denoted as F_{IMT} and F_{IMC} . A numerical search algorithm is employed to explore the fracture plane angle α within the range of 0° to 180° , at an increment of 1° . This is done to maximise the failure indices for the matrix failure modes. Damage initiation in a specific mode occurs when the corresponding failure indices reach a value of one.

Generally, the strengths associated with matrix-dominated failure in a composite should not be expected to be material properties. They are structural properties, dependent on the thickness of the ply, and on the neighbouring plies in the laminate. In LaRC05, the strengths Y_T^{is}, S_T^{is} and S_L^{is} are in-situ strengths as their values depend on the thickness and location of the ply in the laminate. This is expanded for filaments in this study since the micro-cracks propagation within a filament is almost the same with a unidirectional (UD) laminate. In LaRC05, it is considered that boundary conditions of the fracture mechanics problem for crack growth are changed by two separate factors: the thickness of the ply and the presence of neighbouring plies. However, the micro-cracks propagation within the filaments does not benefit from these two factors as the surrounding fibres are in the same direction. Thus, a fracture mechanics solution of ply in a UD laminate is used and the strength values of Y_T, S_L are assigned with the material properties of CF/epoxy filament and S_T is calculated with Eq. (5-16).

$$S_T = \frac{Y_c}{2 \tan(\alpha_0)} \quad (5-16)$$

where Y_c is the failure strength of unidirectional composites (i.e. the printed filaments in this study) under transverse compressive load. The specific value of the transverse compressive stress, denoted as α_0 , is a quantifiable material property obtained through experimental measurement. Existing literature has consistently reported that for composites made of either glass or carbon, the typical angle of fracture ranges between 51 and 55 degrees [115, 260, 261]. In this study, the fracture angle α_0 is taken as $\pm 53^\circ$, which is widely used for carbon composites by other research [116].

The friction coefficients η_T and η_L are introduced to account for the effect of pressure on the failure response by increasing the respective shear strengths in the presence of compressive normal traction and reducing the respective shear strengths in the presence of tensile normal traction. In this study, these two coefficients are defined based on the work of Garulli *et al.* [262]. Coefficient η_T is calculated with the following Eq. (5-17), where α_0 is the same fracture angle mentioned above. The value of η_L is an independent material property that is directly taken as 0.082 which is commonly used for carbon fibre/epoxy composite [129].

$$\eta_T = -\frac{1}{\tan(2\alpha_0)} \quad (5-17)$$

5.2.2.4. Damage evolution

As mentioned earlier, damage initiation occurs at the integration point within an element where failure indices reach unity. Following the initiation of damage, the stiffness at this specific location starts to degrade, as outlined in Eq. (5-8). To determine the stiffness degradation factors in Eq. (5-8), it is necessary to calculate the damage parameters (d_f , d_m , and d_s) at the point of damage initiation. For this purpose, a linear damage evolution law, which is based on equivalent strain, is employed to compute the damage parameters at the material points. This linear damage evolution approach is detailed in Eq. (5-18).

$$d_i = \varepsilon_{eq}^{f,i}(\varepsilon_{eq}^i - \varepsilon_{eq}^{o,i}) / (\varepsilon_{eq}^i(\varepsilon_{eq}^{f,i} - \varepsilon_{eq}^{o,i})), (i = f_t, f_c, m_t, m_c) \quad (5-18)$$

In this analysis, the equivalent strains at the onset of damage and at the point of complete fracture are denoted by $\varepsilon_{eq}^{o,i}$ and $\varepsilon_{eq}^{f,i}$, respectively. The equivalent strain, ε_{eq}^i , requires continuous updating at each incremental step during the simulation. Furthermore, the damage parameter for a particular failure mode, d_i , is defined to vary between zero, representing an undamaged state, and one, signifying a fully damaged state, as described by Eq. (5-18). Consequently, the stiffness matrix C_d is modified to reflect the reduced stiffness as per the relationship established in Eq. (5-18), along with Eqs. (5-4) and (5-8). The terms for equivalent strain relevant to each failure mode, detailed in Eq. (5-18), are computed in accordance with Eqs. (5-19) to (5-22) [263].

For fibre failure in tension ($i = ft$)

$$\varepsilon_{eq}^{ft} = \langle \varepsilon_1 \rangle; \sigma_{eq}^{o,ft} = \frac{X_T}{E_1}; \varepsilon_{eq}^{f,ft} = \frac{2G_c^{ft}}{X_T L_{ch}} \quad (5-19)$$

For fibre failure due to kinking ($i = fc$):

$$\begin{aligned} \varepsilon_{eq}^{kink} &= \sqrt{(\langle \varepsilon_n \rangle^2 + \gamma_T^2 + \gamma_L^2)} \\ \sigma_{eq}^{kink} &= \sqrt{(\langle \sigma_n \rangle^2 + \tau_T^2 + \tau_L^2)} \\ \varepsilon_{eq}^{o,kink} &= \varepsilon_{eq}^{kink} |_{F_{kink}=1}; \sigma_{eq}^{o,kink} = \sigma_{eq}^{kink} |_{F_{kink}=1} \\ \varepsilon_{eq}^{f,kink} &= 2G_{kink} / \sigma_{eq}^{o,kink} L_{ch} \end{aligned} \quad (5-20)$$

For matrix failure in tension ($i = mt$):

$$\begin{aligned} \varepsilon_{eq}^{mt} &= \sqrt{(\langle \varepsilon_n \rangle^2 + \gamma_T^2 + \gamma_L^2)} \\ \sigma_{eq}^{mt} &= \sqrt{(\langle \sigma_n \rangle^2 + \tau_T^2 + \tau_L^2)} \\ \varepsilon_{eq}^{o,mt} &= \varepsilon_{eq}^{mt} |_{F_{MT}=1}; \sigma_{eq}^{o,mt} = \sigma_{eq}^{mt} |_{F_{MT}=1} \\ \varepsilon_{eq}^{f,mt} &= 2G_{c,mix}^i / \sigma_{eq}^{o,mt} L_{ch} \end{aligned} \quad (5-21)$$

For Matrix failure in compression ($i = mc$):

$$\begin{aligned}
\sigma_{eq}^{mc} &= \sqrt{(\langle -\sigma_n \rangle^2 + \tau_T^2 + \tau_L^2)} \\
\sigma_{eq}^{mc} &= \sqrt{(\langle -\sigma_n \rangle^2 + \tau_T^2 + \tau_L^2)} \\
\epsilon_{eq}^{o,mc} &= \epsilon_{eq}^{mc} \big|_{F_{MC}=1}; \sigma_{eq}^{o,mc} = \sigma_{eq}^{mc} \big|_{F_{MC}=1} \\
\epsilon_{eq}^{f,mc} &= 2G_{c,mix}^i / \sigma_{eq}^{o,mc} L_{ch}
\end{aligned} \tag{5-22}$$

where $\langle \rangle$ is the Macaulay bracket operator and is defined as $\langle x \rangle = (x + |x|/2)$. To mitigate mesh dependency, the model employs a characteristic length, L_c , for each element. This characteristic length is used to normalise the critical energy dissipated, denoted as G_{ft} or $G_{c,mix}^i$, (where $i = fc, mt, mc$, during the damage evolution process, following the theories proposed by [264, 265]. The progression of matrix damage is regulated by the critical mixed-mode strain energy release rate, $G_{c,mix}^i$, which is predicated on a quadratic relationship between mode-I and mode-II. The critical strain energy release rates, G_{Ic} and G_{IIc} given by Eq. (5-23) [263].

$$G_{c,mix}^i = (\sigma_i^n / \sigma_{eq}^i)^2 G_{Ic} + (\tau_L / \sigma_{eq}^i)^2 G_{IIc} + (\tau_T / \sigma_{eq}^i)^2 G_{IIc}; i = mt, mc \tag{5-23}$$

Additionally, the terms σ_{eq}^i and ϵ_{eq}^i (where $i = fc, mt, mc$) represent the equivalent stress and strain on the kink-band or fracture plane for the respective damage modes (refer to Fig. 5-2). These values are computed using the stress and strain components that act upon the specific planes and the calculation of the stress and strain components on the kink-band plane and fracture plane follows the methodology outlined in the previously mentioned Eqs. (5-12) and (5-15). The variables $\sigma_{eq}^{o,i}$ and $\epsilon_{eq}^{o,i}$ denote the equivalent stress and strain at the onset of damage.

The detailed method for determining the characteristic length L is based on other's research [263] and the schematic diagram is shown in Fig. 5-3:

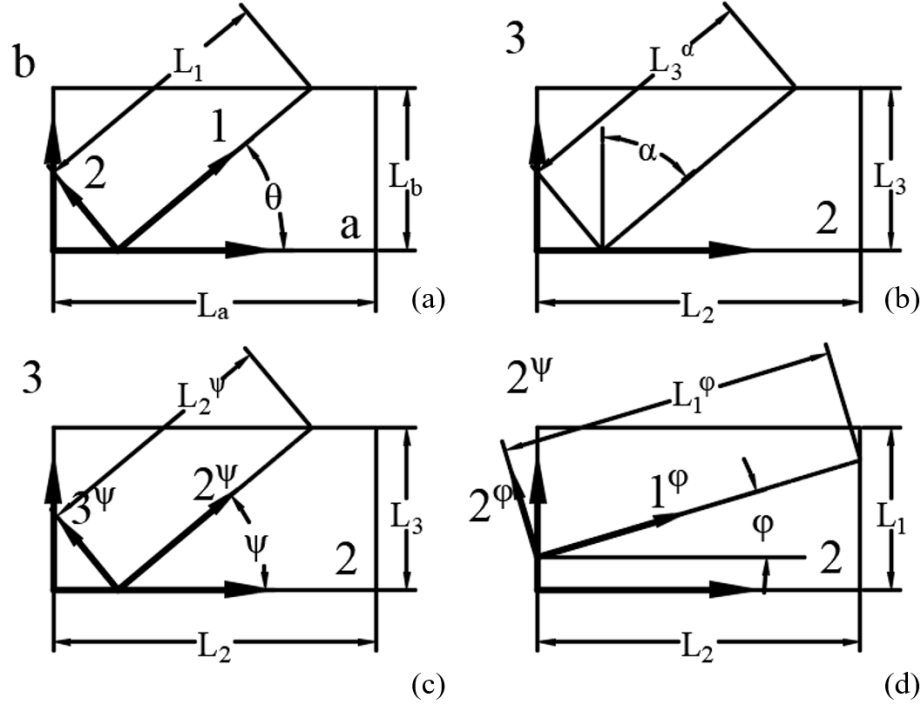


Fig. 5-3. Calculation of characteristic lengths for brick elements subject to varying angles of matrix fracture planes.

The determination of the fracture area is not straightforward due to the arbitrary orientation of the fracture plane identified through LaRC05 within an element, even for a rectangular brick voxel element, and under the assumption that the fracture plane intersects at the integration point located at the element's centre [263]. The heuristic approach presented here is an approximation. The element dimensions L_1 , L_2 , and L_3 are derived from the nodal coordinates in the material subroutine. Fig. 5-3 (a) illustrates the transition from the element axes (a, b, c) to the material axes (1, 2, 3).

The conversion from the material axes to a matrix fracture plane is depicted in Fig. 5-3 (b). As inferred from Fig. 5-3 (a) and (b), the fracture area for matrix failure A and the corresponding characteristic length L_{Matrix} are determined through Eqs. (5-24)-(5-27).

$$\begin{cases} L_1 = \min \left\{ \frac{L_a}{\cos \theta}, \frac{L_b}{\sin \theta} \right\} \\ L_2 = L_c L_b / L_1 \\ L_3 = L_c \end{cases} \quad (5-24)$$

$$L_{3\alpha} = \sin \left\{ \frac{L_3}{\cos \alpha}, \frac{L_2}{\sin \alpha} \right\} \quad (5-25)$$

$$A = L_1 L_3^\alpha \quad (5-26)$$

$$L_{Matrix} = \frac{L_a L_b L_c}{L_1 L_{3\alpha}} \quad (5-27)$$

Regarding fibre kinking, the transition to the splitting/kinking plane is shown in Fig. 5-3(c), and to the misaligned frame in Fig. 5-3(d). Hence, the characteristic length for fibre-kinking is derived as follows,

$$\begin{cases} L_{2\psi} = \min \left\{ \frac{L_2}{\cos \psi}, \frac{L_3}{\sin \psi} \right\} \\ L_{3\psi} = L_2 L_3 / L_{2\psi} \end{cases} \quad (5-28)$$

$$L_{1\varphi} = \min \left\{ \frac{L_1}{\cos \varphi}, \frac{L_{2\psi}}{\sin \varphi} \right\} \quad (5-29)$$

$$L_{fibre\text{-}splitting/kinking} = \frac{L_a L_b L_c}{L_{1\varphi} L_{3\alpha}} \quad (5-30)$$

In the case of fibre tensile failure, the fracture plane is perpendicular to the fibres, thereby, the characteristic length for fibre-tension is determined by Eq. (5-31)

$$L_{fibre\text{-}tension} = L_1 \quad (5-31)$$

It's worth mentioning that the computation of the characteristic length for embedded filament elements is relatively straightforward due to the voxel mesh's uniform brick element size. This

allows the calculation to be conducted based on the fixed size ratios. However, when considering resin-rich regions in Abaqus, the mesh generated is not as regular as voxel mesh. This means that in resin-rich regions, the size of each element varies. Consequently, it's not feasible to use a fixed size to calculate the characteristic length based on the fracture surface. Instead, each element in the resin-rich regions approximates the calculation of the characteristic length using Abaqus' default method[266], which is the cube root of the element volume. Additionally, effort is made to ensure the element size ratios are cubic throughout the meshing process, aiming to maximise accuracy.

In order to approximate the simulation of matrix cracking, elements are removed during the simulation when the damage parameters of fibre failure in tension and matrix failure in tension reach 0.99, indicating that the stiffness is essentially fully degraded. However, compressive stresses near micro-crack tips promote both friction and mechanical interlocking between the faces of the microcracks [129]. Therefore, in this study, elements are not removed when the damage parameters related to compressive failure reach 0.99. This is crucial for simulating the failure of stress transmission in composite structures caused by the loss of the matrix in continuous carbon fiber composites. Additionally, to avoid unrealistic element distortion resulting from the strain-softening constitutive behaviours, elements are deleted from the mesh if the determinant of the deformation gradient F , *i.e.*, the ratio of the deformed to the undeformed element volume satisfies $0 < \det F < 0.2$ or $\det F > 2$. The limits on $\det F$ are user defined and the quoted values were found to yield good results. This element deletion strategy is commonly applied in other research [146, 258, 267] to ensure computational continuity. It should be noted these bounds must be reviewed if the element size and/or material properties are changed, to ensure elements have dissipated all of their fracture energy before they are removed from the model.

5.2.3. Macroscale Model

The FE simulation is conducted on a The FE simulation is conducted on a macroscopic level using the Abaqus/Explicit software to determine the macro-strains of the entire woven structure that resulted from the applied loads. For assembling fibre-reinforced composites, a commonly used approach is the continuous mesh where the matrix is subtracted or partitioned and then combined with the fibres [268]. However, as this approach involves numerical issues, like poor mesh quality and interpenetration of reinforcing fibre, its high computational cost makes it almost impossible to model the pseudo-woven composite with locally steered fibres/filaments 3D printed in this study. Therefore, as mentioned above, an embedded element (EE) technique (shown in Fig. 5-5) is used for the mesoscale basic unit of the pseudo-woven CFRP composite. The reason this technique is applied is that the filament interpenetration issue mentioned above can be resolved by generating individual filaments separately and embedding them later in the matrix. Although this leads to the fact that multiple filaments could be overlapping or intersecting at the same location, as shown in Fig. 5-5. (a), the relationship between matrix and filaments is still accurate with the help of the EE technique. This is because, in the EE technique in Abaqus, the displacement of all nodes in the embedded grid is assumed to be interpolated from the host grid [257], as shown in Fig. 5-5. For any embedded node (marked as ‘A’ in Fig. 5-5(b)) falling in the host element, all the degrees of freedom (DOFs) at the node are constrained to the host nodes (marked as ‘1,2,3,4’). The weight factors of this constraint are determined based on the geometric location of the embedded node in the host element. Additionally, the stiffness will be amplified by the number of the filaments within the same host grid based on the Eq. (5-32) [269]:

$$f^R = \left(K^h + \sum_i w_i K_i^e w_i^T \right) d^h \quad (5-32)$$

where f^R is the reacting force; K^h and d^h are stiffness matrix and DOFs of the host grid; i is the node number of an embedded node, K_i^e is the stiffness matrix of the node and w_i is the transformation matrix between the displacement of the host grid and the node.

Also, when using the EE technique, additional mass and stiffness due to the embedded elements are added to the model. This issue is resolved by calculating the new constitutive tensor based on the volume fractions of the mesoscale components, resin-rich region and filaments. Since the filament in this model is generated according to the actual size, it is considered that its stiffness contribution is the actual value. As for the resin-rich region, its stiffness contribution should be reduced according to the actual volume fraction. From previous work, the porosity and average volume fraction of the fibre within the UD laminate, assumed to be equivalent to an individual filament in this study, were found to be 0.3% and 56%, correspondingly [221] and it was observed from SEM (shown in Fig. 5-4) that the fibre volume fraction in the oven-cured pseudo-woven composite structure was about 48.4 %. This suggests, taking case D as an example, that the Resin-rich region occupied 11.8% of the total volume of the entire composite. Calculations for other cases were conducted in the same manner. It is assumed that the resin-rich region is evenly separated within the entire woven structure to represent the resin between each filament.

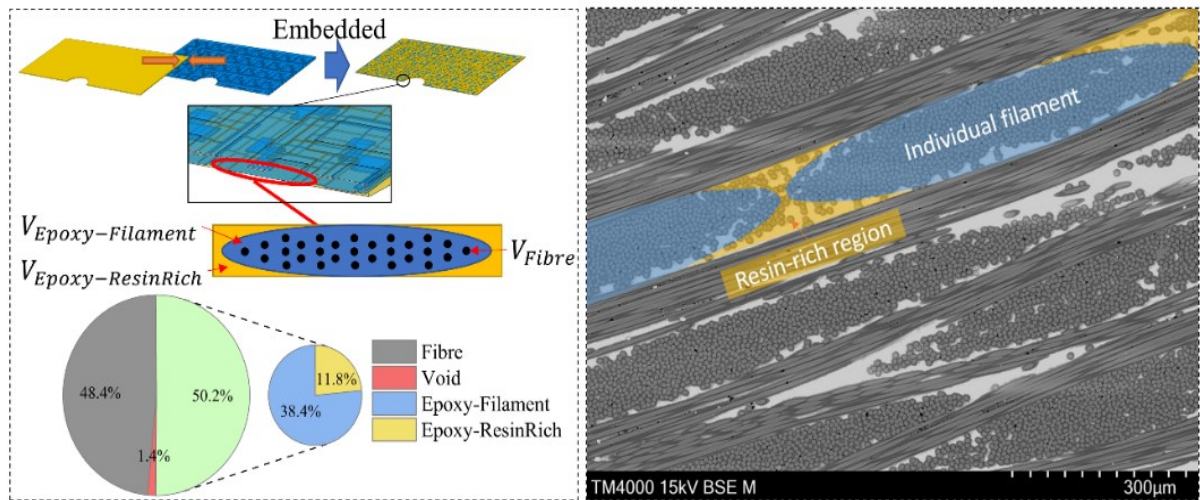


Fig. 5-4. Definition of the volume fraction of each component in the specimen (case D).

To reduce the computational cost, the pseudo-woven composite far away from the joint hole was assumed to be elastic without any damage and homogenised as an equivalent plain weave composite. The in-plane elastic modulus, Poisson's ratio and shear modulus were determined according to a 36 mm × 36 mm plain board textile model, generated with the same pseudo-woven woven pattern from the TexGen. As this part was reasonably assumed only under in-plane tensile loading, the through thickness elastic properties, E_{33} , ν_{23} , G_{13} and G_{23} , would have negligible effect on the overall structural response of the composite plate. Thus, they were considered as the same values as typical woven composite laminate found in other research [270]. The elastic properties are summarised and shown in Table 5-1. The steel bolt was considered as a rigid body.

Table 5-1 Mechanical properties of equivalent plain woven composites

$E_{11} = E_{22}$ (GPa)	E_{33} (GPa) [270]	$\nu_{12} = \nu_{13}$	ν_{23} [270]	G_{12} (GPa)	$G_{13} = G_{23}$ (GPa) [270]
36.85	11.78	0.11	0.44	4.80	4.18

5.2.4. Multiscale Modelling of Double Shear Test

The multiscale simulation framework presented above is implemented as a VUMAT subroutine in the finite element software Abaqus/Explicit. Note that the composite filament is pressed into a stripe once it is printed out under pressure from the printer nozzle. The geometrical model is firstly generated in TexGen [271] according to the printing paths defined by the G-code, and then each filament is meshed separately and imported into the Abaqus software for FE modelling via Python and Abaqus Macro scripts (details provided in the Appendix A and B). Finally, these filaments are embedded in an epoxy matrix, with boundary conditions and constraints set up according to the physical double-shear test. Only one layer of the printed composite as modelled based on symmetry to reduce the computational cost.

The difference in the model thickness compared to the experimental specimen might affect the mechanical response through the thickness direction, shown in Fig. 5-5. (a). In this study, no matter how many layers of filament were overlapped, they were all compressed into a thickness of two filaments to ensure that the thickness around the hole is the same as in other woven areas. However, it is assumed negligible during the throughout the elastic stage, up until the occurrence of initial failure, because the overlapped region around the hole is constrained by the bolt clamping pressure along the thickness direction and this could be treated as a planar issue. And the mechanical properties corresponding to each filament do not change, only the geometric position in the thickness direction overlaps. Although the interaction between the host and embedded materials is simplified, the FE model based on this technique is still reasonably reliable because it has been verified by many researchers [149, 217, 268, 272], like Tabatabaei, Lomov *et al.* [268], that the EE technique is able to solve inherent problems of the continuous mesh method without compromising the predicted mechanical performance. Additionally, according to previous research [221], fibres could be considered to be perfectly bonded with the matrix. In terms of the mesh quality, the matrix and filament are generated and meshed separately in this study, thus enabling the easy control of the mesh for each.

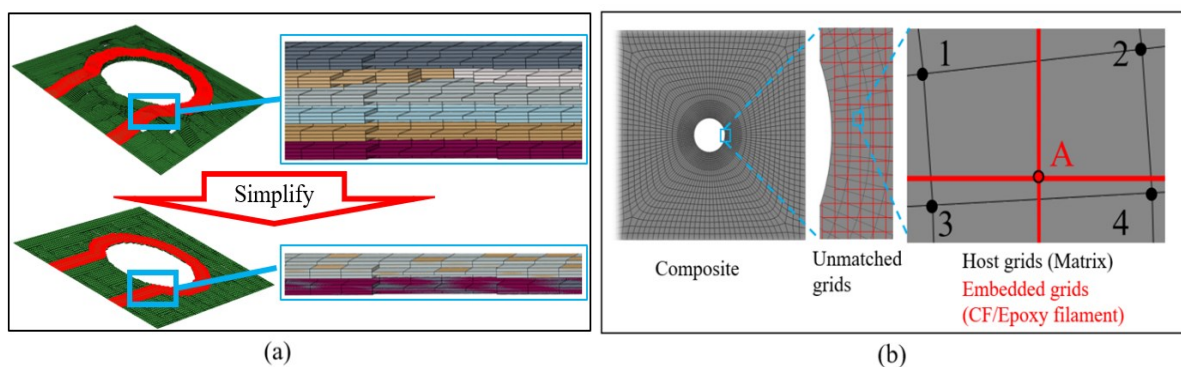


Fig. 5-5. Schematic representations of the FE model based on EE technique: (a) Simplification of the overlap issue (b) An illustration of the relationship between the host and embedded nodes on the grids.

The details of assembling the model are illustrated in Fig. 5-6. All individual filaments are embedded into the matrix domain of the composite and the green part is assigned with homogenous woven composite material properties to further reduce the computational cost. A symmetric boundary condition is enforced in the Z-axis direction, and a fixed boundary condition is applied to the clamped end of the specimen, while a displacement is imposed on the bolt. Simulations are run for the four test cases of a bolted joint laminate, featuring the four distinct fibre steering patterns in previous experiments that lead to complicated three-dimensional stress state and a confluence of various damage mechanisms. Subsequently, by updating the solution-dependent state variables (SDVs) within the Abaqus input file and the VUMAT subroutine, simulations provide comprehensive insights into the influence of the steered filaments on the load transfer, damage initiation, failure modes and progression of failure. During the simulations, a mass scaling method is employed, which is a common practice in quasi-static analyses to address complex nonlinear phenomena and often associated with intricate contact conditions and details are shown in the Abaqus manual [266].

According to section 4.2.2, the loading process in the experiment to be simulated is uniformly paced. Since inertial forces due to acceleration or deceleration are negligible, it can be considered as quasi-static loading. Therefore, it is acceptable to use the mass scaling technique to enhance computational efficiency, which has been used in other study [273]. The target time increment was verified to be correct by ensuring its impact is minimal to the model's internal energy. Step times have been properly extended to guarantee a negligible kinetic to internal energy ratio (less than 5%), thus securing a quasi-static solution. Notably, the 'Scale to target time increment' value is set to $1e-4$ here, following a series of data check and iterative processes. The mass scaling value was continuously updated, re-detected, and adjusted during the process to achieve the target time increment. The 'Semi-automatic mass scaling' method was chosen,

where the mass scaling area was applied to the entire model. Moreover, the element mass only gets scaled if it is below the minimum target.

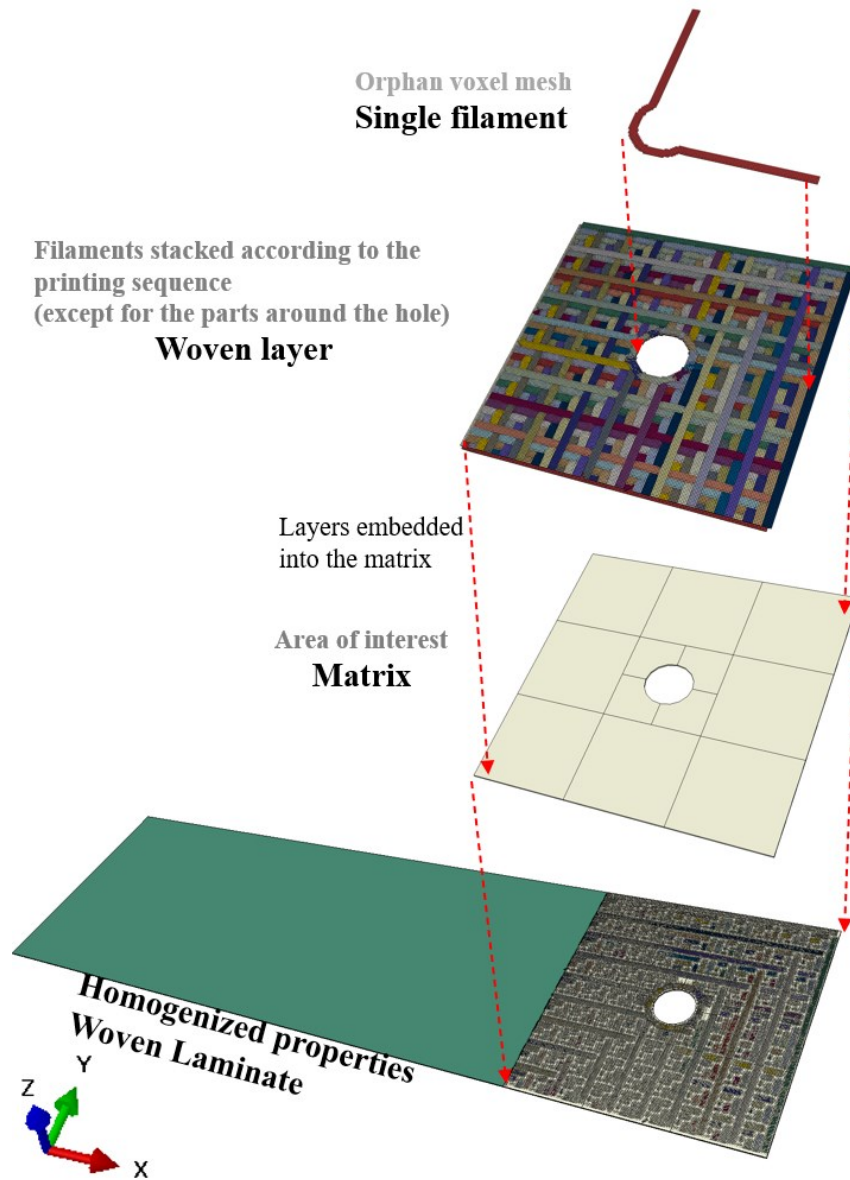


Fig. 5-6. Steps to generate a geometrical model of a shear-bearing specimen based on the actual printing paths.

5.3. Results and Discussion

This section analyses the results obtained from the FE modelling and presents a detailed discussion of the findings. Firstly, validation of the model is conducted by comparing the modelling against the experimental in terms of the load-displacement curve (mentioned in

section 4.3.1) and relative mechanical performance. Then the macroscopic failure evolution is examined, providing a comparative analysis of the structural failure development in each of the four distinct cases. Finally, a case-specific analysis of the damage evolution is performed in specially steered filaments, exploring the difference of damage states arising in those cases and revealing the influence of filament steering patterns on the integrity of the composite joint.

5.3.1. Validation of Multiscale Modelling

As mentioned in Chapter 4, the woven composite was fabricated by stacking thirteen pseudo-woven layers produced through 3D printing. Consequently, the load results derived from the simulation were scaled by a factor of thirteen to facilitate a direct comparison with the experimental outcomes. Fig. 5-7 shows a comparative analysis for all four cases, which includes a mechanically drilled sample (Fig. 5-7 (1)) for comparison, where all fibre paths remained linear and a through-hole was drilled. The other three cases, referred to as Cases C, L, and U respectively, employed unique fibre steering patterns: squeeze-apart, diverted-away, and loop-back, as depicted in Fig. 5-7 (2 to 4).

By comparing curves and numerical data, it is evident that the simulation results mirror the experimental results. In all cases, the stiffness in the elastic phase correlates closely with experimental data, while the onset of initial plastic deformation and subsequent damage evolution are also analogous. This confirms that the model effectively replicates the macroscopic behaviours observed in experiments. Inherently, there are some imperfections in the simulation results, such as noticeable fluctuations in the curves. Given the complexity of the model, which incorporates advanced bolt-hole contact interactions and damage progression, the stability of the solution is considered to be at an adequate level, consistent with findings from prior simulation studies [274].

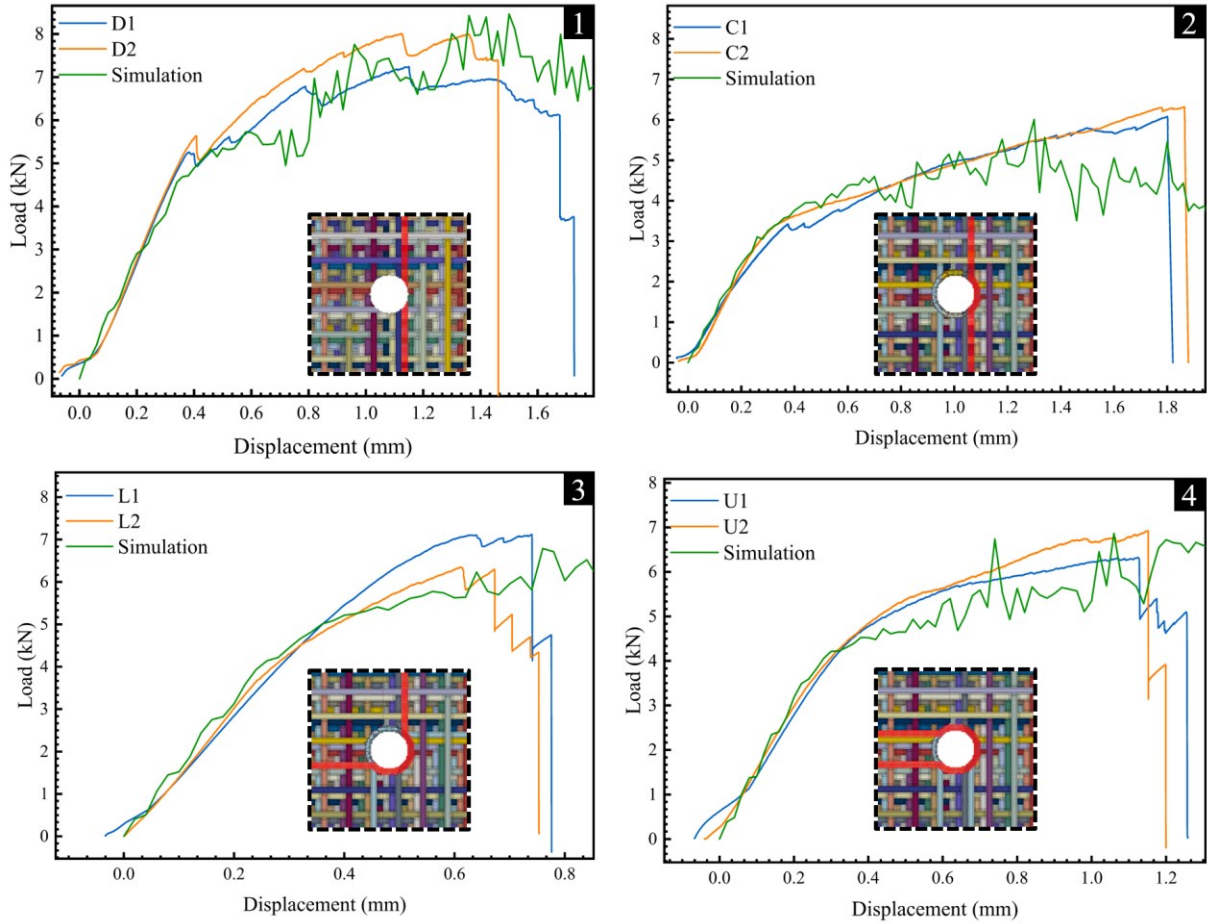


Fig. 5-7. Comparative analysis of experimental and simulated responses with schematic details beneath curves (distinct fibre configurations highlighted in red).

Fig. 5-8 displays the contours of filament constitutive degradation for all cases, alongside comparative images captured through Micro-CT in the mid-section of the specimen along the thickness direction. The ultimate failure displacement for each case is assumed to be the average ultimate displacement observed experimentally. Therefore, the contours shown in Fig. 5-8 were captured at displacements of 1.56 mm, 1.84 mm, 0.76 mm, and 1.22 mm from models D, C, L, and U, respectively. It should be mentioned that the contour is of the deformed type and therefore elements that are destroyed have been removed. From the figure, it can be seen that at the moment of final failure, the experimental and simulated damage distributions are almost the same across all cases. Judging solely from the crack distribution in the CT images: For Cases D and C, the onset location and widespread direction of damage closely align with the CT results. In contrast, Cases L and U exhibit less pronounced failure patterns, which also

correspond well with the CT results. A notable omission in all results is the lack of final fracture along the position of the bolt hole neck. This difference is attributed to porosity, which is believed to cause randomness in extensive crack propagation. Generally, it is evident that the model closely aligns with the experimental data for all cases. The subsequent subsection will interpret the phenomena observed in experiments based on the simulation results.

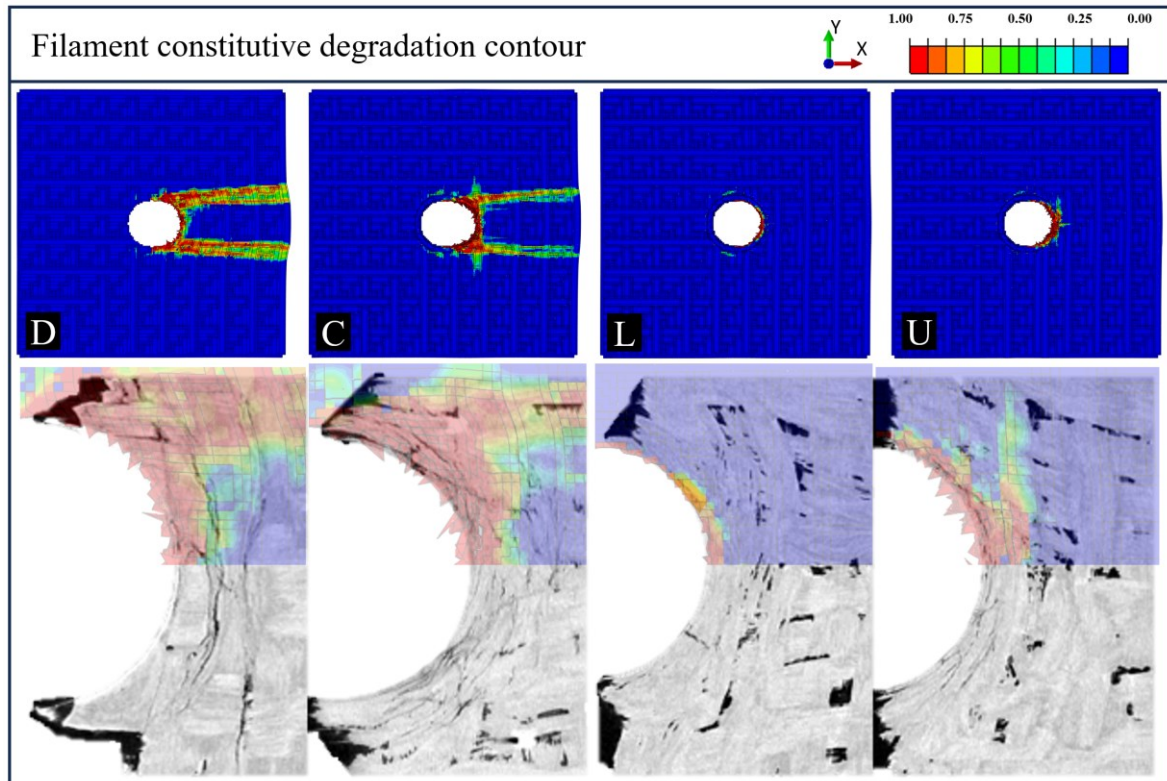


Fig. 5-8. Comparative analysis of filament constitutive degradation with bolt displacement up to the final experimental displacement along the X-axis across all cases (1 indicating near-complete destruction, 0 indicating no damage), accompanied by Micro-CT slice images from the mid-thickness region around the bolt hole of the tested final specimen.

5.3.2. Macroscopic Failure Evolution

The global structural failure progression in the four cases will be discussed and it should be noted that: In this study, the resin-rich region was merely utilised as a medium for conveniently defining contact and constraints, as well as accurately capturing the reactions within the macroscopic structure. For the investigation of failure evolution, only the filament components, which serve as embedded elements in the analysis, were extracted for comparison.

Firstly, a discussion is conducted on all cases, exploring the reasons for the differences from the onset of loading to the initial failure. Based on the load-displacement curves for all cases in Fig. 5-7, this study determines that adopting the interval from 0.3 mm to a bolt displacement of 0.8 mm to evaluate the degree of failure across all cases offers the most conducive approach for comparative analysis. This interval is selected because initial damage onset is consistently observed across the cases within this range. Fig. 5-9 (a) depicts the progressive contour series of matrix constitutive degradation in the filament. To better observe the distribution, the contour of the undeformed shape was outputted from the simulation results here. It can be observed that case D exhibits significant differences in failure compared to other fibre-steered cases. case D demonstrates a matrix damage zone extending beyond the hole edge, suggesting shear cracks. Meanwhile, the C, L, and U cases demonstrate relatively less damage propagation, indicating that the matrix integrity is maintained by the continuous steered fibres under initial loading conditions. The fibres contribute to distributing the stress more evenly and preventing stress concentration.

An important detail to point out here is that the damage extension in case C is slightly larger than that in cases L and U, suggesting that the fibre steering patterns in L and U may be more effective. To validate this, the contours of fibre tensile failure initiation at the 0.8mm bolt displacement are compared, as shown in Fig. 5-9 (b). Firstly, the tensile failure initiation contour is instrumental in examining the effectiveness of fibre load transfer in the longitudinal direction of the fibre throughout the entire evolution process. It is inferred that for case D, the discontinuity of fibres after drilling results in minimum load transfer to areas other than the neck region around the bolt hole. Consequently, only fibres in the neck vicinity on both sides of the bolt hole can share the tensile load caused by bolt movement. In contrast, other cases exhibit load-bearing in the steered fibres around the hole, preventing excessive stress concentration in the neck region and instead distributing it into other regions. Subsequent

damage evolution reveals that for areas with fibre steering, compared to the benchmarking D case where tension failure is concentrated in the neck region of the open connection components, the distribution of the tensile failure index is more uniform. This indicates that maintaining fibre continuity throughout the entire joint is critical for effective load transferring. Simultaneously, it is also observed that among the fibre-steered cases, case C exhibits a more obvious initiation of fibre tensile failure. This aspect is further compared by independently extracting and analysing the uniquely steered filament of each case (shown in Fig. 5-9 (b)). From these independent filaments, it can be inferred that the broader extent of damage in case C, as shown in Fig. 5-8, is due to fibre breakage of filament b leading to structural instability, which in turn causes earlier stiffness loss and lower initial strength. Such fibre damage is not as prevalent in cases L and U. Additionally, it should be highlighted that for cases L and U, there is generally a concentration of damage distribution at the turning points of the steered filaments facing the bolt bearing load. Moreover, at a displacement of 0.8 mm, the experimental outcome of case L is a direct brittle failure, with the failure location roughly at these turning points. This suggests that while the steered filament in case L can maintain structural stiffness, there is a risk of brittle failure. In contrast, the filaments in case U facing the bearing load exhibit almost no tendency for such failure, especially filament c. This is advantageous because there is no abrupt change in fibre orientation in the load-bearing direction, which aids in more uniform stress distribution and reduces the likelihood of fibre failure. Therefore, unlike the experimental curve of case L, there is no direct brittle failure at this displacement.

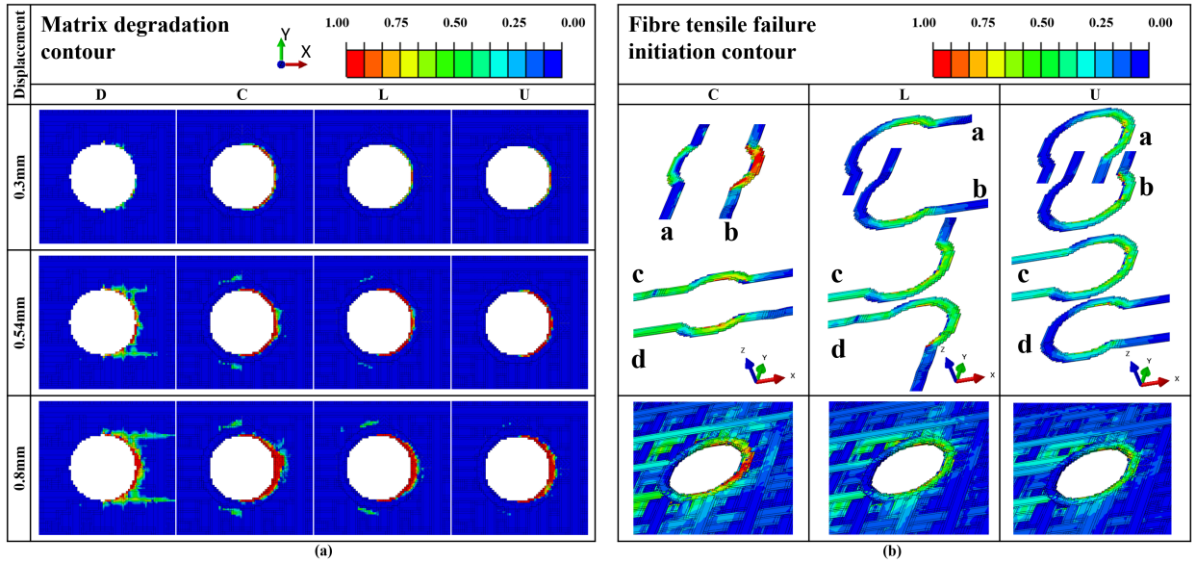


Fig. 5-9. Comparative analysis of each case from plastic deformation to initial failure: (a) Progressive contour series showing distribution of matrix constitutive degradation (1 indicating complete destruction, 0 indicating no damage); (b) Filament tensile failure initiation (1 indicating failure initiation, 0 indicating no failure) of each case with bolt displacement at 0.8 mm along the X-axis.

The following paragraph explores the failure modes and distributions for each case as bolts reach their ultimate failure displacements mentioned in section 5.3.1. As previously discussed, following the onset of initial plastic deformation, cases D and C lack steered continuous fibres that would otherwise help distribute the load over a broader area. This loss of structural integrity potentially leads to severe compression failure occurring at the regions directly subjected to bolt displacement. This is evident from the compression load applied on the fibres in these regions when initial fibre compression failure occurs in the composite. Thus, the comparative analysis of fibre compression damage initiation modes distribution is further corroborated, as shown in Fig. 5-10. Considering this model reflects a woven structure, to improve the observation of the distribution, only the filaments primarily responsible for bearing the bolt load have been extracted for the progressive series of images. Progressive series of images depicting the failure mode distribution and comparison of simulated and experimental results are shown in Fig. 5-10 (a) and (b), respectively.

The progressive series of images reveals that fibre kinking invariably occurs in the area directly subjected to the compression load of the in-situ displacing bolt, while splitting predominantly occurs near this area. Comparatively, the extent of both types of damage is most pronounced in cases D and C. This is considered to be due to the absence of continuous fibre steering around the hole leads to stress concentration on the compressively loaded composite material, which does not disseminate across the entire structure, thereby resulting in kink band. It should be noted that, although the final distributions of cases D and C are similar, featuring both structural compression and shear failure trends, the sequence in which these damages occur is distinctly different. In case D, shear failure is initially induced at 0.54 mm, resulting in a loss of structural integrity. This degradation leads to a reduction in load transfer capabilities within the composite structure, consequently concentrating compressive stresses from the bolt. According to the previously mentioned LaRC05 criteria, this experimental observation is more susceptible to the initial failure mode of fibre kinking. Conversely, in case C, the distribution indicative of shear failure does not appear until a displacement of 0.8 mm is reached. This is the point at which the steered continuous fibres around the hole experience failure. This can be further validated through the CT images (shown in Fig. 5-10 (b)), extracted from the simulation contour maps highlighted in red and brown with corresponding dashed outlines. The distribution of two distinct fibre compression damage mode are denoted in red and green respectively. A notable distinction between case D and case C lies in the distribution of the kink band areas: in case D, the occurrence is predominantly at the interface with the bolt, whereas in case C, it is more distinctly observed in regions outside the steered continuous fibre areas. This contrast shows the reinforcement provided by the steered continuous fibres in case C, enhancing the structural integrity of the designated areas. In contrast, the simulations for cases L and U do not exhibit a significant tendency towards shear failure along the loading direction. This suggests that the fibre steering configurations in these cases are more effective

in load transfer, specifically manifested in alleviating shear-dominated matrix failure that induces shear and compression failure of the composite. However, it is evident that, unlike in cases C and D, the macroscopic structural rigidity in cases L and U does not precipitously decrease. This is reflected in the experimental results where brittle structural failure occurs directly at the bolt hole neck through tensile damage, which could be observed from the relatively uniform fracture surfaces in the corresponding CT images of the case shown in Fig. 5-10 (b). Therefore, in addition to reinforcing the initial damage resistance by steering filaments at the hole edge, design improvements should also be implemented in other areas.

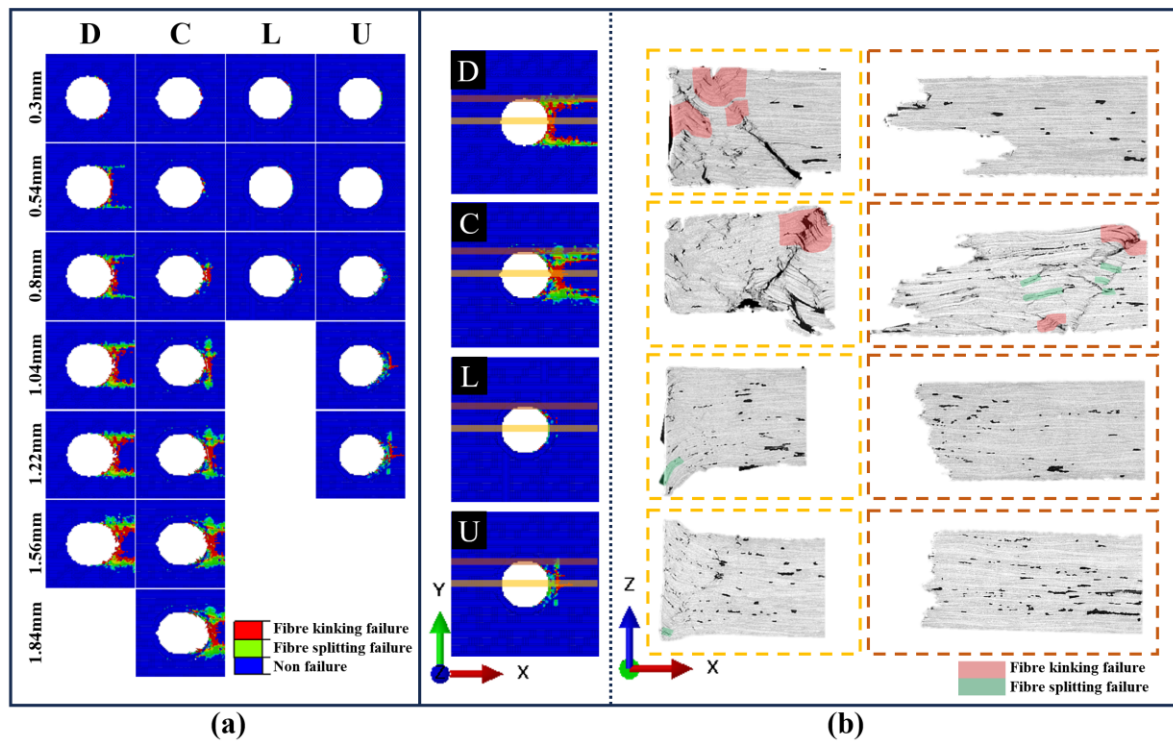


Fig. 5-10. Fibre kinking/splitting failure evolution contour of individual filament around the hole based on the LaRC05 criteria.

5.4. Conclusions

This study explored the critical importance of maintaining filament continuity along the edge of bolt holes in bolt-jointed composites by using a multiscale numerical model. It is evident that such continuity not only significantly influences the load transfer capabilities of the joint

during the elastic stage but also plays a decisive role in the onset and propagation of matrix damage in the subsequent stages. The main findings can be summarised as follows:

- 1) This study achieved a good agreement between experimental results and simulation outcomes. The evolution results obtained from the model successfully analysed and interpreted phenomena observed during the experimental processes, which cannot be easily captured by experimental methods. Moreover, as the model is composed of 3D printed continuous filaments at the mesoscale, it allows for independent analysis of the role and failure modes of individual filaments within the overall structure. This will fill the research gap in simulating advanced composites manufactured through additive manufacturing methods and provide a simulation tool for designing advanced composites based on fibre steering in the future.
- 2) Ensuring fibre continuity at the bolt hole is crucial in composite bolted joints to maintain structural integrity and prevent premature shear failure by effectively distributing the bearing load. Comparative analysis of experimental and simulation data clearly demonstrates that fibre continuity mitigates stress concentration around the bolt hole, enabling stress distribution across the entire structure and preventing early matrix shear failure.
- 3) The pattern of the steered filament is found to be a determinant in the failure mode of the joint. This study also reveals that merely ensuring fibre continuity is not the optimal fibre steering strategy. Optimization can further be achieved through various fibre orientations. Specifically, while Case C maintains continuity, the orientation of its fibres does not effectively bear the load from the bolt, leading to relatively premature fibre tensile failure. In contrast, Cases L and U, through different fibre steering directions, achieve superior load transfer effects, thus avoiding this issue and further enhancing the structural integrity during the loading process.

Chapter 6. Enhance the Bolted Joint Performance of Woven Composite Laminates using 3D Printed Interlayers with Tailored Fibre Architectures

6.1. Chapter Introduction and Overview

This chapter investigates the effect of incorporating 3D printed interlayers (with continuous fibres) on the stress distribution and mechanical behaviour of plain woven CFRP composite bolted joints. The 3D printed interlayers were designed using three different methods and the modified hybrid laminates were subjected to a double shearing test to evaluate their capabilities. The multiscale FE modelling approach developed in Chapter 5 was adopted to use the as-manufactured fibre architectures to correlate with the experimental test and reveal the damage progression mechanisms that are difficult to observe by experiments. The results of this study will provide insights into the potential of 3D printed interlayers in providing better stress distribution and fracture toughness for CFRP composite laminates. The method of altering the mechanical behaviour of CFRP laminates with customised interlayers not only tailors the laminate to meet specific requirements but reduces the use of carbon fibre while maintaining or even enhancing certain mechanical properties.

6.2. Methodology

6.2.1. Material System and Specimen Design

As mentioned in section 3.2, Pyrofil TR30S 3K 1 x 1 plain weave fabric mats sourced from Easy Composites were pre-impregnated with PE6405 powder epoxy (FreiLacke, Germany) to form CF/epoxy composite layers. The continuous CF/epoxy filament (Pyrofil TR30S 3K fibre tow impregnated with PE6405 powder epoxy) for printing was produced using a customised electrostatic powder deposition tapeline, a method similar to those detailed in the references [30, 31]. The dimensions of the composite laminate samples are detailed in Table 6-1. It should be noted that the dimensions of the specimens were slightly deviated from the ASTM standard

D5961/D5961M for evaluating the bearing response of the laminate. This is allowed by the standard, which is mentioned in the section 4.2.1.2. Specifically, the overall length of the specimens was reduced to expedite the experimental process, according to a similar modification applied by other researchers in previous studies [59, 62, 275]. Furthermore, the bolt hole size was increased to a diameter of 10 mm. This modification was necessary due to the use of 3K CF/epoxy filaments, which, after 3D printing, resulted in a relatively large bandwidth of up to 1.5 mm. The enlarged bolt hole accommodates a more extensive range for customising the fibre steering path, hence the increase of its diameter to 10 mm. Also, both the width-to-diameter ratio and the edge distance ratio were deliberately chosen to be lower. With the decreasing of these two ratios, the stresses increase rapidly moving away from the hole edge in the net-tension and shear-out planes. This leads to an increased likelihood of both net-tension failure and shear-out failure [276], which consequently helps induce a variety of failure modes in the specimens, rather than limiting them to one type of failure mode alone. Such a strategy is helpful in maximising the comparative analysis of damage mitigation across different cases.

There were 4 cases in this study, including one mechanical drilled case and three hybrid laminates with custom 3D printed continuous CF/epoxy interlayers. Fibre paths of the 3D printed layers were designed with an aim to achieve various capacity enhancement, based on three different methods: 1) Geometric offset; 2) Load path trajectories and 3) Failure plane informed fibre architecture. For the first method, the path was simply generated by offsetting the geometrical edges of the structure and has been previously evaluated by other researchers [62, 149]; The second method was based on the concept of Kelly's load path [277] inspired by the fluid stream where the force is constant along the stream tube. In this path, the 3D printed interlayer with strategically oriented fibres was designed to enhance both the tensile strength in instances of net-tension failure and the compressive strength at the bearing edge [65]. In this

study, the load path was obtained by tracing the direction of the selected pointing stress vector based on the stress distribution of a plain weave CF layer (shown in Fig. 6-3(a)); In the third design method, the fibre orientation was planned according to the failure planes. The failure planes were identified by in-plane critical stress distributions around a bolt-loaded hole with the normal stresses at the net-tension plane, shear stresses at the shear-out plane and the compression (bearing) stresses at the bearing plane [276]. In the region around the bolt hole, which is primarily subjected to the bearing load during the elastic stage, the fibres were tailored based on the main stress trajectory instead, which is intended to enhance the stiffness of the laminate.

The lay-up configuration, as detailed in Table 6-1, employs a (0/90) orientation for each plain woven layer, constructed by interweaving weft yarns over and under warp threads. In all composite laminates, the warp orientation was aligned with the 0 direction. In this research, a quasi-isotropic (QI) lay-up sequence, which involves $\pm 45^\circ$ fibre placement, was not utilised. This decision was driven by the study's focus on investigating the reinforcing effects of interlayers on the orthogonal weave of the plain weave mats under bearing load conditions in the tangential direction. The introduction of $\pm 45^\circ$ fibre placement would have complicated the comparison of results.

For hybrid cases involving 3D printed interlayers, the stacking sequence alternated between the plain weave mat and 3D printed interlayers as shown in the Fig. 6-1. Additionally, these 3D printed interlayers consisted of a single layer of printed filament, aimed at reducing the usage of carbon fibre and the overall weight of the specimen, while maintaining or enhancing the mechanical performance.

Table 6-1 Composite laminate dimensions and stacking configurations

Length (mm)	Width (mm)	Bolt hole diameter (mm)	Width to Diameter Ratio	Edge Distance Ratio
80	40	10	4	2
Case	Code	Lay-up	Plies	Avg. Thickness (mm)
Drilled	DR	[(0,90)/(0,90)/(0,90)/(0,90)] _s	8	2.4
Offset	OF	[(0,90)/ OF /(0,90)/ OF] _s	8	1.8
FailurePlane	FP	[(0,90)/ FP /(0,90)/ FP] _s	8	1.8
LoadPath	LP	[(0,90)/ LP /(0,90)/ LP] _s	8	1.8

6.2.2. Numerical: Multiscale FE modelling

To pre-evaluate the mechanical capacity of these 4 different cases, a multiscale finite element (FE) modelling approach developed in the previous Chapter 5 was adopted in this study. Specifically, the approach simulates the bearing response of composite laminate by integrating the embedded element technique (EET) with the LaRC05 failure criteria [129], all implemented via the VUMAT subroutine in Abaqus/explicit. The applied damage modelling strategy is listed in Table 6-2.

Table 6-2 Failure criteria and damage evolution models

Constituent	Failure criteria	Damage evolution
Embedded plain weave tow/3D printed continuous CF filament	LaRC05	Linear
Host Matrix	LaRC05 (matrix failure only)	Linear
Homogenised plain woven laminate (far away from the hole)	N/A	N/A
Inter-laminar interface	Quadratic traction criterion	Linear

The setup of the FE model is shown in Fig. 6-1. Within the laminate, each layer - whether it's a plain woven layer or a 3D printed interlayer - is composed of host matrix elements and embedded tow/filament elements. The thickness of the plain woven is 0.3 mm, while the

printed interlayer measures 0.15 mm. The host element is modelled directly in Abaqus and the internal embedded tow/filament is firstly generated as a voxel mesh using Python scripts in the open-source post-processing software TexGen and then imported (details shown in the Appendix A and B). TexGen defines the material properties and orientations within the element based on the fibre direction using analytical fields. These two parts are assembled with the embedded element constraint within Abaqus. To minimise computational demand, only a quarter of the thickness is modelled by symmetry, with the final simulation result derived through a mirroring process. The model was subjected to specific boundary conditions and constraints as follows: 1) To account for the symmetry in the geometry and loading conditions of the double-lap joint, symmetry boundary conditions were imposed along the transverse and thickness planes; 2) Displacement and fixed boundary conditions were respectively implemented on the loading plate of the fixture and the gripping section of the laminate, illustrated in Fig. 6-1, highlighted in red; 3) The fixture was designed for robust performance, assigned with rigid body constraints. Furthermore, an embedded constraint was utilised, designating the matrix as the host region and the 3D-printed continuous carbon fibre interlayer/plain woven layer as the embedded region.

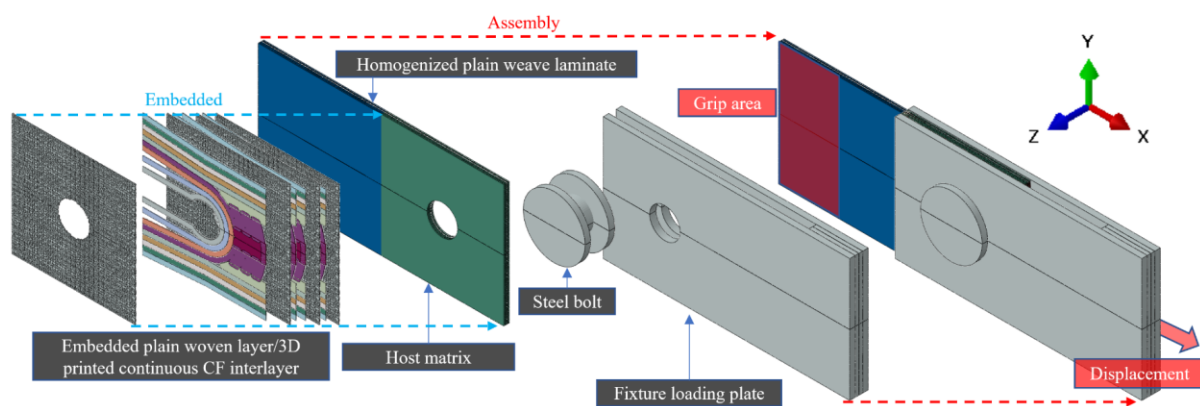


Fig. 6-1. Setup of the finite element model.

According to the ASTM standard D5961/D5961M, a longitudinal displacement of 5 mm is applied to the model, equal to half of the hole diameter. The elastic properties of the printed

3K filament and homogenised 3K plain woven laminate are shown in Table 3-4. The properties were obtained through a combined approach of experimental testing and empirical calculation. The strength parameters of the material and the intra-laminar and inter-laminar fracture toughness properties are presented in Table 3-5. The critical energy release rates for fibre intra-laminar damage evolution, including fibre tensile failure G_{ft} and fibre kinking G_{fkink} are sourced from literature [129] shown in Table 3-5. The fracture toughness for matrix modes is assumed to be the same as the inter-laminar fracture energies for Modes I and II (G_{IC} and G_{IIC}), as detailed in

Table 3-6. For the interface properties of composite laminate, the normal and tangential stiffness values K_n , K_t , maximum contact stresses σ_{max} , τ_{max} and critical fracture energies G_{cn} , G_{ct} are given in

Table 3-6. Additionally, modelling delamination presents a nonlinear challenge often leading to convergence issues. To address this, an artificial damping coefficient ($n = 5 \times 10^{-4}$), expressed in time units, is implemented. This coefficient is critical for stabilising the simulation and must be smaller than the minimum time increment, which is required to be relatively small. This approach effectively mitigates the convergence problems typically associated with delamination modelling, ensuring more reliable and accurate simulation results. Also, mass scaling method was employed to enhance the computation efficiency with the same manner detailed in section 5.2.4.

6.2.3. Experimental: Manufacturing, Testing and Characterisation

As mentioned in section 3.2, CF/epoxy woven layers were formed by Pyrofil TR30S 3K 1 x 1 plain weave fabric mats impregnated with PE6405 powder epoxy. The prepreg layers were precisely cut using a Hama A4 Guillotine wet saw, ensuring accurate alignment. For prepreg layers used for the interlayer cases, the bolt hole was drilled before the oven curing process.

To avoid delamination and damage of the prepreg during drilling, fastener holes were created using a backing aluminium plate. These prepreg layers, featuring a nominal thickness of 0.3 mm after the oven curing process, were utilised in creating the composite laminates.

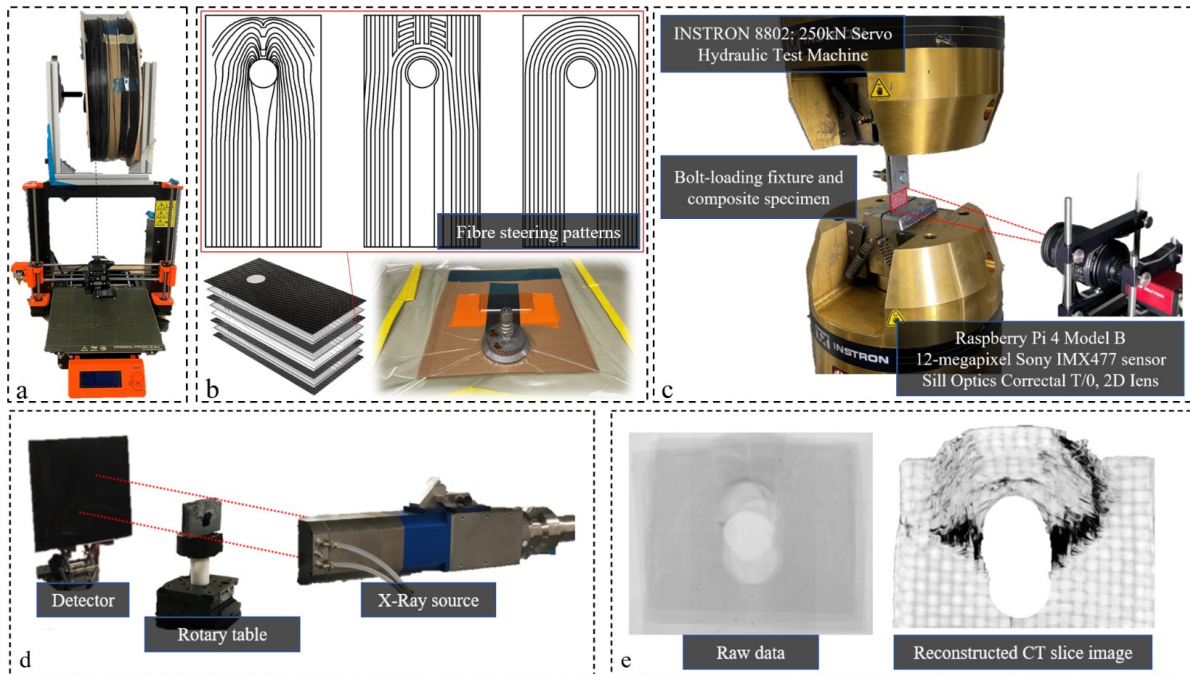


Fig. 6-2. Fabrication and characterisation of hybrid laminates: (a) Modified Prusa i3 MK3S printer for printing interlayers; (b) Diagrams of fibre steering patterns and laminate stack sequence, followed by vacuum bagging process for oven curing; (c) Experimental setup for testing; (d) Configuration of custom-built Micro-CT scan equipment; (e) Reconstruction of Micro-CT data using Avizo software.

The 3D printing was executed on a modified Prusa i3 MK3S printer, depicted in Fig. 6-2 (a). The printer operation was managed through Pronterface, a GUI host interfaced via USB. A passive continuous CF/epoxy filament feeding mechanism was employed, correlating the feed rate with the printing speed. Optimum temperature of 120 °C for the extruder and room temperature for the printing bed were set. These temperatures were crucial for ensuring filament softening within the nozzle and immediate solidification upon deposition, considering the weak bed-to-layer and layer-to-layer adhesion. The nozzle-bed distance was precisely set at 0.15 mm, leading to a printed filament width of about 1.5 mm and a thickness of 0.15 mm. The filaments were printed in patterns based on the three fibre steering designs mentioned

above through a customised G-code formulated through a Python-scripted continuous printing path, with further information available in Appendix A. The Python program dynamically adjusted the feed rate for efficient printing, setting 400 mm/min for straight paths and 200 mm/min for curves to prevent filament detachment. Following the 3D printing, prepreg woven layers and 3D printed layers were stacked in the sequence listed in Table 6-1 and subjected to vacuum bagging curing. Non-stick PTFE sheets and release fabrics were employed to hold the stacked layers. Furthermore, a completely enclosed mould was not utilised for the laminate. Instead, the desired shape of the laminate was achieved directly through the pressure exerted by the vacuum bag, supported by a steel plate beneath the assembly (shown in Fig. 6-2(b)). The heating cycle includes a critical gap between the epoxy's melting (40-60 °C) and curing phases (above 150 °C). This gap facilitated the expulsion of excess epoxy and voids, enhancing the fibre volume fraction. This strategy ensured that the samples did not adhere to the vacuum bag following epoxy consolidation. As such, the laminate was vacuum-packed and thermally processed in three stages: initial 40 °C for 2 hours to remove moisture, increased to 120 °C to melt the epoxy, and finally, raised to 180 °C for 2 hours for complete consolidation.

In this research, the experimental tests were conducted using the double-lap joint configuration. Each specimen was securely placed in a strong steel fixture, held together by grade 8.8 M10 steel nut and steel bolt. To ensure that the test specimens do not rotate around the bolt axis, and to minimise resistance from the friction, the nuts were tightened to a low and precise torque of 3 N·m using a torque wrench. The tests were carried out on an INSTRON 8802: 250kN Servo Hydraulic Test Machine, as illustrated in Fig. 6-2(c). A loading rate of 0.5 mm/min was used and a 0.5 kN preload was applied to each sample before the tests. Two specimens per case were examined. A high-speed camera was utilised as a visual extensometer in all tests, capturing displacements at designated locations (as shown in Fig. 6-2(c)). This data was further calculated with the displacement of the load cell to quantify the bearing strain.

To explain the failure behaviours attributed to fibre steering patterns, Micro-CT was employed. The Micro-CT imaging was performed at an in-house facility located in the Grant Institute, School of Geosciences, University of Edinburgh, as depicted in Fig. 6-2(d). Specimens were sectioned into uniform pieces, approximately 40 mm in width, to ensure enhanced resolution (around 40 μm pixel size). The focus was placed on the region around the bolt hole, a critical area for damage accumulation. The Micro-CT scans employed an X-ray source with an accelerating voltage of 70 kV and a power of 24 W. Optimum image quality, in terms of contrast and intensity, was achieved by setting the exposure time to 2 seconds. During scanning, each specimen underwent a 360° rotation, enabling the acquisition of hundreds of projections. The raw data from these scans were reconstructed using Octopus 8.9 in LabView®, resulting in the final imagery. The threshold value for image analysis was determined based on empirical experience.

Crack distribution due to bearing load was successfully captured through Micro-CT imaging. Avizo software was utilised for three-dimensional visualisation and analysis. Its capabilities in slice and volume rendering were instrumental in tracing cracks and delamination at any location within the scanned specimen. The sequence of reconstruction is illustrated in Fig. 6-2(e). Through analysis of the slices, the damage mode of each case was identifiable and correlated with mechanical test results.

6.3. Results and Discussion

In the development of fibre pathways guided by the load path concept, stress distribution in the plain woven at the elastic stage layer was analysed by the FE model. The orientation of vectors within the load path field was determined based on the load path illustrated in Eq. (6-1). The load path for a force with a specific direction is an area where the force magnitude in that direction is unchanging. In the bolted joint case, considering the path as defining an area where

the force is consistent, the vector field is identified by the constrain where both normal and tangential loads do not contribute to the force in the loading direction.

$$\int V_x \cdot \mathbf{n} dA = 0 \quad (6-1)$$

where V_x is the stress vector and $\mathbf{n}$ is the unit vector perpendicular to V_x . The vector field of $\mathbf{n}$ determines the fibre trajectory.

To prevent excessive overlap around the bolt hole, path selection was conducted by defining a starting point near the edge and tracing along the load path vector field to obtain a more rational path. This process was facilitated through Python scripts and resulted in a fibre tailored pattern detailed in Fig. 6-3(a). Analysis of the matrix damage degradation contour clearly demonstrated regions of shear, bearing, and tension damage. Consequently, fibre paths were designed based on these identified failure planes, allowing the fibres to withstand shearing, tension, and compression in the corresponding areas, as demonstrated in Fig. 6-3(b). These paths were interconnected to create a continuous trajectory suitable for 3D printing. Prior to fabrication, simulations were conducted: a comparison of the bearing stress-strain curves indicated that interlayers enhance the bearing response of the plain woven laminate using a reduced amount of carbon fibre. This finding confirms the value of conducting experiments to validate the simulation results as well as clarify the load transfer and failure mechanisms in each case. A detailed validation of the FE model against the experiment using the drilled case, which will be included in the following sections for the purpose of better comparisons with the designed interlayers. The validated FE model was then used to inform the tailoring of the fibre architecture and print paths for the interlayers. The following sections will present the correlated experimental and numerical results to evaluate the effectiveness of the 3D printed interlayers in terms of joint bearing performance, load transfer and damage progression, as well as failure mechanisms.

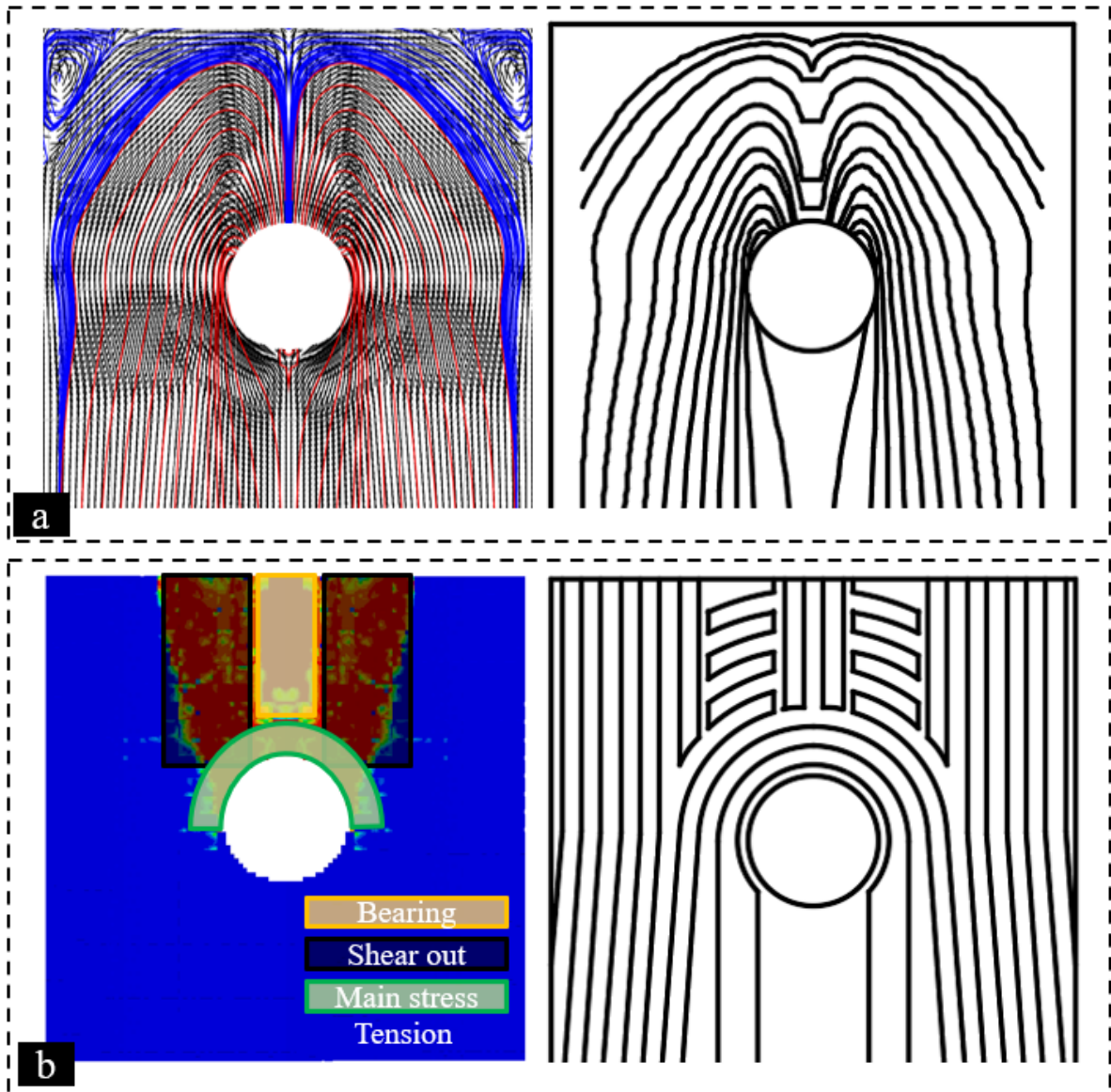


Fig. 6-3. Interlayer design (a) Path tracing within the load path vector field and load path fibre steering pattern, (b) Region based on principal stress and failure planes and failure plane fibre steering pattern.

6.3.1. Bearing Response and Performance

Fig. 6-4 (a) displays the stress-strain curves derived from the bolted-joint bearing tests. For a clearer visual comparison among the four cases, a representative curve from each case was selected for analysis. A quantitative comparison across all cases was conducted by compiling the average of five mechanical properties from these four data sets, presented in Fig. 6-4 (b). This comparison evaluates the performance of each case based on the following mechanical

properties: The bearing chord (BC) stiffness, measured between 50 MPa to 100 MPa, reflects the bearing resistance capacity during the elastic deformation phase; The initial peak bearing (IPB) strength gauges the bolt's resistance to initial cracking, characterised by a notable decrease in bearing stress; At this critical stress drop point, both IPB strength and initial fracture (IF) energy were analysed for comparative purposes; Upon reaching maximum stress, ultimate bearing (UB) strength and ultimate fracture (UF) energy were recorded, highlighting the maximum bearing capacity of the specimen.

From Fig. 6-4, it is evident that during the elastic phase, the LP case demonstrated superior stiffness, approximately 58% greater than other cases. Furthermore, for IPB strength and corresponding IF energy, all interlayer cases, particularly the FP case, showed significant enhancements of 95% and 496% respectively, indicating a robust resistance to the onset and propagation of initial peak bearing failure. This is observable in the stress and strain curves, where, despite early plastic deformation, stress drop occurred later. For UB strength, all interlayer cases once again outperformed the drilled case, with the FP case achieving the highest increase of 58.51%. Finally, in terms of UF energy, variations were noted; interlayer cases OF and LP exhibited lower capabilities, whereas the FP case demonstrated similar performance to the drilled case. Fig. 6-4 (c) shows macroscopic photographs of deformed holes in the composite plate after ultimate failure. Analysis of these images reveals that the predominant modes of damage are bearing and shear-out. Notably, in the OF case, it is observed that shear-out damage, upon reaching a certain extent, induced tensile failure. And it is worth noting that as each interlayer case has reduced the thickness of the laminate joint, by comparing with the original plain woven case, the weight of laminate has also decreased by 22.68%, 21.13% and 22.16% among the case OF, LP and FP respectively.

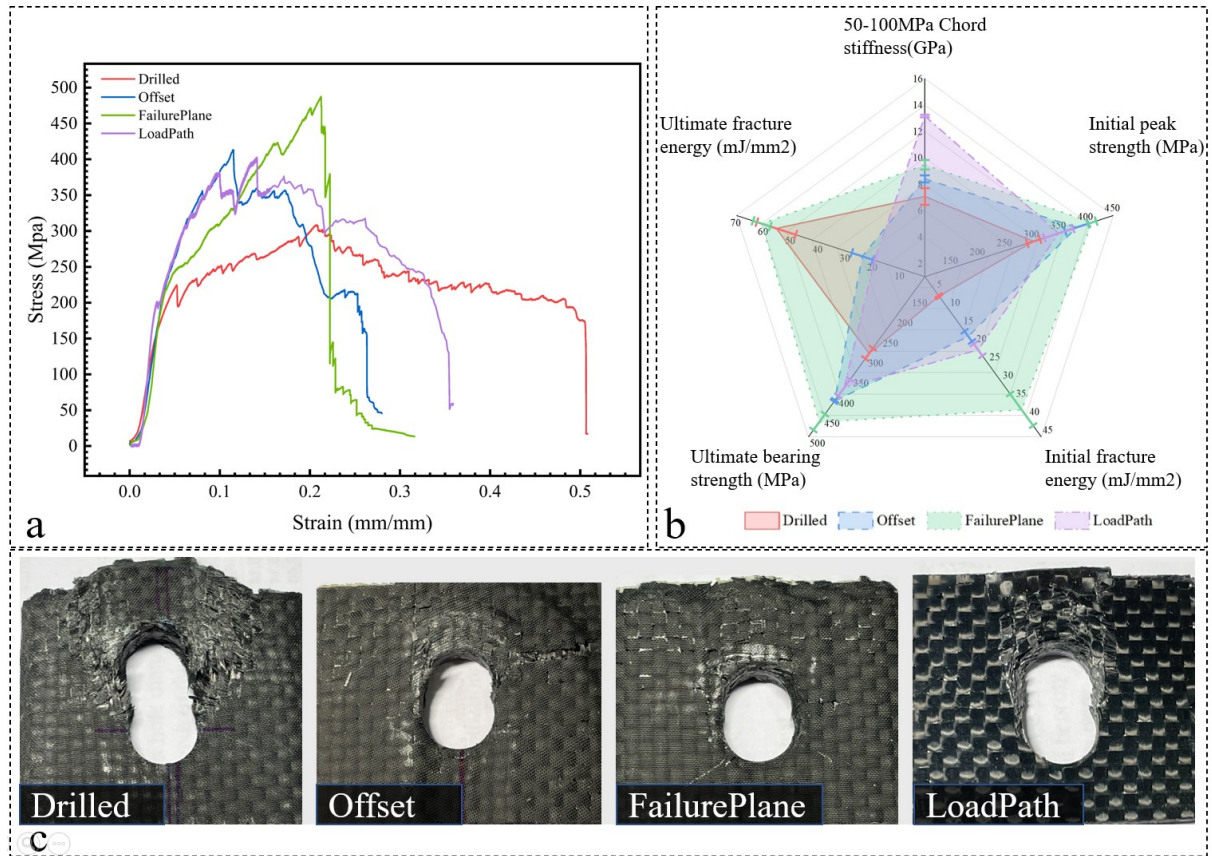


Fig. 6-4. Bearing response of the composite laminate: (a) Stress-strain curves; (b) Radar chart of comparative mechanical properties of four cases; (c) Deformed holes in composite plate after the ultimate failure.

These average five mechanical properties measured from experimental tests were further used to compare with the FE modelling results, with the accuracy ratios listed in Table 6-3. The stress-strain curve from FE modelling for each case was plotted in Fig. 6-5 in the next section to correlate with the damage progression, but the five mechanical properties were calculated and compared here for model validation purposes. It is found that all five mechanical properties have been excellently predicted by the multiscale FE model for the conventional DR case. The initial fracture energy was underestimated by the FE model for the OF, LP and FP cases with 3D printed interlayers, due to the pre-mature matrix cracks that occurred around the bolt hole edge, leading to a loss of contact between the bolt and the laminate and consequently a sequence of load drop appears during simulation. This is one of the challenges in fastened joint modelling, caused by complex contact definitions, a phenomenon also observed in other

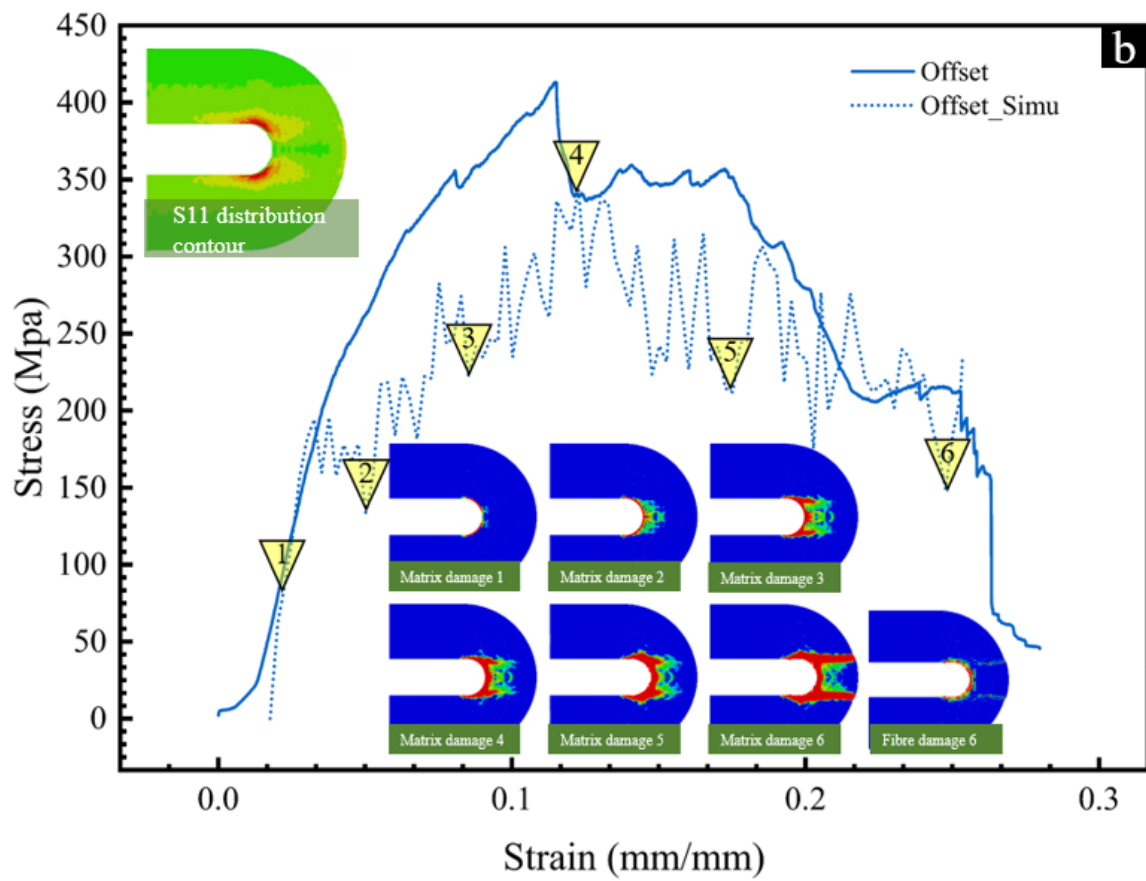
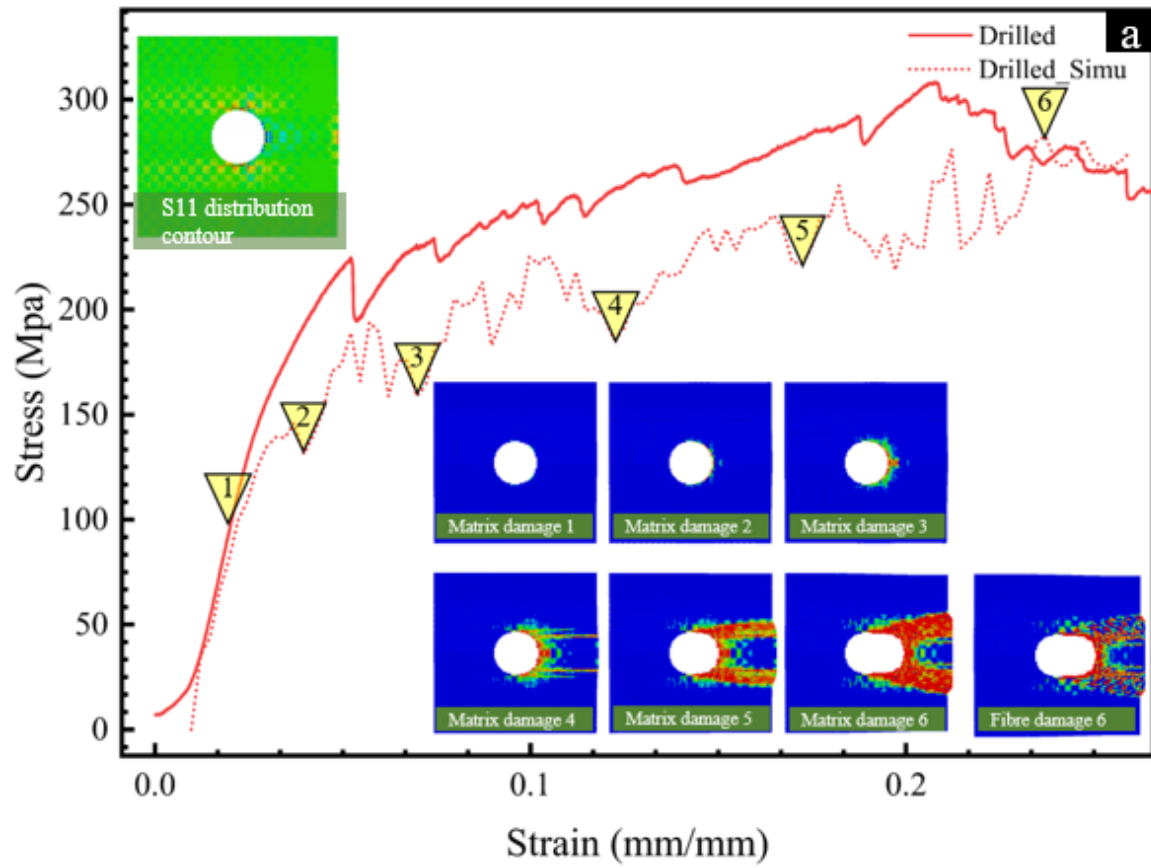
research [274]. The other four mechanical properties showed very good agreement between the FE simulation and experimental test, further confirming the viability of the multiscale modelling approach.

Table 6-3 Accuracy ratios of FE simulation to experimental test for mechanical bearing capacities in four cases

Mechanical bearing capacities	DR	OF	LP	FP
50-150 MPa Chord stiffness (GPa)	96%	79%	94%	93%
Initial peak strength (MPa)	92%	51%	69%	71%
Initial fracture energy (mJ/mm ²)	92%	15%	26%	12%
Ultimate bearing strength (MPa)	97%	84%	88%	91%
Ultimate fracture energy (mJ/mm ²)	76%	98%	100%	99%

6.3.2. Load Transfer and Damage Progression

This section initiates with a comparative analysis of the mechanical performance of four distinct composite bolted joints as shown in Fig. 6-5, focusing on the differences in elastic stage and damage evolution. This comparative study highlights the benefits and drawbacks associated with each type of fibre steering in the 3D printed interlayers. To better identify the reason for the stiffness difference among these cases, the contour of the stress along fibre direction ('s11') was extracted at the elastic stage (as marked as point 1) for each case shown at the top left corner of each chart. As mentioned above, matrix cracking is the dominant failure mode and induces the final rupture of the joints [147]. Thus, here only the matrix damage propagation contours at six different loading points were listed, which cover the elastic (point 1), plastic (points 2-5) and final failure (point 6) stages. Additionally, the fibre damage contour at the final failure stage was also plotted (at the right bottom of each figure) for a better understanding of the failure mechanism.



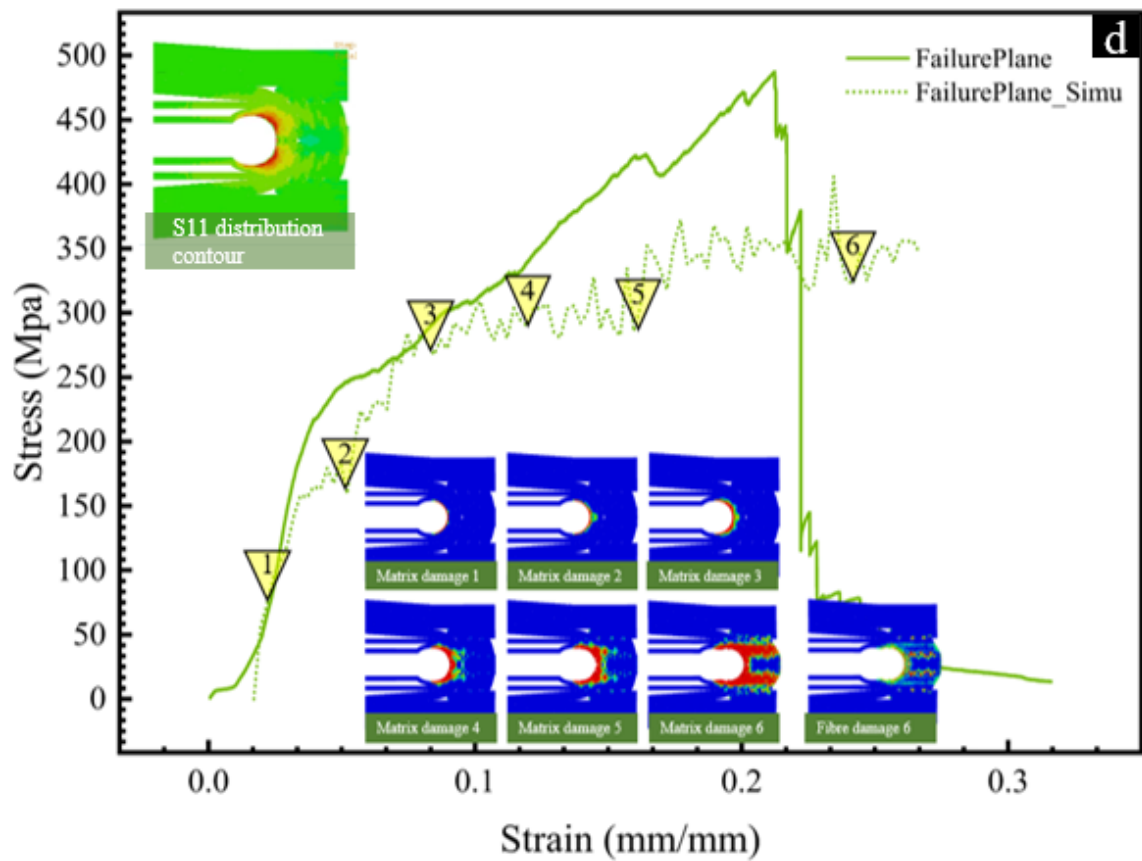
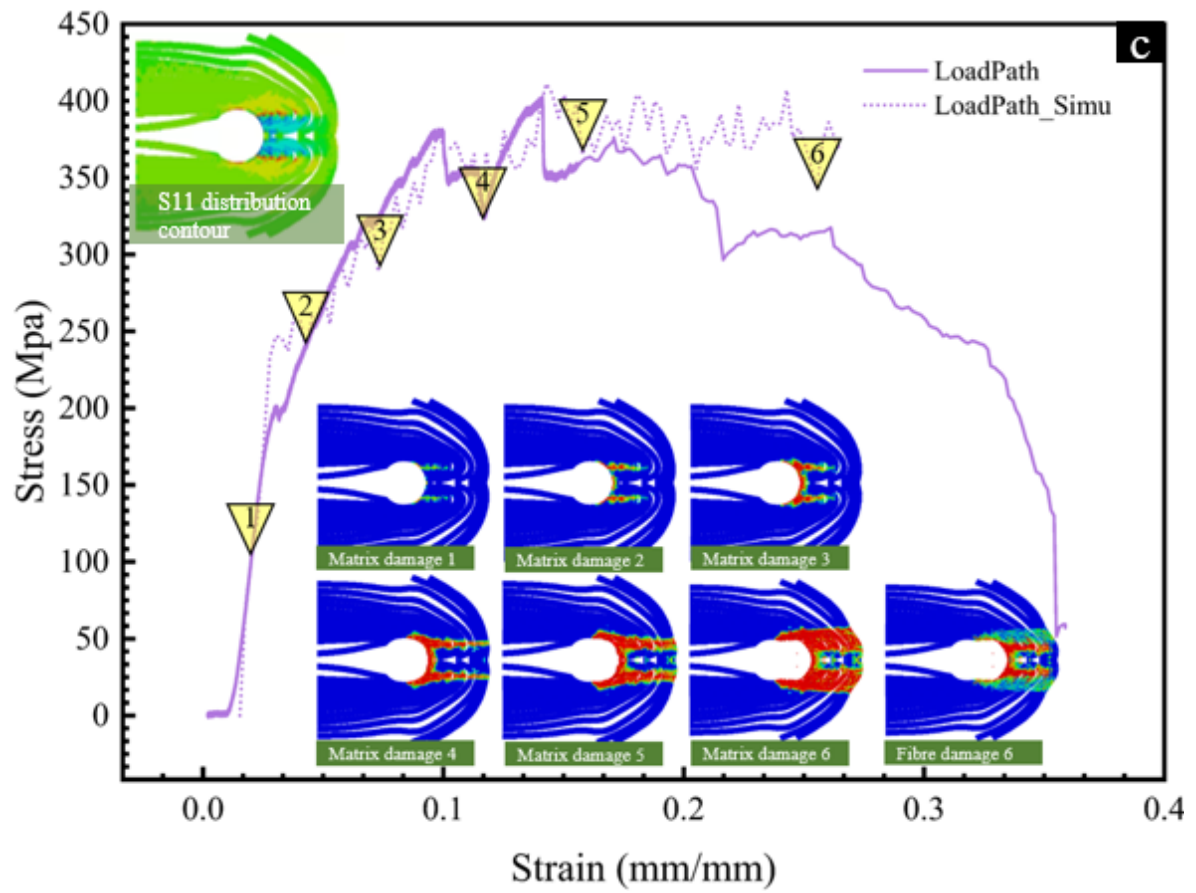


Fig. 6-5. Load transfer and damage progression: (a) DR (b) OF (c) LP (d) FP.

Each case displayed different stiffness characteristics at the same bearing strain. This is explained by the stress s_{11} (fibre direction) distribution contour of the filaments in Fig. 6-5 exported at loading point 1, as the stiffness of the composite laminate is mainly determined by the fibre. The LP and OF cases demonstrated the highest stiffness, with FP being slightly lower and PW the weakest. From Fig. 6-5, it is evident that, aside from the load path case, the other three cases exhibited pronounced stress concentrations along the fibres around the hole. In the drilled case, the discontinuity of fibres around the hole led to an obvious stress concentration, which was only distributed at the neck of the open-hole laminate and the position directly subjected to the bolt bearing. In contrast, the OF and FP cases, due to the continuity of fibres around the interlayer holes, experienced stress concentration as well, but the load transfer area was broader than in the DR case. In the LP case, the fibre steering pattern, designed based on stress distribution, allows the fibres oriented along the load path to transfer loads more effectively, reducing internal stress concentration and thereby enhancing the overall rigidity of the structure.

The onset of plastic deformation in the four cases occurred at approximately the same strain, around 0.05 mm/mm (loading point 2). At loading points 3-5, it is evident that all cases demonstrated an extended plastic phase, yet they differed significantly, broadly categorised into three types: 1) For the DR and LP cases, despite maintaining the load, a substantial area of damage occurred in the matrix within the shear region, undermining its structural rigidity. This damage probably resulted from shear out induced deformation. 2) For the OF case there was a partial loss of stiffness (around 30%) in the plastic phase, but the structure remained stable without losing stability. However, the plastic phase was relatively short, rapidly reaching its ultimate bearing. 3) For the LP case, there was a significant stiffness loss (around 50%) in

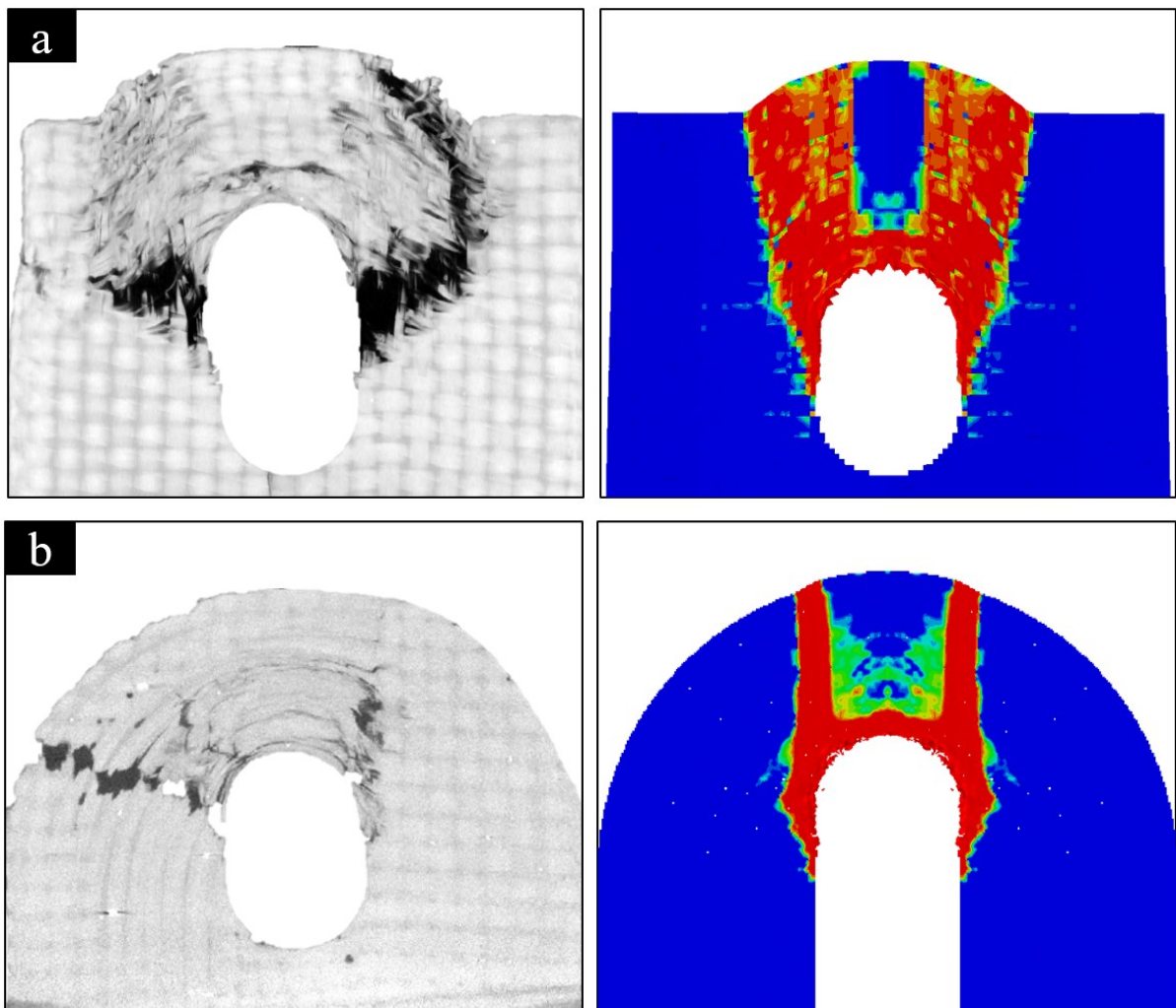
the plastic phase, yet it sustained a longer plastic phase. Thus, the ultimate bearing fracture energy absorption performed better.

The comparative contours of matrix and fibre damage propagation at loading point 6 were used to explain the difference in the plastic stage. The matrix damage distribution in the DR and LP cases was more severe, forming a clear shear out deformation. Additionally, the fibre damage contour diagram revealed that most fibres in the structure were completely damaged, explaining the loss of stiffness at these points. In contrast, in the OF and FP cases, the fibre damage was primarily concentrated around the bolt hole. As the fibres did not suffer significant damage, they still enabled the structure to maintain a degree of stiffness, although matrix cracks appeared along the shear out plane.

6.3.3. Failure Patterns and Mechanisms

The distribution of matrix damage from the FE simulation was compared with experimental observation. This is because matrix cracking is the dominant failure mode and induces the final rupture of the joints [147], and capturing matrix crack distribution in Micro-CT images was more straightforward. As depicted in Fig. 6-6, four cases of Micro-CT image slices were compared with the matrix damage variable contour from FE simulation at the final failure stage (loading displacement 5 mm). It is essential to clarify beforehand that, in the FE contour, blue signifies undamaged areas, while red indicates complete destruction. The FE model assumed a default, constant displacement of 5 mm whilst the experimental tests continued until the complete joint failure. This explains the different degrees of deformation of the bolt hole that appeared in the DR case between the FE simulation and experimental test (see Fig. 6-6(a)). This comparison primarily aims to verify the alignment of damaged regions. The figure reveals an acceptable similarity between the simulation and experiment of all four cases for the matrix's bearing and shear out failures. The Micro-CT results clearly showed matrix damage in areas facing the bearing load from the bolt, a phenomenon also observed in the FE model. The

accompanying shear out failures, particularly pronounced in the DR and LP cases, were widely distributed and can be discerned in the Micro-CT images, especially the DR case. In the LP case, matrix cracks were primarily concentrated in the bearing region, with a distribution pattern slightly different from the simulation, predominantly around the shear out plane. Conversely, for the OF and FP cases, the simulation results indicate a less wide-ranging but more apparent shear out damage path, closely matching the Micro-CT images. Net-tension failures in the DR and OF cases, however, were not clearly captured by the FE modelling. The likely reason for this omission in the DR case would be the insufficient displacement applied in the simulation. In the OF case, although the simulation suggested matrix damage propagation along areas susceptible to net tension failure, the trend leaned more towards shear out failure.



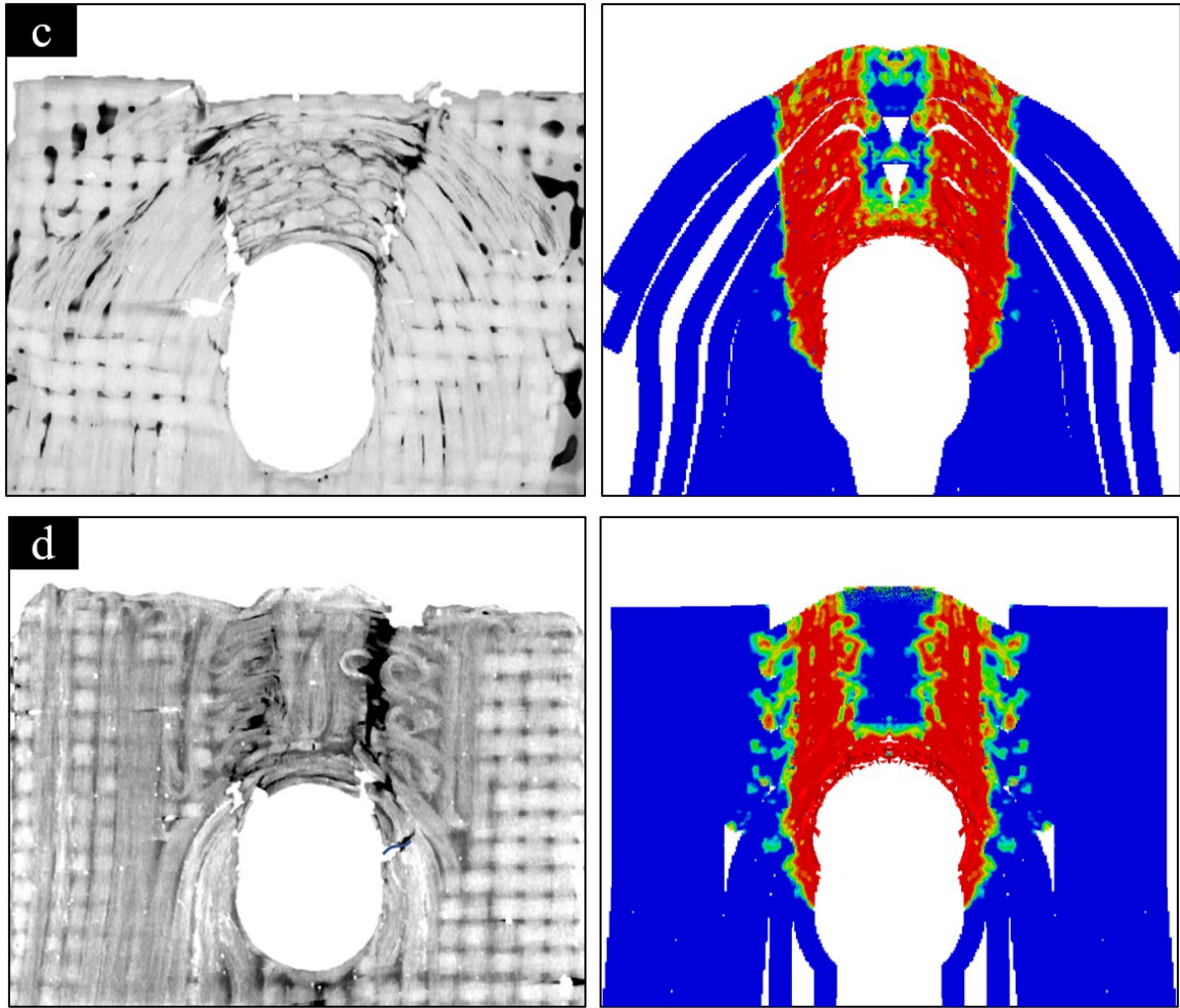


Fig. 6-6. Comparison of Micro-CT imaging and FE modelling of matrix damage in 3D printed interlayer: (a) DR, showing woven layer as no printed interlayer, (b) OF, (c) LP and (d) FP.

6.4. Conclusions

The results of the double shearing tests indicate that the modified hybrid laminates with the 3D printed interlayer generally performed better compared to the plain woven laminate. The stress-strain curves and the radar chart of the modified hybrid laminates showed improved mechanical behaviours, with a smoother and higher stress capacity before failure. This research demonstrates the promising potential of using 3D printing technology to tailor the fibre architecture of interlayers for plain woven CFRP laminates and enhance their performance in

bolt joint applications. The comparison includes mechanical testing, Micro-CT microstructural characterisation, and finite element analysis. The focus is on understanding the impact of fibre architecture on the mechanical properties of composite joints. Key conclusions drawn from the study are as follows:

(1) Compared to conventional laminate structures, fibre placement utilises the 3D printing technique to steer and maximise the orthogonal anisotropy of filaments, enabling diverse characteristics in the modified hybrid composite laminates, particularly in bolted joint applications. By embedding customised fibre steered patterns into widely used plain woven laminates, significant reinforcement was achieved. This enhancement, while preserving the detachability of the components, improves the laminate's stiffness (with increases up to 86% in case LP), initial peak strength (increases up to 95% in case FP), and ultimate bearing strength (up to 58% in case FP). Correspondingly, the capability for energy absorption is also enhanced, evidenced by increases in initial fracture energy (up to 496% in case FP) and ultimate fracture energy (up to 10%). In the case OF, these values were enhanced, but not as noticeably as in other cases.

(2) The improvement in stiffness is most notably realised through the alignment of load paths based on stress distribution, *i.e.*, the LP case in this study. This is primarily due to the consistency in the orientation of carbon fibres with the direction of applied stress. When the carbon fibres are aligned with the primary direction of force, the material's stiffness increases significantly, attributable to the high stiffness of carbon fibres along their length.

(3) Regarding the suppression of failure, *i.e.*, the strength and energy absorption at both initial load drop and ultimate failure points, the fibre placement pattern generated based on failure planes (namely the FP case in this study) exhibits optimum performance. These failure planes are distinctly outlined in the case of bolt joint connections in composite laminates. This is

validated through finite element modelling, where contour diagrams of fibre and matrix damage degradation show minimal areas of complete matrix damage under the same bolt displacement in FP and OF cases. Furthermore, complete fibre damage is least distributed in the FP case, maximising the use of orthotropic characteristics of carbon fibre filament in preventing damage evolution.

(4) The finite element model employed in this study, using printed filament as the basic unit, accurately evaluated the mechanical properties and failure behaviours of traditional plain woven composite laminate joints. The simulation results were further used to guide the design of fibre steering patterns within the laminate joints and achieved better bearing performance. The model also helped to study the failure mechanism within the modified joints. The model demonstrates high average accuracies in predicting stiffness, ultimate strength, and corresponding energy absorption, with average accuracies among all the cases respectively being 90%, 90%, and 93%. However, the model has limitations, particularly in capturing the initial failure in cases with prolonged damage evolution under bearing loading. This is due to the complex interaction between the bolt and the specimen interface, leading to significant fluctuations in the post-failure response curve. Future work will focus on model refinement to address these issues.

Chapter 7. Novel Repair of Bolted Composite Joints using 3D Printed Continuous Fibre Patch with Custom Fibre Paths

7.1. Chapter Introduction and Overview

This Chapter presents a novel technique for repairing deformed bolt holes in mechanically fastened composite plates, which are commonly considered as non-reusable under service conditions. Targeting the inherent weakness in bolt holes, this method is particularly significant given the widespread use of fastening joints in large assembled thermoset composite structures. The approach involves the use of 3D printed continuous carbon fibre patches to restore bolt holes in thermoset material systems to their original dimensions and functionality, with minimal alteration to the damaged laminate. The key advancement of this method lies in the ability to customise fibre orientations within the patches, which is not feasible with traditional unidirectional or plain weave mat methods.

In conventional fabrication techniques such as autoclave and resin transfer moulding, carbon fibres are usually positioned homogeneously within each layer [155, 156]. However, as mentioned above, the matrix material is usually a thermoset of higher heat resistance than thermoplastics but is mechanically more brittle than those thermoplastics. Thus, the maintenance of thermoset composites is an ongoing issue. Thermoset composites tend to crack, and the cracks tend to propagate and fracture; such behaviour is typical of brittle materials. Special repair treatments are required [158]. Many researchers have developed particular repair methods aiming to meet various repair requirements.

The most commonly employed repair method involves removing a substantial portion of the damaged composite material and then directly joining it with a new composite. A typical joining repair features excision of the damaged area, followed by riveting and bolting. However, such repair creates holes in the composite and increases stress concentrations around the

cracked area [159, 160]. Another method is bonded repairs, such as scarf and lap joint repairs. Kim designed a carbon fibre printer for direct CFRP repair [157], which used dry carbon roving and liquid epoxy to bind fibres to substrates. Tests showed that printer-repaired samples had similar fracture loads to conventionally repaired ones but were thinner, possibly resulting in higher stiffness. This increased stiffness was linked to fewer voidages from the printing mechanism and raw material structure. However, despite the utilisation of 3D printing technology, the fibre placement remains unidirectional, thus not fully exploiting the potential of carbon fibre's anisotropic properties. Li *et al.* [173] explored two CFRP laminate repair methods: single bonded hybrid repair and double bonded hybrid repair, utilising both 3D printing and traditional processes. The 3D printed patch showed superior mechanical properties compared to the traditional laminate patch for angle ply laminates. For quasi-isotropic laminates, patch design, particularly the scarf shape, played a crucial role in repair performance. 3D printing allows for cost-effective, flexible fabrication of complex shaped patches with enhanced mechanical performance, especially for thin CFRP laminates common in automotive and aerospace applications. Damghani *et al.* [172] presented a detailed design of a stepped scarf repair for heavily loaded composite structures using linear finite element analysis, introducing a novel scarf patch design aimed at size minimisation. The study suggested a need for improved bonding between the repair patch and parent laminate. However, existing repair methods for composite laminate primarily address impact damage/tensile damage and to the best of the author's knowledge, there lacks a specific method for repairing damage in bolted joints for thermoset composites. This gap highlights the need for further research and development in this area, essential for maintaining the integrity of composite structures.

In the field of composite materials, the integrity of joint structures is critical. These joints, serving as assembly components within larger composite structures, are often the most crucial yet vulnerable elements. Among the three primary joint types - mechanically fastened,

adhesively bonded, and hybrid bolted-bonded (HBB) joints [30] - mechanically fastened joints, which employ pins, rivets, and bolts, are extensively used in industries like aerospace due to their reliability [35-38]. However, they exhibit a significant drawback: high stress concentrations around fastener holes, leading to premature damage and reduced load capacity, especially in composite laminates compared to metal plates [47]. Adhesively bonded joints offer a structurally efficient alternative, excelling in load distribution and substantially reducing the high stress concentration issues inherent in bolted joints [48, 49]. Despite their effectiveness, adhesive bonds are plagued by several deficiencies, such as vulnerability to humidity and peel stresses, coupled with the absence of effective inspection methods [50]. To enhance joining performance, a combination of bolted and adhesive bonded joints, termed hybrid (bolted/bonded) joints, has been developed [52]. While this hybrid approach addresses some of the limitations of both methods, it compromises the ease of assembly and reassembly inherent to bolted joints. Consequently, bolted joints remain irreplaceable in situations where frequent assembly and disassembly of the structure are necessary.

For a well-designed bolted joint in a composite structure, bearing failure is typically the predominant mode of failure [176]. This failure presents as crack propagation around the through-hole region, which directly endures the bearing load from the bolt. Once deformation occurs, the dimensions of the bolt alter, rendering it unsuitable for reuse and potentially leading to significant material loss even with a single deformed bolt hole. Thus, addressing this issue is of critical importance.

This study introduces a novel approach for repairing deformed bolt holes in composite structures. It has been discovered that the removal of a minimal quantity of the parent material through a simple mechanical drilling process creates sufficient space for the application of 3D printed continuous carbon fibres as a patch, effectively restoring the bearing capacity of the bolted joints. Moreover, two distinct patch patterns are designed and analysed. Both simulation

and experimental results suggest that the fibre steering pattern of the patch can be further optimised to enhance performance. These findings reveal the significant potential of 3D printed continuous carbon fibres in improving the repair processes of composite bolted joints, pointing towards new directions in composite material research and application.

7.2. Methodology

This study aims to use 3D printed patches to repair composite bolted joints that have been subjected to deformation with damage during service. Conventional plain weave laminates were initially fabricated and tested under double shear loading. Subsequent to damage induction, the damaged area was identified via Micro-CT. Quantitative analysis was then performed to identify the size and shape of the damage region, based on the Micro-CT slice images rendered in Avizo. This analysis informed the design of repair patches, in which fibre paths are customised using two distinct methods. Following this, the patches were 3D printed and applied to the damaged specimens for testing again. The effectiveness of the repairs was assessed by comparing the mechanical performance of the repaired laminates to that of the original laminates. Finally, the finite element (FE) modelling approach developed in Chapter 5 was adopted for each repair case to reveal the failure mechanisms involved alongside Micro-CT characteristics. The following subsections will provide details for the materials, case design, experimental procedures and FE modelling employed in this study.

7.2.1. Material System and Case Design

This study focuses on the repair of open-hole bolted composite laminates under shear loading. The base material system for this purpose consists of Pyrofil TR30S 3k 1 x 1 plain woven fabric and PE6405 epoxy [217]. Correspondingly, the continuous carbon fibre filament used for 3D printed repair patches is Pyrofil TR30S 3k carbon fibre tow, impregnated with PE6405 epoxy, which is manufactured through a self-built tapeline similar to the one reported in our

previous study [221]. In this context, the epoxy serves not only as a matrix material but also as an adhesive for the patch through co-bonding. Specifically, the vacuum-bagging-only (VBO) curing conditions for both the base and repair materials, including temperature and pressure, are listed in Table 7-1.

The dimensions of the original open-hole laminate were designed in compliance with ASTM D5961 standards, as detailed in

Table 7-2. The original laminates were initially used as a control group for experimental purposes. Subsequently, two types of patches were designed and applied to the tested samples from the control group to facilitate direct comparison as well as FE modelling in the later stages of the study. Consequently, three distinct cases were designed for this study. For the purpose of referencing, these cases have been differentiated using alphabetic codes detailed in

Table 7-2.

Table 7-1 Composite raw materials		
	Specification	Cure Temperature (°C)
<i>Base material</i>		
Fabric	Pyrofil TR30S 3k 1 x 1 plain woven carbon fibre fabric	Cure Pressure (Pa)

Resin	PE6405 Epoxy	180	101.35
<i>Repair materials</i>			
Fibre	Pyrofil TR30S 3k Carbon Fibre tow		
Resin	PE6405 epoxy	180	101.35

Table 7-2 Laminate dimension and case code

Length (mm)	Width (mm)	Thickness (mm)	Bolt hole diameter (mm)	Width to Diameter Ratio	Edge Distance Ratio	Number of Woven Layers
135	36	2.4	6	6	3	8
<i>Case</i>					<i>Code</i>	
Original plain woven laminate					PW	
Offset patch repaired laminate					OF	
Load path patch repaired the laminate					LP	

The fibre steering pattern of the patches was designed using two different methods. The path designed with the first method, is based on an offset approach from the hole edge and the outer contour of the geometric shape of the open-hole laminate itself. This geometric patch design method has been evaluated by other researchers in different applications [62, 149] and has been proven to be a simple and intuitive method for path generation. The second method was based on load path theory [38]. This method of path design has been previously evaluated in Chapter 6 and it achieved targeted reinforcement of the fibre in both the tensile and compressive regions within the same structure, thereby enhancing the corresponding tensile and compressive strengths of the structure [65]. In this study, this path design method was further explored in

the application of fastened joint repair for the first time by guiding the design of the repairing patch. In this approach, a vector field of load paths, responsible for generating the printing path in the patch, was computed using a Python script (Further particulars can be found in Appendix A). The basic data used in this script is the stress contour field of a patch derived from FE simulation, where a plain woven composite laminate was repaired with a pure epoxy patch under bolt bearing loading conditions. The load path vector fields were generated based on the same logic described in section 6.3.

To generate the fibre steering path for the continuous printing filament, multiple starting points were established around the edge of the repair zone. From these points, paths were traced according to the load path vector field. Subsequently, all potential paths were selected and optimised based on specific constraints, including the geometric offset case with an equal number of filaments, filament width, and patch thickness distribution. These optimised paths were then integrated into a continuous printing path.

The G-code for printing these patches was generated through Python scripts. To compensate for regions previously deformed and removed by mechanical machining, these paths overlapped to fill the open regions identified by Micro-CT scans of the damaged area. Thus, the G-code needs to be carefully designed in terms of the Z coordinates. The G-code was firstly output with an in-plane pattern and then the z coordinates were modified to achieve variable thickness. The G-code modification sequence is: (a) convert the designed pattern into a continuous printing path; (b) discretise the path into multiple short lines and export the coordinates of the breakpoints along the path; (c) modify the z coordinates of these nodes based on the real printing sequence through Python script (details in Appendix A).

7.2.2. Experimental: Manufacturing, Testing and Characterisation

The manufacture of the conventional plain woven laminate follows a traditional hand method: manually laying up eight layers of large plain weave mats in a steel mould. Simultaneously, each layer is coated with a calculated weight of epoxy powder, determined to achieve the target fibre volume fraction (49%). Following oven curing, the laminate is cut into specimens using a wet saw and drilled to create an open hole. These original laminates are then referred to as parent laminates, awaiting repair, and are subsequently tested to assess their suitability for this purpose. For the manufacture of the repaired laminate, damaged areas were identified within the parent laminate using Micro-CT scans instead of naked-eye observations for the purpose of precise determination of the area of damage, and subsequently removed using an industrial-grade, high-power, variable-speed grinder. This process resulted in a composite laminate with enough open region, ready for the patch to repair.

The 3D printed patches utilised continuous carbon fibre epoxy filaments, which were produced from a custom-built tapeline. The printing was executed using a modified Prusa i3 MK3S printer (Fig. 7-1 (a)), employing a passive filament feeding mechanism. The printing speed varied according to the path, *i.e.* straight paths were assigned a rate of 400 mm/min, while curved paths had a minimum rate of 100 mm/min. It should be noted that the printing rate for curved paths mentioned here is lower than the 200mm/min discussed in Chapter 4. This is due to the larger radius of curvature, which increases the likelihood of the filament detaching from the bed during the printing process. After several trials with speed parameters, 100mm/min has been found to be optimal for this scenario to prevent filament detachment from the print bed while maintaining good printing efficiency.

The 3D printed patches (as illustrated in Fig. 7-1(b), (c)) and the parent plate were adhered together by using a vacuum bagging technique in a co-bonding process. Both the top and bottom of the parent plate were attached with a patch and the components were situated in a

mould 3D printed using short carbon fibre reinforced polyamide-6 (sCF/PA6) material (Fig. 7-2(d)), which surfaces were then treated with a release agent. The bolt hole was formed by adding a 3D printed sCF/PA6 disc at the predetermined location, which was later removed during post-processing. This setup was followed by a three-stage oven curing process customised based on the material's thermal characteristics. Initially, the oven was set to 40°C for 2 hours to remove moisture. The temperature was then elevated to 120°C for 1 hour to melt the epoxy powders. In this stage, the fibre within the patch will flow with epoxy and infill the voids [217]. Finally, the assembly was consolidated at 180°C for 2 hours. During the 120 °C melting phase, the molten epoxy, carrying continuous carbon fibres, infiltrated into the areas of the parent plate that had previously been mechanically stripped. The end result was a composite plate with a hole diameter identical to that of the original component. Also, in addition to the base thickness, each side patch added approximately up to 0.3 mm of extra thickness.

Both the original and repaired open-hole composite laminates were tested under double shear loading in accordance with the ASTM D5961 standard. A test fixture was used, consisting of a pair of steel laps, a bolt and a nut. The laps were made of Domex 500 MC high-strength steel. Same as the composite plate, the steel laps were fabricated into an in-plane dimension of 135 mm × 36 mm and a hole diameter of 6 mm with a thickness of 3 mm. Grade 8.8 steel M8 bolts with a shank diameter of 6 mm were used. A fastening torque of 3 N·m was applied to assemble the fixture with laminate using a torque wrench. In this study, a total of 2 mm displacement was applied to the steel fixture bolt, providing a quasi-static loading condition on an Instron 8802 tensile testing machine. The test setup is shown in Fig. 7-2(c).

As mentioned above, to identify the location and size of the damaged areas within the laminate under a 2 mm displacement deformation of the bolt joint, and to gain a detailed understanding of the internal cracks within the composite, Micro-CT scans were conducted at the custom-

built Micro-CT facility at the Grant Institute, School of Geosciences, the University of Edinburgh, as depicted in Fig. 7-2(d). Initial scans covered a broad area to capture the overall distribution of crack propagation. For higher resolution imaging of the repaired regions, the tested specimens were sectioned into smaller pieces. The scans were carried out at an accelerating voltage of 70 kV and a power of 24 W, with an exposure time set at 2 seconds to secure high-quality images in terms of contrast and intensity. The raw scan data (Fig. 7-2(e)) were then reconstructed using Octopus 8.9 in LabView[®], and an expert-determined threshold value was applied for image analysis. This Micro-CT imaging successfully captured the crack propagation within the specimens induced by bearing loads.

For 3D visualisation and analysis, the commercial software Avizo was employed, specifically leveraging its volume rendering capabilities (Fig. 7-2(f), (g)). This enabled the pinpointing of crack propagation and material deformation at any given location within the scanned specimen.

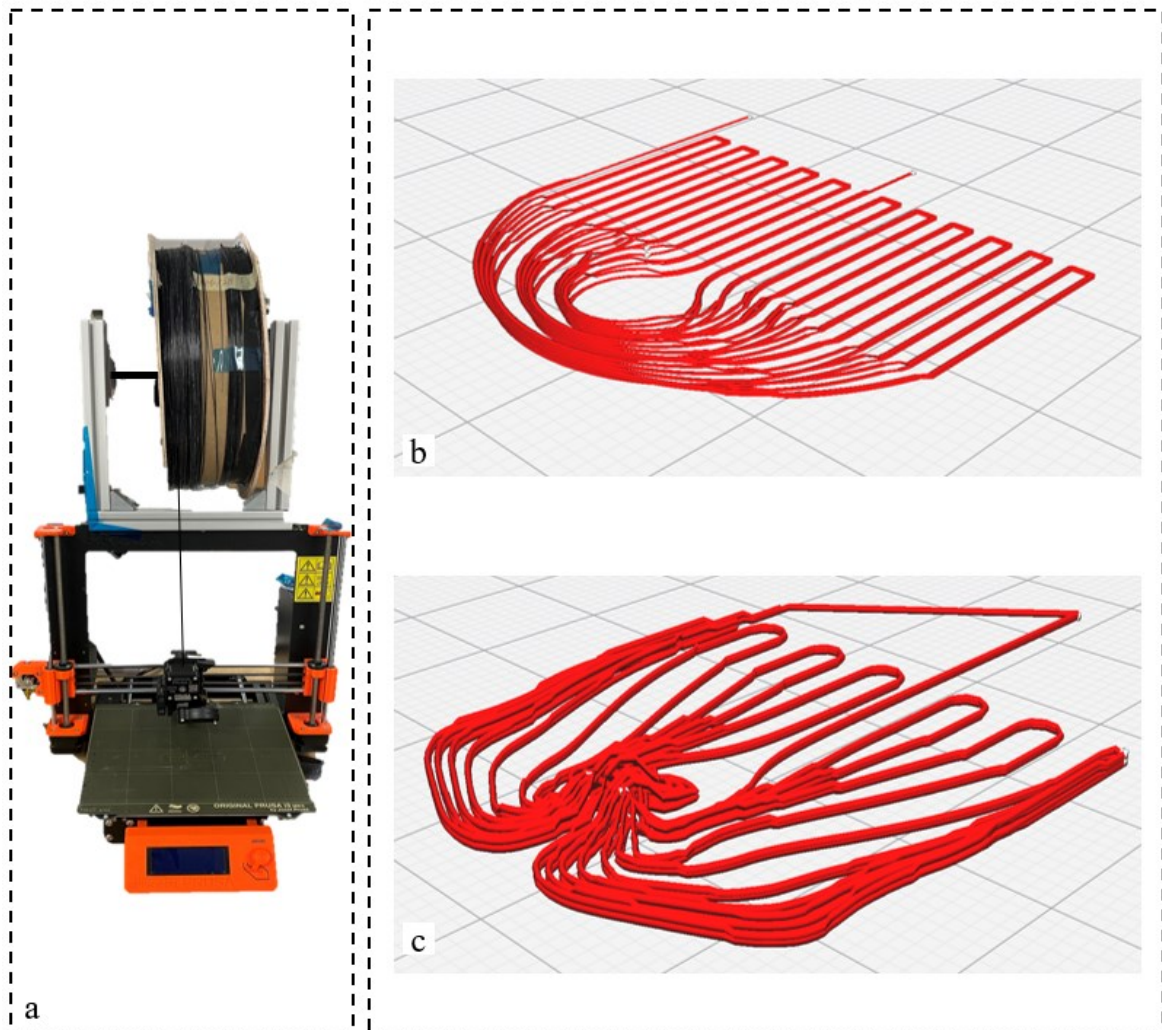


Fig. 7-1. Fabrication of repairing continuous carbon fibre patch: (a) Modified Prusa i3 MK3S printer for printing patches; Visual representation of G-code utilised for printing patches: (b) offset pattern and (c) load path pattern.

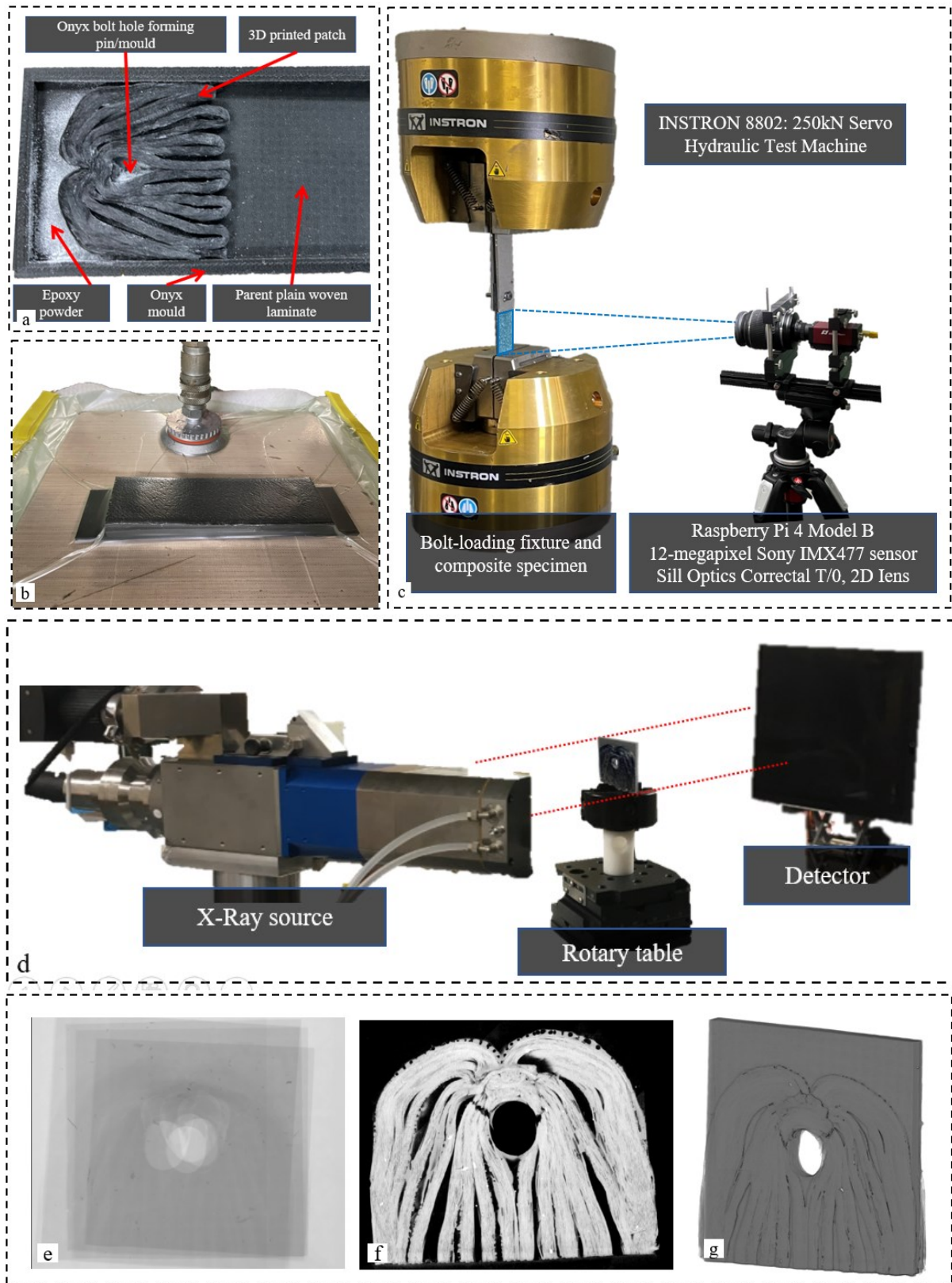


Fig. 7-2. Fabrication and characterisation of repaired joint: (a)(b) Vacuum bagging curing setup; (c) Experiment setup; (d) Configuration of custom-built Micro-CT scan equipment; (e) Raw data from Micro-CT scan, (f) reconstruction slices and (g) 3D model of Micro-CT data illustrated in Avizo software.

7.2.3. Numerical: Multiscale FE Modelling

The methodology for simulation in this study is an extension of previous work, where a multiscale FE modelling technique was employed. In particular, this research incorporates the embedded element technique in conjunction with the LaRC05 failure criteria to simulate the bearing behaviour of the 3D printed continuous carbon fibre patch. These components are all implemented through the VUMAT subroutine within the Abaqus/explicit. More details of this modelling method are shown in Chapter 5, section 5.2.1.

The material properties of 3K CF/Epoxy filament and homogenised elastic properties of 3K plain woven laminate employed in the simulations are shown in Table 3-4, Table 3-5, derived from the previous study in Chapter 3.

It is important to note that the model used for designing the path does not incorporate embedded elements to reinforce the pure matrix. Additionally, to capture the cohesive behaviour between patches, zero-thickness cohesive elements are defined on the symmetry plane of the patch (host matrix) along the thickness direction. Also, the defined cohesive interface exists between the patch (host matrix) and the homogenised plain woven laminate. The cohesive surface properties for carbon fibre/epoxy composite laminate are given in

Table 3-6. For other interactions such as bolt and laminate contact, normal behaviour employs standard hard contact, while tangential behaviour is modelled using a penalty approach with a friction coefficient of 0.3. Additionally, to augment computational efficiency, the mass scaling approach was adopted, as meticulously described in Section 5.2.4.

Table 7-3 Failure criteria and damage evolution models

Constituent	Failure criteria	Damage evolution
Embedded 3D printed continuous CF filament	LaRC05	Linear
Host Matrix	LaRC05 (matrix failure only)	Linear
Homogenised plain woven laminate (far away from the hole)	N/A	N/A
Cohesive surface	Quadratic traction criterion	Linear

The damage modelling strategy is detailed in

Table 7-3. The 3D model for the repaired laminate (case LP for example) in Abaqus is illustrated in Fig. 7-3. To optimise the modelling process and reduce the computational cost, only one-quarter of the specimen was simulated, leveraging the symmetry of the structure. Appropriate boundary conditions, constraints and interactions were applied throughout the model: 1) Symmetry boundary conditions along the transverse and thickness direction of the joint were applied, as the double-lap joint geometry and loading conditions are symmetrical about these planes; 2) Displacement and fixed boundary conditions were applied to the end of the fixture loading plate and the grip area of the laminate, respectively. These are depicted in Fig. 7-3, marked in blue; 3) In accordance with ASTM standards, the fixtures were designed to avoid failure; therefore, rigid body constraints were applied to them. 4) An embedded constraint was employed, with the matrix serving as the host region and the 3D-printed continuous carbon fibres (CF) as the embedded region. 5) General contact (Explicit) was applied for this model with individual property assignments for the initial hard contact between

fixture and cohesive behaviour between patch and parent laminate. It is important to note that the region defining cohesive behaviour between the patch and the parent laminate was confined exclusively to the areas covered by the embedded filament. This was achieved through the strategic partitioning of the patch's surface based on the filament distribution.

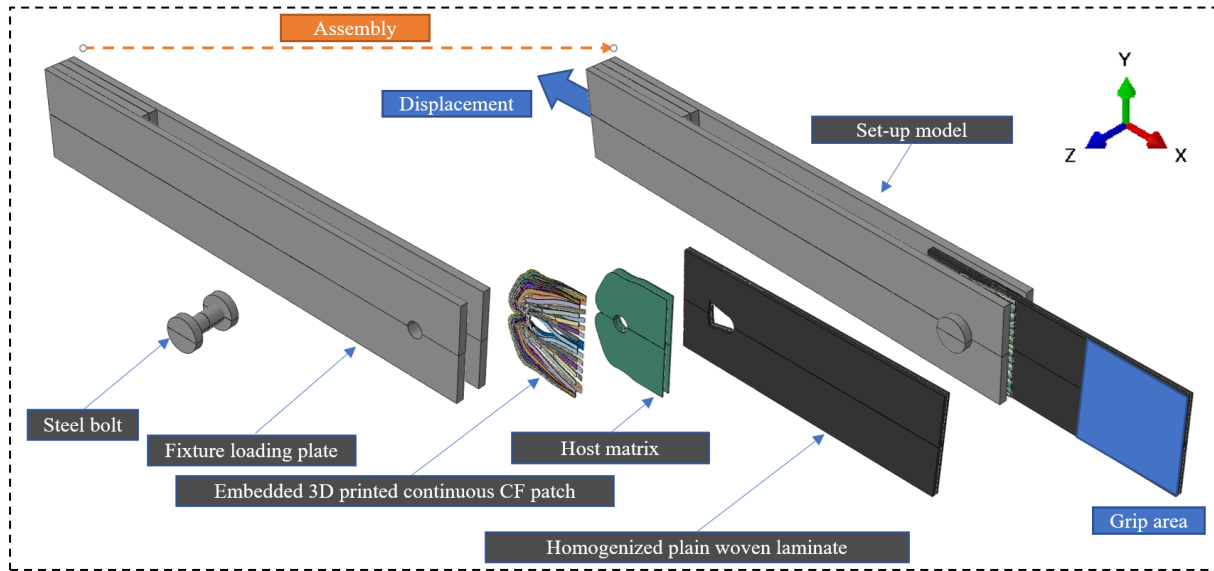


Fig. 7-3. Setup of the finite element model.

7.3. Results and Discussion

In this section, the repair region identification and relative repair designs are first discussed. Subsequently, the repair qualities of two distinct cases are independently presented and discussed. The concluding part of this section was focused on a comparative analysis of these cases. The differential characteristics observed between the cases are clarified through a combination of experimental and numerical results, providing a comprehensive understanding of the primary reasons for these variations.

7.3.1. Damage Identification and Repair Patch Design

The failure mode and damaged region of the composite laminate with a 2 mm displacement are clearly illustrated in the Micro-CT scan image, as shown in Fig. 7-4 (a). It is obvious that the specimen experienced a mixed failure of bearing and shear, a classic failure mode for plain

woven laminates. The shape of the damaged areas were outlined and highlighted with brown on the Micro-CT image slices. According to this area, the experiment commenced the removal of damaged material from the narrowest neck position of the bolt hole. The removal region is highlighted by the blue curved line. Furthermore, the relevant dimensions are marked in red. This measurement was calibrated in ImageJ, an open-source image processing program for image analysis, including geometric operations and colour processing. As micro cracks existed within the damaged region, the critical damage zone must be mechanically removed and this also created space for the 3D printed continuous carbon fibre patch that is used for repair.

As mentioned in section 7.2.1 two types of patches designed by the geometrical characteristics of the infilling area and the load path of the patch were attached to drilled parent laminate. The design details of these patches are depicted in Fig. 7-4(b), (c), from left to right. This includes the establishment of derived paths using two methods, aimed at adequately filling the drilled void to match the thickness of the original laminate. Subsequently, the G-code for the patch was developed by adjusting the z coordinates to align with the continuous printing sequence. This adjustment accounts for the ideal thickness of the printed filament and its subsequent integration with the parent laminate. The ideally repaired laminates are illustrated through 3D models, providing a comprehensive visual representation of the expected outcomes.

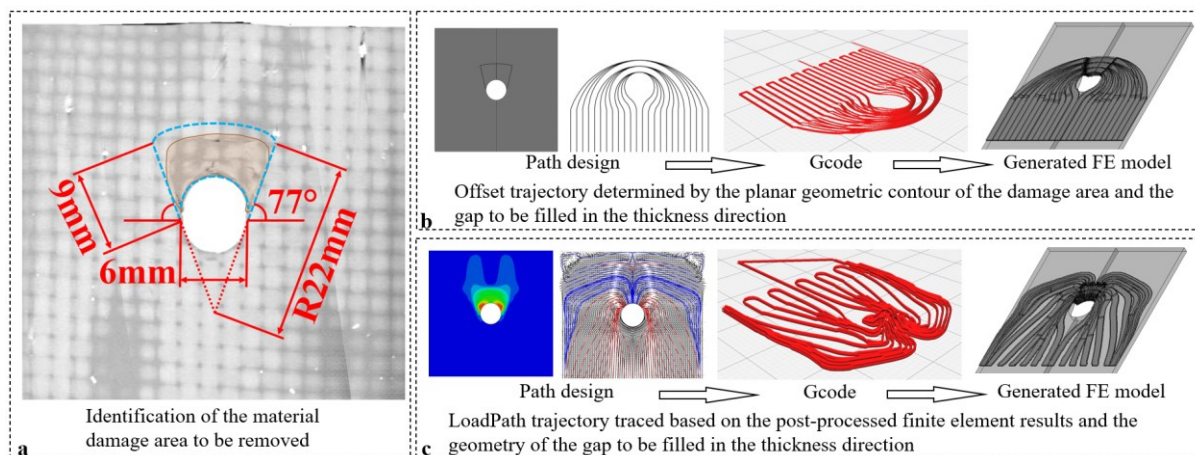
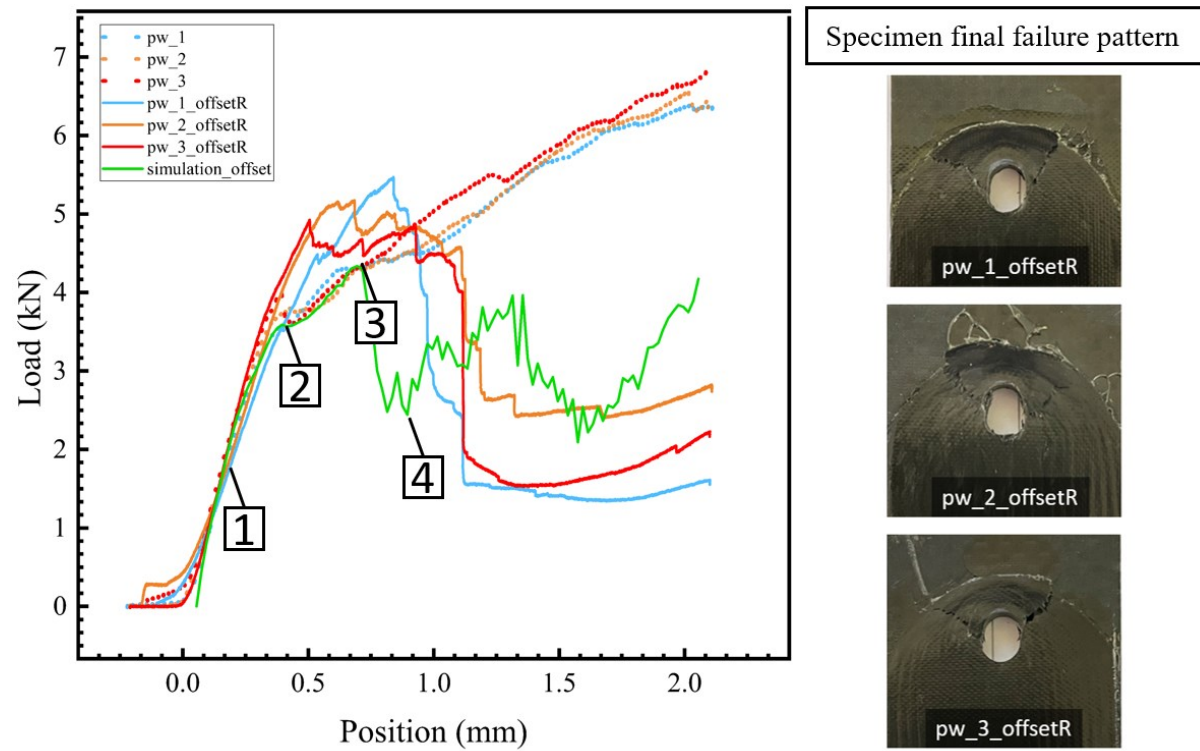


Fig. 7-4. The flowchart of fibre steering path design: (a) Identification of damaged region through Micro-CT slices of original plain woven laminate; (b) A path designed based on the laminate geometric shape; (c) A path designed based on the finite element results.

7.3.2. Repair Damaged Composite using 3D Printed Patches with Off-set Fibre Placement

In Fig. 7-5, both the experimental and simulation results are listed. From the experimental load and displacement curves, it could be seen that the patch has achieved the requirement of repair to a certain degree, regarding the bearing stiffness and initial peak strength. However, the final failure behaviour of the repaired laminate is more brittle with much less ultimate bearing strength. To understand the failure mechanism behind this, the load and displacement curve from the FE simulation is compared with the experimental curves, which are shown in Fig. 7-5. Along the curve, 4 of the critical time points are selected to describe the entire loading process, in regards to the stage of elastic, plastic initiation, first sharp load drop and final stage. It is found from the simulation that the plastic imitation of the repaired open hole laminate was due to the detachment of the patch. There are two types of detachments for this offset patch, *i.e.*, patch to patch and patch to parent laminate, of which the locations are spotted with arrows on the Micro-CT image slices and the indexes contour of quadratic traction damage initiation criterion are taken from the four time points (TPs) shown in Fig. 7-5. Based on the contours of two types of cohesive failure progression, the onset of the failure in the offset patch repaired laminate is more likely initiated at the cohesive surface of the patch to patch at TP 2. The damage propagates along the surface (TP 3) and the hole completely fails at TP 4 as illustrated with cohesive elements deleted. This cohesive surface failure contributes to the initial sharp load drop and this structural integrity loss led to a series of subsequent load drops. The cohesive failure index for the patch to the parent laminate does not propagate much until the patch-to-patch attachment entirely fails (TP 4). During the loading process, the fibre within the patch mainly holds the load by tension, illustrated by fibre failure indexes at TP 3 shown in Fig. 7-5, and this also indicates that brittle fibre tension failure is more likely to occur. All these

simulation results could be verified by the final failure patterns of 3 specimens, as there is a detachment of the patch appearing and there are obverse cracks perpendicular to the fibre orientation. More details of the failure mode will be discussed in section 7.3.4.



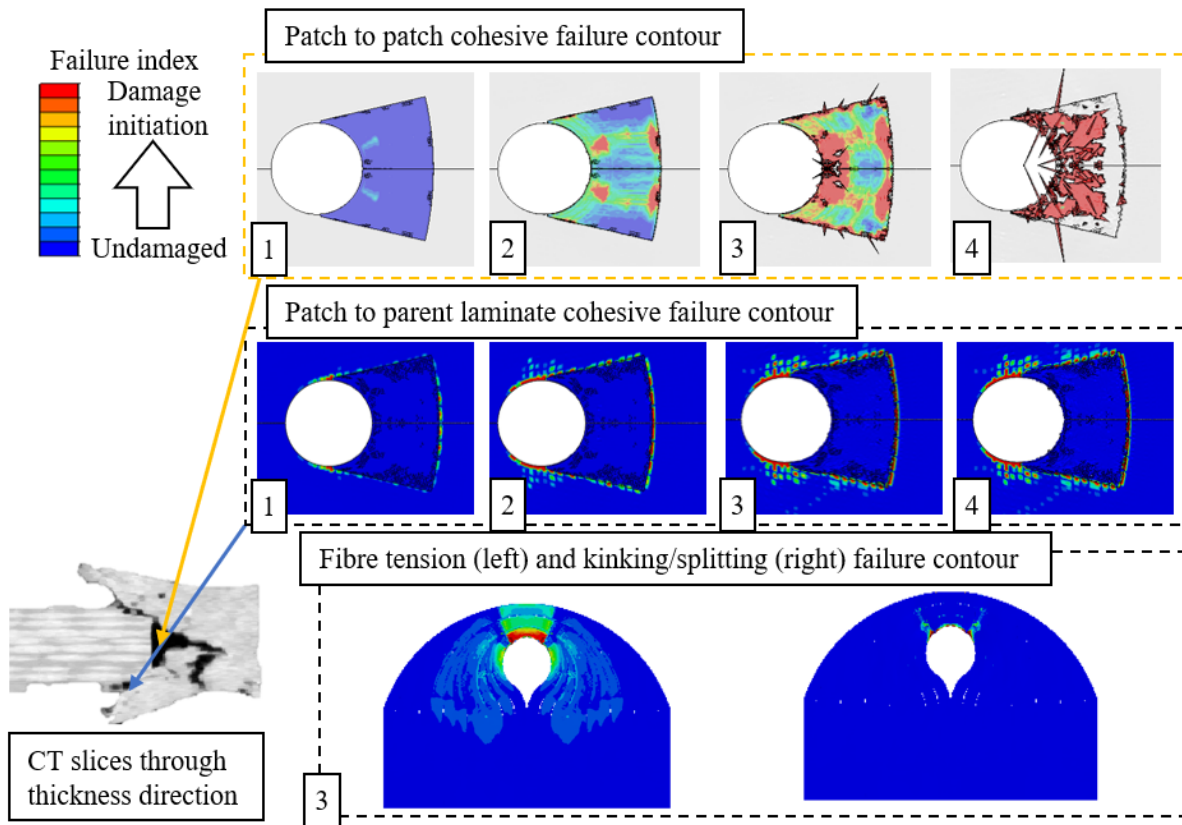


Fig. 7-5. Experimental and simulation results of the OF case.

7.3.3. Repair Damaged Composite using 3D Printed Patches with Load-path Fibre Placement

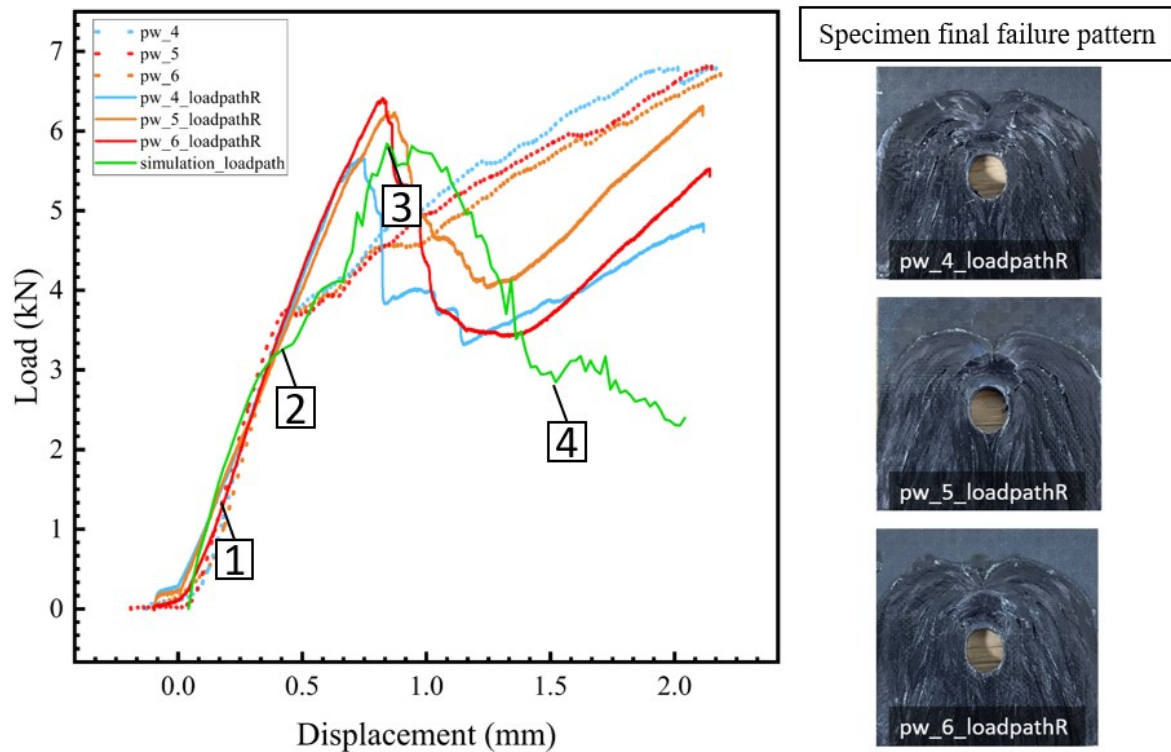
The discussion of the failure mechanism of the load path repair case will be in the same manner as the offset case mentioned in the above section. The comparison of load-displacement curves among original open hole laminate, repaired laminate and simulation results is shown in Fig. 7-6. For the experimental results, it could be seen that the load path repair method not only recovers the bearing stiffness and enhances initial peak strength, but also prevents the laminate from catastrophic failure shown with the load rising after the sharp load drop.

This noticeable load rise is much unlike the outcomes in the OF case. In the OF case, once the patch is damaged, there is no force transmission could be identified from the load-displacement curves (shown in Fig. 7-6). However, in this instance, a consistent force transmission

relationship between the parent laminate and the patch is observed, which is crucial for the repair of composite joints. This relationship pertains to the energy absorption capacity of the joint, implying a more extended buffering phase of post-damage, thereby preventing excessive brittleness.

Although the curve from the simulation is not exactly the same as the experimental result, the trend of the bearing performance is similar, thus the simulation result could still provide useful information to explore the failure mechanism. Same as discussed above, four time points are selected along the simulation curve. According to the simulation results, there is rarely patch-to-patch cohesive failure in this load path case, which is different from the offset case. However, there is damage propagation on the patch to the parent laminate cohesive surface. From the cohesive failure index contours shown in Fig. 7-6, it could be seen that the plastic initiates when detachment occurs (TP2) and load drop follows after it propagates beyond the hole edge (TP3 and TP4). Finally, this leads to the out-of-plane deformation of the patch but without detachment of the patch to the patch surface, illustrated with the displacement contour along the thickness direction and further verified by the Micro-CT slice images. It can be observed from the curve that at TP 2, there is a significant discrepancy between the experimental results and the model. This is primarily due to the voxel mesh of the filament, where a compromise on model precision was made considering the computational cost. This means that the matrix responsible for hosting embedded filaments cannot adequately match with the cubic mesh of embedded voxel-meshed elements in geometric shapes with curves, such as around the bolt hole. This misalignment causes the matrix around the bolt hole to lack filament reinforcement, leading to minor damage at the TP2 location. However, the overall integrity of the structure remains intact and still reflects the phenomena observed in the experiments. Subsequent improvements may further optimise the geometric model's mesh precision to address this issue. The fibre failure indexes captured at the TP3 show a hugely different failure mode compared

to the OF case with fibre mainly failed by the bearing compression load. The failure mode observed from the simulation could be preliminarily verified by the failure pattern in the photograph shown in Fig. 7-6. It could be seen that a shear out failure region appeared in all three specimens instead of a long breakage crack. Further verification and discussion of the failure mode will be shown in section 7.3.4.



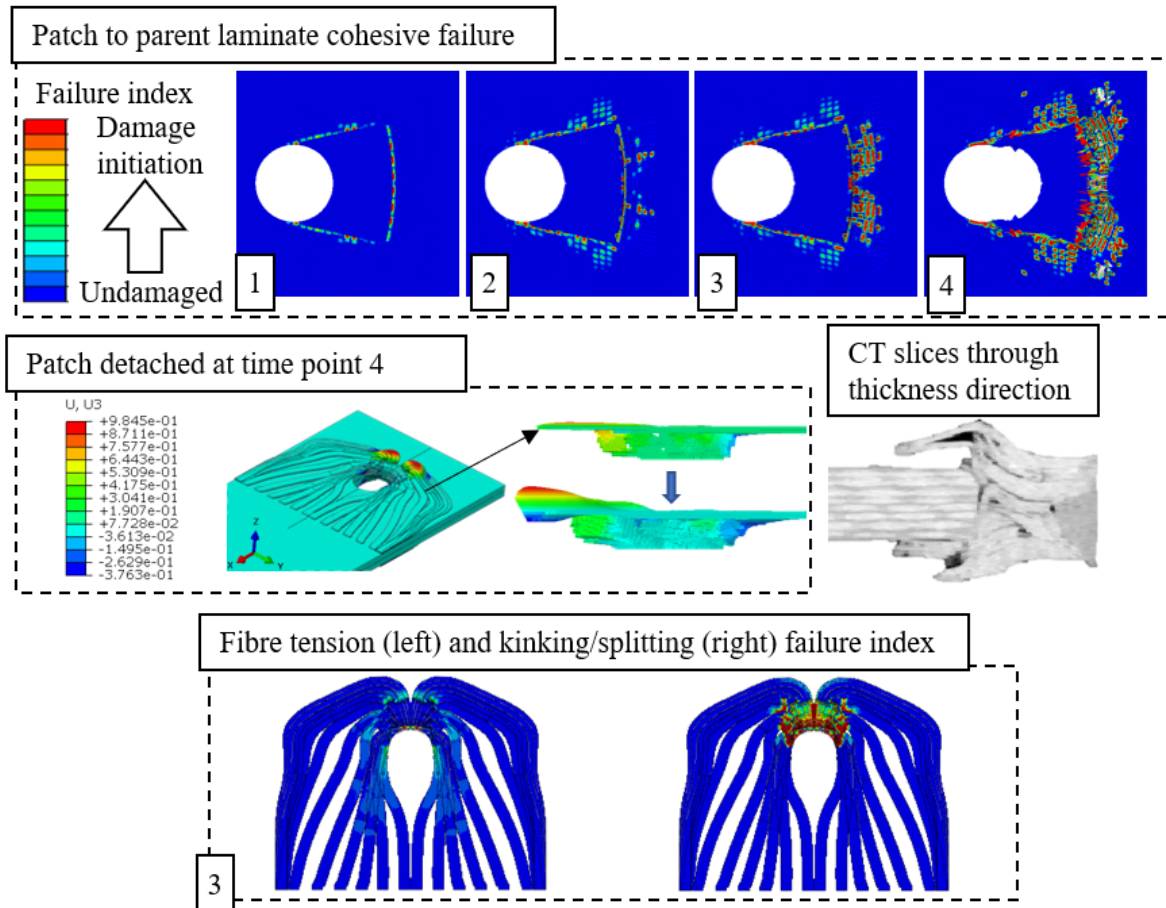


Fig. 7-6. Experimental and simulation results of the LP case.

7.3.4. Evaluation of Repair Effectiveness

The bearing performance of both the original composite laminate and the damaged laminate repaired with two different types of patches is listed and compared in Fig. 7-7, in terms of 5 mechanical values same as above sections. These values include 50-100 MPa Chord Stiffness, Initial Peak Bearing Strength, Ultimate Bearing Strength, as well as Initial and Ultimate fracture toughness, which are calculated based on bearing strain. It needs to be specific that in this study, the initial peak bearing strength is taken when a sharp load drop [176] appears and a total of 2 mm bolt displacement is applied for all the cases therefore, the values are only taken within this range of this displacement based on the ASTM 5961.

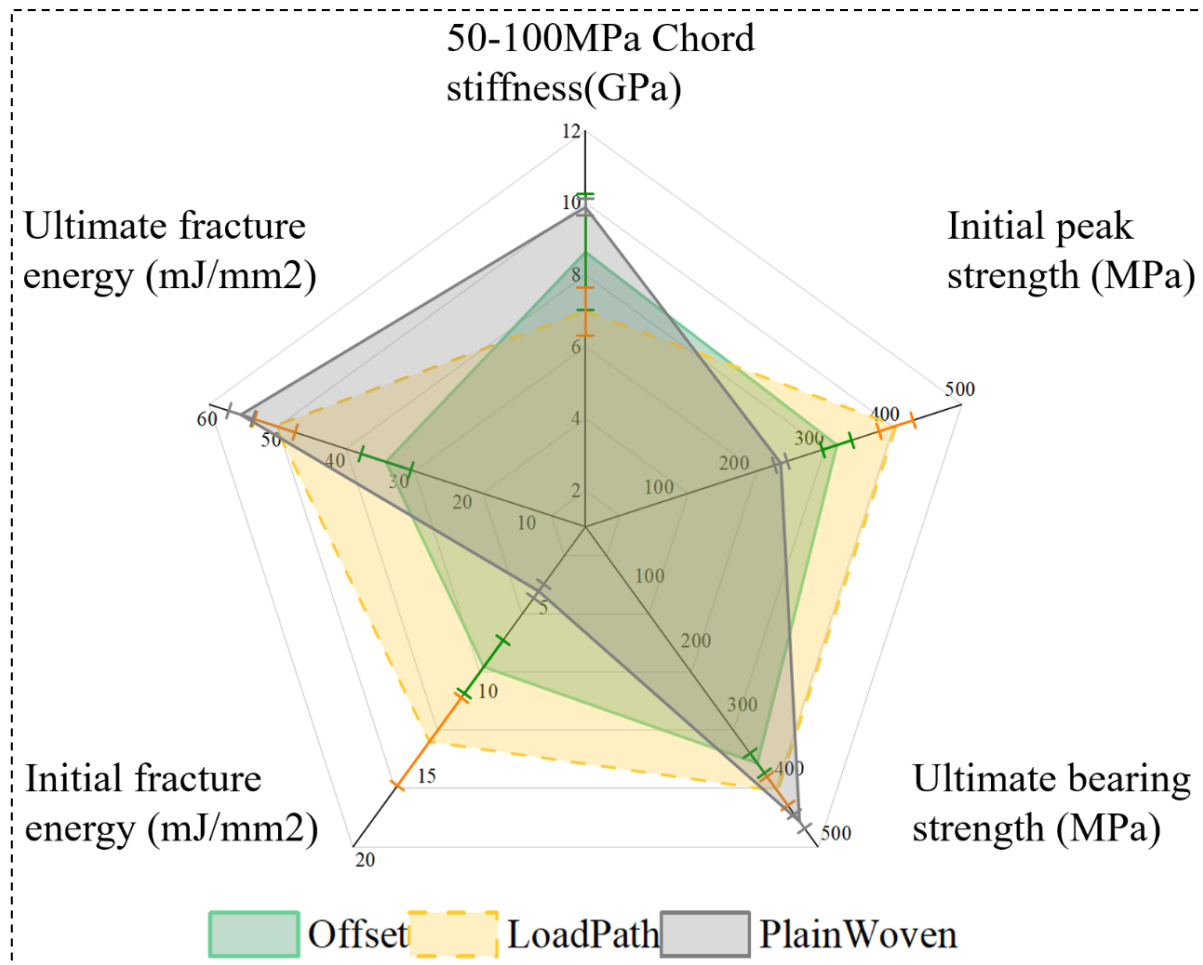


Fig. 7-7. Comparative analysis of the bearing performance of original composite and recovery capabilities of two distinct repair patterns in five aspects.

The data is comprehensively analysed and presented in a radar chart (refer to Fig. 7-7), offering a clear comparison of the capabilities of the two distinct repair patterns. By evaluating the average bearing performances of 3 cases, it is found that 2 types of patches achieve different repair purposes. For the bearing stiffness, up to 85.73% amount could be recovered using the offset pattern and the load path pattern patches could recover 72.06%. The initial strength is fully recovered compared to the original case, and an increase of 30.43% and 56.68% is even achieved in the OF and FL cases respectively. In terms of the ultimate strength, a recovery of 82.13% (OF) and 87.8% (FL) is achieved. The relative energy absorptions regarding the initial peak and ultimate points, the maximum recovery ratio is 59.31% (OF) and 89.29% (FL), respectively.

Notably, the load path method exhibits a more balanced performance relative to the offset method. The main reasons for these differences are discussed as follows. First, the FE simulation results are exported at the elastic stage of each case to explain the difference in the stiffness. As detailed in Sections 7.3.2 and 7.3.3, a salient distinction emerges, *i.e.*, in the offset (OF) case, the fibres predominantly endure tensile forces, whereas in the load path (LP) case, fibres primarily bear compressive loads along the load path. This is further substantiated by comparing the stress contour images (S11) of the filaments, aligned with fibre orientation (see Fig. 7-8). Here, the maximum tensile and compressive stresses are observed in the LP and OF cases respectively. Notably, under identical displacement conditions (0.12mm), the tension-induced stress S11 is higher in Case OF, and the stiffness is predominantly attributed to the fibres within the composite, thereby enhancing bearing stiffness.

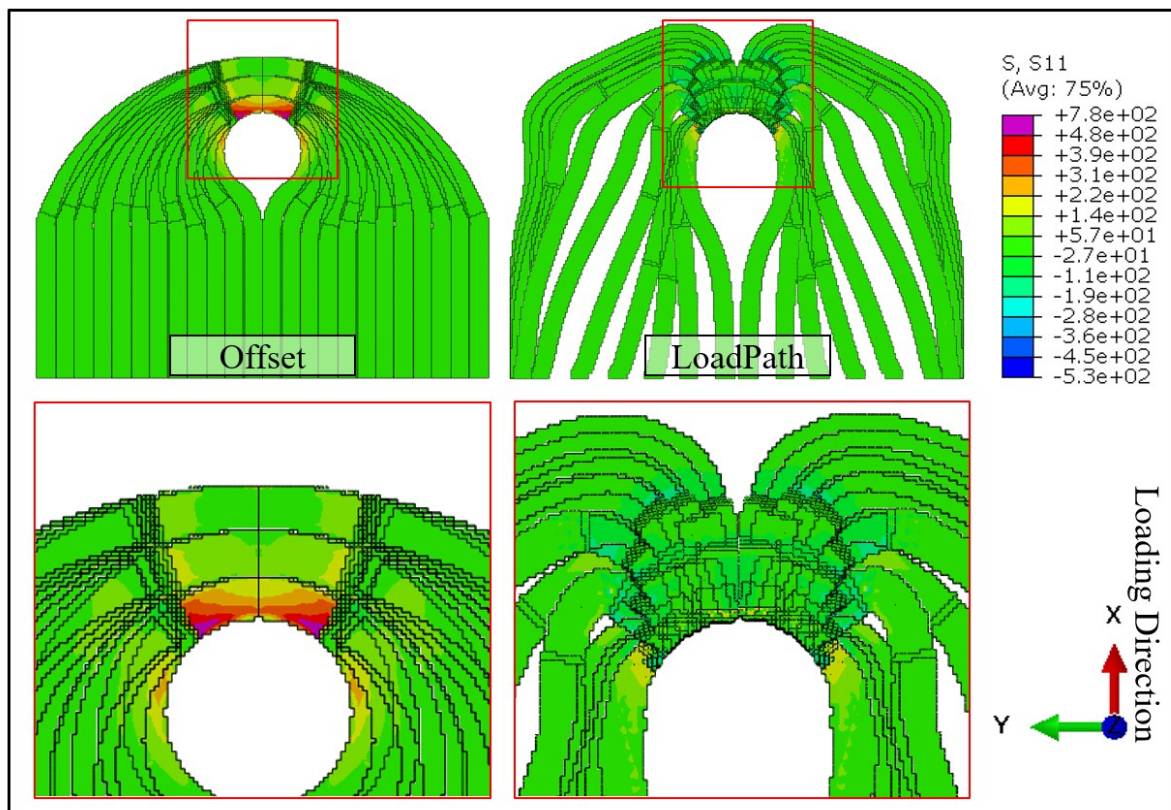


Fig. 7-8. Distribution contour of the stress along fibre direction in each patch during the elastic stage.

In terms of mitigating initial sharp load drops – for instance, achieving a higher initial peak bearing strength – it is observed that in the OF cases, detachment at the patch interface occurs prematurely. Conversely, in the LP pattern, the fibre infill in the repair region collaborates with the matrix to counteract bolt compression loads, diminishing the likelihood of crack initiation at the patch interface. This mechanism effectively delays the onset of sharp load drops in the LP case.

For the ultimate failure, as discussed in the above sections, there is a huge difference between the two types of repair patches. Micro-CT scan slices with the most critical images are shown in Fig. 7-9. The slices of two cases along the thickness direction (Fig. 7-9(a) & (b)) are captured from the region directly taking the bolt bearing load. It is obvious that there is a severe delamination (marked with red line infill) occurs in the OF case and also the delamination leads to further breakage of the repair region, contributing to an absence of material directly in contact with the parent laminate. With this absence, the load from the bolt (illustrated with a yellow arrow) could rarely be transferred further to let the parent laminate hold it (shown with a blue arrow). For the LP case, the delamination is less - although the bearing load also pushes part of the patches out of the plane, there is still sufficient material in contact with the parent laminate, providing load transfer (shown with blue arrows).

The load transfer difference could be further verified by the crack propagation along the in-plane direction within the parent laminate. From the cracks marked with the orange regions shown in Fig. 7-9(c), in both cases, the contacts along the intra-laminate direction were disabled but at different levels. The patch in case OF was completely detached from the parent laminate, while only a little appeared in case LP. This means the load transfer still existed in case LP. From cracks marked with red region on the patch pattern slices Fig. 7-9(d), there is a long crack that appeared in the OF case and a short one for the LP case. Based on their stair-case shape,

these cracks are believed to result from fibre tension. As mentioned above, most of the fibres in the OF patch pattern hold the load with tension, making the patch more likely to fail brittlely. For the LP pattern, each fibre is placed in various orientations and this leads to holding the load with both tension and compression. The fibres served in compression prevent the matrix from breakage, providing a better load transfer to the parent laminate. Thus, the final failure mode of the LP patch is more ductile, resulting in better ultimate fracture energy absorption.

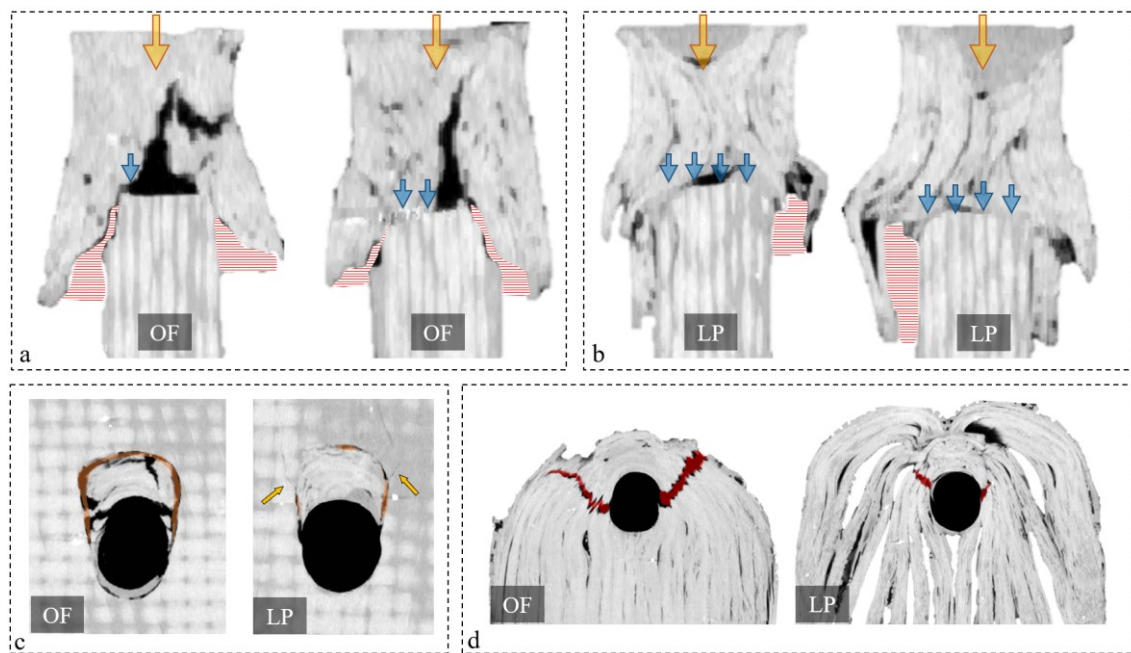


Fig. 7-9. CT slice images along through-thickness direction for (a) OF case and (b)LP case; In plane direction (c) within the laminate and (d) above the laminate.

7.4. Conclusions

This research introduces an innovative approach for repairing mechanically fastened bolt hole composite plates, particularly those with damaged bolt holes resulting from partial displacement under service conditions, which may otherwise be considered non-reusable. This repair technique demonstrates considerable potential, considering that fastening joints remain a prevalent method for assembling thermoset composite materials. The susceptibility of bolt

holes to deformation, often being the weakest points in the structure, further emphasises the significance of this repair method. Based on both experimental and simulation results, it can be concluded that:

(1) In the widely used thermoset material system, deformed bolt holes can be effectively repaired using patches 3D printed with continuous carbon fibres. These patches aid in restoring the hole to its original dimensions and functionality, almost the same as the original structure, thereby conserving materials and enabling extended service life. This is achieved with relatively minimal modification to the damaged laminate, demonstrating the efficiency and effectiveness of this repair method.

(2) The mechanical design of the continuous fibre path, implemented in the 3D printed continuous fibre patch, not only achieves the necessary recovery of mechanical properties but also surpasses its original capacity in terms of initial strength and relative fracture energy absorption. The reason is that 3D printing technology enables the fabrication of patches in various complex shapes, with fibres tailored based on different design methods. This capability facilitates integrated and flexible manufacturing, demonstrating a significant advancement over conventional patching methods using unidirectional or plain weave mats.

(3) Comparative analysis through Micro-CT scanning, mechanical numerical studies, and finite element modelling reveals that although simple geometrically-based fibre paths (*i.e.* offset) can achieve a certain level of repair, their unscientific fibre distribution may lead to brittle failure, resulting in low energy absorption. In contrast, fibre paths generated based on the load-path method optimise stress distribution and force transfer across various regions of the joint, improving not just the strength but also the energy absorption capability of the repaired part. This enhancement is achieved by diminishing the dominant role of cohesive contact within the patch, which is often the trigger for initial failure onset. The results indicate that the continuous fibre path design has a significant influence on the repair performance and failure mode.

(4) The model applied in this study successfully captured the failure mode of such a complex 3D problem, although the specific value of strength was not exactly the same as the model based on the ideal situation. This simulation method provided valuable and clear results to study the progressive failure which could not be easily captured with the experimental method. By using this multi-scale model, reliable guidance could be provided for the continuous fibre patch design in future composite applications.

In anticipation of future real-world applications, the design of the patch can be optimised through FE modelling, taking into account specific boundary conditions, and then printed accordingly to meet distinct repair needs. While the current state of this repair method does not yet extend to on-site, real-time printing capabilities, the concept of using continuous fibres for repairing joints remains a promising area of research.

As for the issue of added thickness due to the patch, future advancements in material removal techniques could offer a solution. This would involve removing material in accordance with the printing pattern. In the case of open-hole laminates, where weaknesses are predominantly located around the hole, such targeted material removal is unlikely to compromise the integrity of the entire structure. This approach presents a balanced solution, addressing both repair efficacy and structural preservation.

Chapter 8. Conclusions and Future Works

8.1. Key Findings

With respect to the objectives outlined in Chapter 1, Section 1.3, key conclusions of this thesis are drawn as follows:

(1) Based on the literature review, it has been observed that for current fastened composite joints, mechanical drilling of the open hole leads to discontinuity around the hole's edge, potentially triggering early initial failure. Consequently, both experimental and numerical studies were implemented to investigate the impact of fibre steering on the bearing performance of bolted joints in 3D printed pseudo-woven CFRP composites.

(2) The first study examined the influence of fibre steering on crack initiation and propagation through double-lap bearing tests across four different cases, analysing various damage mechanisms in each case. It also explored the potential of fibre steering to enhance the joint's bearing performance. The key conclusions drawn are as follows:

- Fibre steering can alleviate shear strain concentration at the bolt hole edge by preserving carbon fibre continuity and distributing the bearing load over a larger material volume. Adjusting fibre orientation has been shown to improve the load transfer mechanism, with a 180-degree change in pseudo-woven composites significantly balancing strain distribution and halving the maximum absolute strain value.
- For initial damage toughness enhancement, simply maintaining carbon fibre continuity is inadequate, as shear and bearing damage still occur. Altering the steered fibre orientation around the hole edge reduces the likelihood of shear crack initiation and propagation along the fibre direction. This is evidenced in case U, where notable improvements in IBP strength (by approximately 23.5%) and IF energy (by around 363.7%) were observed.

- The steered fibre provides varying degrees of bearing ductility for the composite joint, influenced by the extent of fibre orientation change. This study finds that a 90-degree change induces brittleness, whereas a 180-degree change increases ductility. Thus, fibre steering offers a practical approach to meet specific bearing requirements by tailoring the fibre orientation.
- Steering fibres solely around the hole edge may not enhance ultimate toughness and could potentially weaken it. Future research should aim at optimising load transfer with steered fibres across the entire structure.

A limitation of the previous study is the absence of extensive data on the progressive failure process and the detailed load transfer mechanisms of specifically steered fibres throughout the entire loading process. To address this gap, further simulation studies are proposed. The literature review reveals a lack of existing modelling methods capable of accurately capturing the full bearing performance of a fastened composite joint with highly customised steered fibres. Consequently, a decision was made to develop a novel modelling approach to provide a solution to this issue.

(3) The second investigation focused on the essential importance of sustaining filament continuity around the edge of bolt holes in fastened composite joints, utilising a multiscale numerical model. This continuity is crucial as it profoundly impacts the load-bearing capacity of the joint during the elastic phase and plays a vital role in initiating and propagating matrix damage in later stages. The key findings are summarised below:

- When bolt holes are mechanically drilled, initial damage typically appears as a sudden and catastrophic matrix shear failure, leading to a significant drop in load. However, with steered fibres, the continuous fibre structure prevents abrupt load reduction by

enhancing shear and transverse strengths, thus suppressing shear and compressive failures. This results in a gradual decline in stiffness, similar to a metallic-like deformation, rather than an immediate failure, which extends the joint's duration.

- The layout of steered filaments significantly influences the joint's failure mode. In configurations with steered fibres, fibre splitting or kinking tends to occur at points where the fibre orientation changes abruptly. Future designs of continuous fibre layouts should avoid significant directional changes in areas prone to shear damage to reduce this failure type.
- Pure filament tension failure is rare during bolt shear loading in thermoset composites, with various types of matrix failures being more common, even when continuous carbon fibres are steered around the hole edge.
- Placing continuous, strategically steered filaments around bolt holes has shown a substantial reinforcing effect. However, this reinforcement diminishes when bolt displacement goes beyond the hole's immediate area, as evidenced by both experimental and simulation results. This stresses the importance of considerate design in regions beyond the hole's edge to ensure structural durability.
- The modelling approach employed is effective and straightforward for thermoset composites, assuming a strong bond between reinforcement fibres and resin. This model can be extended to simulate failure mechanisms in continuous carbon fibre composites, leading to optimised fibre path designs that could significantly improve structural performance and integrity.

(4) Developing further from the knowledge of the second study, it was observed that fibre steering around the bolt hole alone can improve the initial failure response of a fastened joint. However, it is essential to extend the fibre steering path design beyond the edge of the bolt hole to other areas of the joint. Therefore, the third study examined enhancing the performance of

bolted joints in woven composite laminates by integrating 3D printed interlayers with customised fibre architectures.

The results reveal that hybrid laminates modified with a 3D printed interlayer generally outperformed traditional plain weave laminates. The stress-strain curves and radar charts of these modified laminates exhibited enhanced mechanical properties, displaying both smoother curves and higher stress capacity before failure. This study highlights the potential of 3D printing in tailoring the fibre architecture of interlayers in plain weave CFRP laminates, thereby increasing their effectiveness in bolt joint applications. The evaluation included mechanical testing, Micro-CT microstructural characterisation, and finite element analysis, focusing on the influence of carbon fibre orientation on the mechanical properties of the composite joints. Key findings include:

- Embedding interlayer with customised steered fibre patterns into commonly used plain weave laminates resulted in substantial reinforcement. This is demonstrated by notable improvements in laminate stiffness (increases up to 86%), initial bearing strength (up to 95%), and ultimate bearing strength (58%). This enhancement also improved energy absorption, evident in the initial fracture energy (up to 496%) and ultimate fracture energy (10%).
- The alignment of load paths with stress distribution, particularly in the Load Path case of this study, notably increased stiffness. This is primarily due to the alignment of carbon fibres with the applied stress direction, exploiting the inherent stiffness of carbon fibres along their length.
- In terms of failure suppression and energy absorption at initial load drop and ultimate failure, the fibre placement patterns designed based on failure planes (FP case in this study) showed optimal performance. Finite element modelling confirmed minimal complete matrix damage and the least distributed complete fibre damage in the FP case,

effectively utilising the orthotropic properties of carbon fibre filaments to prevent damage progression.

- The finite element model, based on printed filaments, accurately assessed the mechanical properties and failure behaviours of traditional plain weave woven composite laminate joints. The model's predictions on stiffness, ultimate strength, and energy absorption were highly accurate (96%, 97%, and 100%, respectively). However, it faced limitations in capturing the initial failure in situations with prolonged damage evolution under bearing load, due to complex interactions at the bolt-specimen interface. Future efforts will aim at refining the model to address these challenges.

(5) The fibre tailoring technique using 3D printing, as well as the numerical model developed in this study, have proven effective in designing advanced fastened composite joints. This approach was further evolved to address the repair of damaged fastened joints. Consequently, the fourth study introduced an innovative repair method for damaged fastened composite joints, employing 3D printed continuous fibre patches with custom fibre pathways.

This novel method offers a solution for repairing mechanically fastened bolt hole composite plates, particularly those with deformed bolt holes due to partial displacement in service, which might otherwise be considered irreparable. Given the prevalence of fastening joints in assembling composite materials and the vulnerability of bolt holes as structural weak points, this repair technique is notably significant. The findings, based on both experimental and simulation studies, include:

- In common thermoset material systems, deformed bolt holes can be effectively repaired with 3D printed continuous carbon fibre patches. These patches help restore the hole to its original dimensions and functionality, closely matching the original structure's performance, thereby conserving materials and extending service life with minimal modification to the damaged laminate.

- The mechanical design of the continuous fibre path in the 3D-printed patches not only restores but often enhances the original mechanical properties, including initial strength and fracture energy absorption. This is due to the capability of 3D printing to produce patches in complex shapes with fibres tailored through various design methods, offering a significant improvement over traditional patching methods using unidirectional or plain weave mats.
- Comparative analyses, including Micro-CT scanning and finite element modelling, show that while simple geometrically-based fibre paths can provide a degree of repair, their unscientific fibre distribution might lead to brittle failure and low energy absorption. In contrast, fibre paths designed using load-path equations optimize stress distribution and force transfer, improving both the strength and energy absorption of the repaired part by reducing the reliance on cohesive contact within the patch, which is often a precursor to failure.
- The model used in this study successfully captured the failure modes of these complex 3D problems, although the specific strength values differed slightly from those in the ideal conditions. This simulation method provided insightful results for studying progressive failure, which is challenging to capture experimentally. The multi-scale model used offers reliable guidance for designing continuous fibre patches in future composite applications.

8.2. Recommendations for Future Research

In this study, a novel finite element model was developed, integrating with the prevailing Additive Manufacturing (AM) techniques for composite materials, proposing a new method for manufacturing fastened composite joints. This method, distinct from mainstream approaches that only consider stress distribution during the elastic stage of components, also takes into account the factors of damage evolution. The enhanced bearing performance of the

fastened composite joint was validated through experimental methods, confirming the rationale of this approach and demonstrating its potential. This design methodology can also be applied in various engineering fields to guide the distribution of continuous carbon fibres. Nevertheless, some future works are suggested as below:

(1) Although this research successfully combined additive manufacturing with finite element modelling to generate continuous fibre paths for fastening joints in various ways, the modified triaxial Prusa printer that was used limited the printing ability. Future integration with multi-axis advanced techniques such as robotic arms could elevate the path optimisation to higher dimensions, addressing common out-of-plane failures in fastened joints like delamination.

(2) The simulation results of this study indicate that the model's accuracy has not yet reached an ideal level. The study assumed that the failure modes of individual filaments are similar to those of UD laminates, with corresponding material strengths and failure criteria based on UD laminate estimates. Hence, acquiring more accurate strength values or criteria specific to filament failure could refine the model's outcomes, offering a more scientific path optimisation for continuous carbon fibre printing, and potentially evolving towards a digital twin level for real-time simulation.

(3) The modelling approach mentioned in this study, based on the embedded element technique, has limitations, particularly in ignoring the interfacial failure between matrix and fibre, making it more suitable for thermoset composites. However, by redefining the material properties of elements randomly, it could potentially be applied to thermoplastic materials where the bond is relatively weak. Specific algorithms, or even AI, could be used to identify the bond locations between matrix and fibre, incorporating interfacial failure criteria into these elements to simulate debonding effects.

(4) The repair solution proposed in this study, due to its method and the current limits of 3D printing technology, is only applicable to thermoset materials, thus precluding real-time repairing. However, the principle of fibre trajectory generation in this research is applicable to all materials. Future applications might involve thermoplastics combined with advanced AM technologies to achieve on-site repair capabilities.

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Appendices A Python Script

A.1 Gcode generator

```
1. import tkinter as tk
2. from tkinter import ttk, filedialog, messagebox
3. import os
4. import pandas as pd
5. import matplotlib.pyplot as plt
6. from mpl_toolkits.mplot3d import Axes3D
7. from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg, NavigationTo
   olbar2Tk
8. from math import atan, pi
9. from PIL import Image, ImageTk
10. import sys
11. import os
12.
13.
14. # Ex ADDING
15. Ex_incr = 0.0
16.
17.
18. def resource_path(relative_path):
19.     try:
20.         base_path = sys._MEIPASS
21.     except Exception:
22.         base_path = os.path.abspath(".")
23.
24.     return os.path.join(base_path, relative_path)
25.
26.
27. def show_help_image():
28.     help_window = tk.Toplevel(app)
29.     help_window.title('Help')
30.
31.     image_path = resource_path("1.png")
32.     image = Image.open(image_path)
33.     photo = ImageTk.PhotoImage(image)
34.
35.     img_label = tk.Label(help_window, image=photo)
36.     img_label.image = photo
37.     img_label.pack()
38.
39.
40. def preview_gcode():
41.     file_path = filedialog.askopenfilename(filetypes=(("Excel files", "*.csv"
   ), ("All files", "*.*")))
42.
43.     if file_path:
44.         data = pd.read_excel(file_path)
45.
46.         x_data = data['X']
47.         y_data = data['Y']
48.         z_data = data['Z']
49.
50.         preview_window = tk.Toplevel(app)
51.         preview_window.wm_title("Preview")
52.         fig = plt.Figure(figsize=(5, 5), dpi=100)
53.         ax = fig.add_subplot(111, projection='3d')
54.         ax.scatter(x_data, y_data, z_data)
55.         canvas = FigureCanvasTkAgg(fig, master=preview_window)
56.         canvas.draw()
57.         canvas.get_tk_widget().pack(side=tk.TOP, fill=tk.BOTH, expand=1)
```

```

58.         toolbar = NavigationToolbar2Tk(canvas, preview_window)
59.         toolbar.update()
60.         canvas.get_tk_widget().pack(side=tk.TOP, fill=tk.BOTH, expand=1)
61.     else:
62.         messagebox.showinfo("No file selected", "Please select a file to preview.")
63.
64.
65. def browse_file_path():
66.     file_path = filedialog.askopenfilename(filetypes=[("CSV files", "*.csv"),
67. ("Excel files", "*.xlsx;*.xls")])
68.     directory_path = filedialog.askdirectory()
69.     if file_path:
70.         input_file_path.set(file_path)
71.     if directory_path:
72.         output_directory.set(directory_path)
73.
74.
75. def process_file(coords, n_data, sp_min, sp_max, centre_m, output_file, extruder_temp, bed_temp, loop_count, filament_thickness, is_loop, is_reverse, combobox):
76.     with open(output_file, 'w') as f:
77.         # Adding predefined GCode preamble
78.         selected_option = combobox.get()
79.         if selected_option == 'Prusa':
80.             f.write(";AonanBlessing\n"
81. ";Generated with Gcode_Gen\n"
82. f"M82 ;absolute extrusion mode\n"
83. f"G21 ; set units to millimeters\n"
84. f"G90 ; use absolute positioning\n"
85. f"M82 ; absolute extrusion mode\n"
86. f"M104 S{extruder_temp} ; set extruder temp\n"
87. f"M140 S{bed_temp} ; set bed temp\n"
88. f"M190 S{bed_temp} ; wait for bed temp\n"
89. f"M109 S{extruder_temp} ; wait for extruder temp\n"
90. f"G28 W ; home all without mesh bed level\n"
91. f"G80 ; mesh bed leveling\n"
92. f"G92 E0.0 ; reset extruder distance position\n"
93. f"G1 Y-3.0 F600.0 ; go outside print area\n"
94. f"G92 E0.0 ; reset extruder distance position\n"
95. f"G92 E0\n"
96. f"G1 F2100 E-0.8\n"
97. f"M106\n"
98. f"G0 F1200 X5 Y5 Z10.0 E0 ;Reset start location\n")
99.         elif selected_option == 'HighTemp':
100.             # Adding predefined GCode preamble
101.             f.write(";GcodeGen Version 1.1.0\n"
102. f"M104 T0 S{extruder_temp} ; set extruder temp\n"
103. f"M140 S{bed_temp} ; set bed temp\n"
104. f"M190 S{bed_temp} ; wait for bed temp\n"
105. f"M109 T0 S{extruder_temp} ; wait for extruder temp\n"
106. f"M6013 S90.000000\n"
107. f"T0\n"
108.
109. f"M82 ;absolute extrusion mode\n"
110. f"G21 ; set units to millimeters\n"
111. f"G90 ; use absolute positioning\n"
112. f"M107 ;start with the fan off\n"
113.
114. f"G28 X0 Y0 ;move X/Y to min endstops\n"
115. f"G28 Z0 ;move Z to min endstops\n"
116.
117. f"G0 F3600 X0 Y0\n"
118. f"M83 ;set E value is relative\n"
119. f"G0 F400 X10 Z0.4 ;move a bit while down the Z\n"

```

```

120.          f"M221 T0 S300 ;set flow is 300%\n"
121.          f"G1 F200 X30 E+8 ;extrude amount filament to clean the h
otend\n"
122.          f"M221 T0 S100 ;reset flow is 100%\n"
123.          f"M82 ;set E value is absolute\n"
124.          f"G92 E0;zero the extruded length again\n"
125.          f"M106 S159;fan on\n"
126.
127.          f";Put printing message on LCD screen\n"
128.
129.          # Add start points
130.          current_z = 0 # record Z value
131.
132.          global Ex_incr
133.          if is_loop:
134.
135.              for loop in range(loop_count):
136.
137.                  Ex = 0 + Ex_incr
138.                  if loop == 0:
139.                      #RISE UP NOZZLE
140.                      start_point = coords[0]
141.                      f.write(f"G1 F500 X{str(start_point[0] + centre_m[0])} Y
{str(start_point[1] + centre_m[1])} Z10 E0.01\n")
142.                      start_point = coords[0]
143.                      f.write(f"G1 F500 X{str(start_point[0] + centre_m[0])} Y
{str(start_point[1] + centre_m[1])} Z{str(start_point[2] + current_z + filame
nt_thickness/4)} E0.01\n")
144.                      #z_adjustment = loop * filament_thickness
145.
146.                      N_adjustment = (loop) * 1
147.                      if is_reverse and loop != 0:
148.                          coords = coords[::-1]
149.                          n_data = n_data[::-1]
150.                          prev_n = None # record a node of N
151.
152.                      for i in range(1, len(coords) - 1, 1):
153.                          #To achieve differential printing, it is necessary to sa
crifice the first and last points in the printing path.
154.                          extra_increment = False # record if z coordinate increa
se in this loop
155.                          i_coords, j_coords, k_coords = coords[i - 1], coords[i],
coords[i + 1]
156.
157.                          dx, dy, dz = [j - i for i, j in zip(i_coords, j_coords)]
158.
159.                          ddx, ddy, ddz = [i - k for i, k in zip(i_coords, k_coord
s)]
160.
161.                          Ex += (dx ** 2 + dy ** 2) ** (1 / 2)
162.
163.                          if ddx != 0 and dx != 0:
164.                              angle = atan(abs((dy / dx - ddy / ddx) / (1 + dy / d
x * ddy / ddx)))
165.                              sp = sp_min if angle >= (0.01 / 180) * pi else sp_ma
x
166.                              elif ddx == 0 and dx != 0:
167.                                  angle = atan(abs(dx / dy)) if dy != 0 else 0
168.                                  sp = sp_min if angle >= (0.01 / 180) * pi else sp_ma
x
169.                                  elif ddx != 0 and dx == 0:
170.                                      angle = atan(abs(ddx / ddy)) if ddy != 0 else 0
171.                                      sp = sp_min if angle >= (100 / 180) * pi else sp_max
172.
173.                      else:
174.                          sp = sp_max

```

```

173.
174.
175.
176.         if prev_n is not None and n_data[i] != prev_n:
177.             extra_increment = True
178.             prev_n = n_data[i]
179.             if extra_increment:
180.                 current_z += filament_thickness
181.
182.
183.
184.
185.         # Add current_z, when write Gcode
186.         if current_z == 0: # 1st layer
187.             f.write(
188.                 f"G1 F{sp} X{str(j_coords[0] + centre_m[0])} Y{s
189.                 tr(j_coords[1] + centre_m[1])} Z{str(j_coords[2] + current_z + filament_thick
190.                 ness/4)} E{Ex} ;yarn_number {int(n_data[i]) + N_adjustment}\n")
191.             else:
192.                 f.write(
193.                     f"G1 F{sp} X{str(j_coords[0] + centre_m[0])} Y{s
194.                     tr(j_coords[1] + centre_m[1])} Z{str(j_coords[2] + current_z + filament_thick
195.                     ness/2)} E{Ex} ;yarn_number {int(n_data[i]) + N_adjustment}\n")
196.                 current_z += filament_thickness
197.
198.         if loop == loop_count-1:
199.             # Add end points
200.             end_point = coords[-1]
201.             # f.write(f"G1 F500 X{str(end_point[0] + centre_m[0] - 1
202.             0)} Y{str(end_point[1] + centre_m[1])} Z{str(end_point[2] + z_adjustment)} E0
203.             .1\n")
204.             f.write(
205.                 f"G1 F500 X{str(end_point[0] + centre_m[0])} Y{str(e
206.                 nd_point[1] + centre_m[1])} Z{str(end_point[2] + current_z + filament_thickne
207.                 ss/2)} E0.2\n")
208.             # RISE UP NOZZLE
209.             f.write(
210.                 f"G1 F500 X{str(end_point[0] + centre_m[0])} Y{str(e
211.                 nd_point[1] + centre_m[1])} Z{str(end_point[2] + current_z + 10)} E0.2\n")
212.             Ex_incr = Ex
213.         else :
214.             for loop in range(0,1,1):
215.
216.                 Ex = 0 + Ex_incr
217.                 if loop == 0:
218.                     # RISE UP NOZZLE
219.                     start_point = coords[0]
220.                     f.write(f"G1 F500 X{str(start_point[0] + centre_m[0])} Y
221.                     {str(start_point[1] + centre_m[1])} Z{str(start_point[2] + current_z + 10)} E
222.                     0.01\n")
223.                     start_point = coords[0]
224.                     f.write(f"G1 F500 X{str(start_point[0] + centre_m[0])} Y
225.                     {str(start_point[1] + centre_m[1])} Z{str(start_point[2] + current_z + filame
226.                     nt_thickness/4)} E0.01\n")
227.                     #z_adjustment = loop * filament_thickness
228.
229.                     N_adjustment = (loop) * 1
230.                     if is_reverse and loop != 0:
231.                         coords = coords[::-1]
232.                         n_data = n_data[::-1]
233.                     prev_n = None
234.                     for i in range(1, len(coords) - 1, 1):
235.                         extra_increment = False # record if extra Z is added
236.                         i_coords, j_coords, k_coords = coords[i - 1], coords[i],
237.                         coords[i + 1]

```

```

225.
226.         dx, dy, dz = [j - i for i, j in zip(i_coords, j_coords)]
227.         ddx, ddy, ddz = [i - k for i, k in zip(i_coords, k_coords)]
228.
229.         Ex += (dx ** 2 + dy ** 2) ** (1 / 2)
230.
231.         if ddx != 0 and dx != 0:
232.             angle = atan(abs((dy / dx - ddy / ddx) / (1 + dy / dx * ddy / ddx)))
233.             sp = sp_min if angle >= (0.01 / 180) * pi else sp_max
234.         elif ddx == 0 and dx != 0:
235.             angle = atan(abs(dx / dy)) if dy != 0 else 0
236.             sp = sp_min if angle >= (0.01 / 180) * pi else sp_max
237.         elif ddx != 0 and dx == 0:
238.             angle = atan(abs(ddx / ddy)) if ddy != 0 else 0
239.             sp = sp_min if angle >= (100 / 180) * pi else sp_max
240.
241.         else:
242.             sp = sp_max
243.
244.
245.         if prev_n is not None and n_data[i] != prev_n:
246.             extra_increment = True
247.             prev_n = n_data[i]
248.             if extra_increment:
249.                 current_z += filament_thickness
250.
251.
252.
253.
254.         # Add current Z to the Gcode
255.         if j_coords[2] == 0: # 1st layer
256.             f.write(
257.                 f"G1 F{sp} X{str(j_coords[0] + centre_m[0])} Y{str(j_coords[1] + centre_m[1])} Z{str(j_coords[2] + current_z + filament_thickness/4)} E{Ex} ;yarn_number {int(n_data[i] + N_adjustment)}\n")
258.             else:
259.                 f.write(
260.                     f"G1 F{sp} X{str(j_coords[0] + centre_m[0])} Y{str(j_coords[1] + centre_m[1])} Z{str(j_coords[2] + current_z + filament_thickness/2)} E{Ex} ;yarn_number {int(n_data[i] + N_adjustment)}\n")
261.
262.             current_z += filament_thickness
263.
264.             #if loop == loop_count:
265.                 # Add end points
266.                 end_point = coords[-1]
267.                 # f.write(f"G1 F500 X{str(end_point[0] + centre_m[0] - 10)} Y{str(end_point[1] + centre_m[1])} Z{str(end_point[2] + z_adjustment)} E0.1\n")
268.                 f.write(
269.                     f"G1 F500 X{str(end_point[0] + centre_m[0])} Y{str(end_point[1] + centre_m[1])} Z{str(end_point[2] + current_z + filament_thickness / 2)} E0.2\n")
270.
271.                 # RISE UP NOZZLE
272.                 f.write(
273.                     f"G1 F500 X{str(end_point[0] + centre_m[0])} Y{str(end_point[1] + centre_m[1])} Z{str(end_point[2] + current_z + 10)} E0.2\n")
274.                 Ex_incr = Ex
275.

```

```

276.         # Adding predefined GCode postamble
277.         if selected_option == 'Prusa':
278.             f.write("M104 S0 ; turn off extruder\n"
279.                    "M140 S0 ; turn off heatbed\n"
280.                    "M106 S200\n"
281.                    ";M190 S0 ; wait for bed temp\n"
282.                    ";M109 S70 ; wait for extruder temp\n"
283.                    "M107 ; turn off fan\n"
284.                    "M84 ; disable motors\n"
285.                    "M82 ;absolute extrusion mode\n"
286.                    "M104 S0\n"
287.                    ";End of Gcode\n")
288.         elif selected_option == 'HighTemp':
289.             f.write(";End GCode\n"
290.                    "M107 ; turn off fan\n"
291.                    "M104 S0 ; turn off extruder\n"
292.                    "M140 S0 ;heated bed heater off (if you have it)\n"
293.                    "M6013 S0 ;chamber temperature set to zero\n"
294.                    "G91 ;relative positioning\n"
295.                    "G28 X0 Y0 ;move X/Y to min endstops, so the head is out
of the way\n"
296.                    "M84 X Y E ;steppers off\n"
297.                    "G90 ;absolute positioning\n"
298.                    "M117 Print finished.\n"
299.                    ";End of Gcode\n")
300.
301. def create_ui():
302.     global app, input_file_path, output_directory, sp_min_var, sp_max_var, c
enter_x_var, center_y_var, extruder_temp_var, bed_temp_var, loop_var, loop_co
unt_var, thickness_var, reverse_var, combobox
303.
304.     app = tk.Tk()
305.     app.title("Gcode Generator")
306.     app.config(bg='white')
307.
308.     style = ttk.Style()
309.     style.configure("TLabel", foreground="black", background="white", paddin
g=10)
310.     style.configure("TEntry", foreground="black", background="white", paddin
g=10)
311.
312.     input_file_path = tk.StringVar()
313.     output_directory = tk.StringVar()
314.     sp_min_var = tk.StringVar()
315.     sp_max_var = tk.StringVar()
316.     center_x_var = tk.StringVar()
317.     center_y_var = tk.StringVar()
318.     extruder_temp_var = tk.StringVar()
319.     bed_temp_var = tk.StringVar()
320.     reverse_var = tk.BooleanVar()
321.     loop_var = tk.BooleanVar()
322.     loop_count_var = tk.StringVar()
323.     thickness_var = tk.StringVar()
324.
325.     menu = tk.Menu(app)
326.     filemenu = tk.Menu(menu, tearoff=0)
327.     filemenu.add_command(label="Input File", command=browse_file_path)
328.
329.     filemenu.add_command(label="Preview", command=preview_gcode)
330.     menu.add_cascade(label="File", menu=filemenu)
331.
332.
333.     helpmenu = tk.Menu(menu, tearoff=0)
334.     helpmenu.add_command(label="Help", command=show_help_image)
335.     menu.add_cascade(label="Info", menu=helpmenu)
336.

```

```

337.
338.
339.     app.config(menu=menu)
340.
341.     ttk.Label(app, text="Printing speed(Mini):").grid(row=0, column=0, stick
y='w')
342.     ttk.Entry(app, textvariable=sp_min_var).grid(row=0, column=1, sticky='w'
)
343.
344.     ttk.Label(app, text="Printing speed(Max):").grid(row=1, column=0, sticky
='w')
345.     ttk.Entry(app, textvariable=sp_max_var).grid(row=1, column=1, sticky='w'
)
346.
347.     ttk.Label(app, text="Printing center (X):").grid(row=2, column=0, sticky
='w')
348.     ttk.Entry(app, textvariable=center_x_var).grid(row=2, column=1, sticky='
w')
349.
350.     ttk.Label(app, text="Printing center (Y):").grid(row=3, column=0, sticky
='w')
351.     ttk.Entry(app, textvariable=center_y_var).grid(row=3, column=1, sticky='
w')
352.
353.     ttk.Label(app, text="Extruder temperature:").grid(row=4, column=0, stick
y='w')
354.     ttk.Entry(app, textvariable=extruder_temp_var).grid(row=4, column=1, sti
cky='w')
355.
356.     ttk.Label(app, text="Bed temperature:").grid(row=5, column=0, sticky='w'
)
357.     ttk.Entry(app, textvariable=bed_temp_var).grid(row=5, column=1, sticky='
w')
358.
359.     # New loop option checkbutton
360.     ttk.Checkbutton(app, text="Multiple layers", variable=loop_var).grid(row
=7, column=0, sticky='w') # New checkbutton for the loop option
361.     # Add the reverse checkbutton in the UI
362.     ttk.Checkbutton(app, text="Reverse", variable=reverse_var).grid(row=9, c
olumn=0, sticky='w')
363.
364.     ttk.Label(app, text="Layer count:").grid(row=8, column=0, sticky='w')
365.     ttk.Entry(app, textvariable=loop_count_var).grid(row=8, column=1, sticky
='w') # New entry for the loop count
366.
367.     ttk.Label(app, text="Filament thickness:").grid(row=6, column=0, sticky=
'w')
368.     ttk.Entry(app, textvariable=thickness_var).grid(row=6, column=1, sticky=
'w') # New entry for the filament thickness
369.
370.     ttk.Button(app, text="Start", command=start_processing).grid(row=11, col
umn=0, columnspan=2)
371.
372.     ttk.Label(app, text="© 2023 S1887777").grid(row=12, column=0, sticky='w'
)
373.     app.resizable(False, False)
374.
375.     ttk.Label(app, text="Select printer").grid(row=10, column=0, sticky='w')
376.     options = ['Prusa', 'HighTemp']
377.     combobox = ttk.Combobox(app, values=options)
378.     combobox.grid(row=10, column=1)
379.
380.
381.
382.     app.mainloop()

```

```

383.
384.
385. def start_processing():
386.     try:
387.         input_path = input_file_path.get()
388.         #output_path = output_directory.get()
389.         output_path = output_directory.get()
390.
391.         if not input_path or not output_path:
392.             raise ValueError("Please provide both input and output paths.")
393.
394.         data = pd.read_excel(input_path) if input_path.endswith(('xlsx', '.xls')) else pd.read_csv(input_path)
395.
396.         if not all(col in data.columns for col in ['X', 'Y', 'Z', 'N']):
397.             raise ValueError("The input file does not have the required columns (X, Y, Z, N).")
398.
399.         is_loop = loop_var.get()
400.         is_reverse = reverse_var.get()
401.         loop_count = int(loop_count_var.get()) if loop_var.get() else 1
402.         filament_thickness = float(thickness_var.get()) #if loop_var.get() else 0
403.
404.         center_m = [float(center_x_var.get()), float(center_y_var.get())]
405.
406.         sp_min = float(sp_min_var.get())
407.         sp_max = float(sp_max_var.get())
408.         extruder_temp = int(extruder_temp_var.get())
409.         bed_temp = int(bed_temp_var.get())
410.
411.         coords = list(zip(data['X'], data['Y'], data['Z']))
412.         n_data = list(data['N'])
413.
414.         output_file = os.path.join(output_path, 'output.gcode')
415.
416.         process_file(coords, n_data, sp_min, sp_max, center_m, output_file,
417.                     extruder_temp, bed_temp, loop_count,
418.                     filament_thickness, is_loop, is_reverse, combobox)
419.         messagebox.showinfo("Success", "File processing completed successfully.")
420.     except ValueError as e:
421.         messagebox.showerror("Error", str(e))
422.     except Exception as e:
423.         messagebox.showerror("Error", f"An unexpected error occurred: {str(e)}")
424.
425. if __name__ == "__main__":
426.     create_ui()
427.     app.mainloop()

```

A.2 Gcode Z coordinate post processor

```

1. import pandas as pd
2. import numpy as np
3. from tkinter import Tk, filedialog, simpledialog
4.
5. def load_file():
6.     Tk().withdraw()
7.     filename = filedialog.askopenfilename()
8.     return filename
9.
10. def load_print_parameters():

```

```

11.     Tk().withdraw()
12.
13.
14.     print_width = 1.7
15.     print_thickness = 0.3
16.
17.
18.     return print_width, print_thickness
19.
20. def process_data(filename, print_width, print_thickness):
21.     data = pd.read_csv(filename)
22.
23.     data['New_Z'] = data['Z']
24.     data['Tag'] = range(len(data))
25.
26.     for i in range(len(data)):
27.         layer_count = 0
28.         overlap_groups = []
29.         for j in range(0, max(0, i-28)):
30.             dist = np.sqrt((data.iloc[i]['X'] - data.iloc[j]['X']) ** 2 + (data.iloc[i]['Y'] - data.iloc[j]['Y']) ** 2)
31.             if dist <= print_width:
32.                 overlap = True
33.                 for group in overlap_groups:
34.                     if abs(data.iloc[j]['Tag'] - group[-1]['Tag']) < 5:
35.                         group.append(data.iloc[j])
36.                         overlap = False
37.                         break
38.                 if overlap:
39.                     overlap_groups.append([data.iloc[j]])
40.                 layer_count += 1
41.
42.     data.at[i, 'New_Z'] += len(overlap_groups) * print_thickness
43.
44.     for group in overlap_groups:
45.         print("Overlap Group:")
46.         for point in group:
47.             print(point[['X', 'Y', 'Z']])
48.
49.     data['Z'] = data['New_Z']
50.     del data['New_Z']
51.     del data['Tag']
52.
53.     return data
54.
55. def save_file(data, filename):
56.     data.to_csv(filename, index=False)
57.
58. def main():
59.     filename = load_file()
60.     print_width, print_thickness = load_print_parameters()
61.     data = process_data(filename, print_width, print_thickness)
62.     save_file(data, filename)
63.
64. if __name__ == "__main__":
65.     main()

```

A.3 Load Path Generator

```

1. import tkinter as tk
2. from tkinter import filedialog, messagebox
3. import pandas as pd

```

```

4. import numpy as np
5. import os
6. import matplotlib.pyplot as plt
7.
8.
9. def read_and_process_csv():
10.     root = tk.Tk()
11.     root.withdraw()
12.     file_path = filedialog.askopenfilename(title="choose CSV
file", filetypes=[("CSV files", "*.csv")])
13.
14.     if not file_path:
15.         messagebox.showwarning("Error", "No file!")
16.         return None, None
17.
18.     data = pd.read_csv(file_path)
19.     vectors = data[['Centroid_X', 'Centroid_Y', 'Angle']].to_numpy()
20.
21.     points = vectors[:, :2]
22.     angles = vectors[:, 2]
23.
24.     return points, angles, file_path
25.
26.
27. def trace_streamline(start_x, start_y, steps, delta):
28.     x, y = start_x, start_y
29.     X, Y = [x], [y]
30.
31.     #direction = [-1, 0]
32.     direction = [1, 0]
33.
34.     for _ in range(steps):
35.         distances = np.sqrt((points[:, 0] - x) ** 2 + (points[:, 1] - y) ** 2
)
36.         closest_idx = np.argmin(distances)
37.
38.         angle = angles[closest_idx]
39.         u = np.cos(np.radians(angle))
40.         v = np.sin(np.radians(angle))
41.
42.         vector_direction = np.array([u, v])
43.         if np.dot(direction, vector_direction) < 0:
44.             vector_direction = -vector_direction
45.
46.         direction = vector_direction
47.
48.         x += delta * direction[0]
49.         y += delta * direction[1]
50.
51.         X.append(x)
52.         Y.append(y)
53.
54.     return X, Y
55.
56.
57. def visualize(points, angles, tracked_lines_x, tracked_lines_y):
58.     plt.figure(figsize=(12, 8))
59.
60.     for x, y in tracked_lines_x:
61.         plt.plot(x, y, 'b-')
62.
63.     for x, y in tracked_lines_y:
64.         plt.plot(x, y, 'r-')
65.
66.     for point, angle in zip(points, angles):

```

```

67.     plt.arrow(point[0], point[1], np.cos(np.radians(angle)), np.sin(np.ra
dians(angle)), head_width=0.1)
68.
69.     plt.xlabel('X')
70.     plt.ylabel('Y')
71.     plt.title('Streamlines')
72.     plt.grid(True)
73.     plt.show()
74.
75.
76. def save_to_csv(tracked_lines, folder_path, filename):
77.     columns = []
78.     data_dict = {}
79.
80.     for idx, line in enumerate(tracked_lines):
81.         x_col = f'X_{idx + 1}'
82.         y_col = f'Y_{idx + 1}'
83.         data_dict[x_col] = line[0]
84.         data_dict[y_col] = line[1]
85.         columns.extend([x_col, y_col])
86.
87.     df = pd.DataFrame(data_dict)
88.     df = df[columns]
89.     df.to_csv(os.path.join(folder_path, filename), index=False)
90.
91.
92. if __name__ == '__main__':
93.     points, angles, file_path = read_and_process_csv()
94.
95.     if file_path is None:
96.         exit()
97.
98.     start_points_y = [(36, y_val) for y_val in np.arange(0.75, 20.5, 1.5)]
99.     tracked_lines_y = [trace_streamline(x, y, 120, 0.5) for x, y in start_poi
nts_y]
100.
101.     start_points_x = [(x_val, 0.75) for x_val in np.arange(40, 80, 1.5)]
102.     tracked_lines_x = [trace_streamline(x, y, 120, 0.5) for x, y in start_po
ints_x]
103.
104.     visualize(points, angles, tracked_lines_x, tracked_lines_y)
105.
106.     folder_path = os.path.dirname(file_path)
107.     save_to_csv(tracked_lines_x + tracked_lines_y, folder_path, "tracked_lin
es.csv")

```

A.4 TexGen Code Generator

```

1. import tkinter as tk
2. from tkinter import filedialog
3. from tkinter import messagebox
4. import pandas as pd
5. import os
6. import subprocess
7. import json
8.
9. def read_file(file_path):
10.     if file_path.endswith('.xlsx') or file_path.endswith('.xls'):
11.         return pd.read_excel(file_path)
12.     elif file_path.endswith('.csv'):
13.         return pd.read_csv(file_path)
14.     else:
15.         raise ValueError(f"Unsupported file format: {file_path}")
16.
17.

```

```

18. class Application(tk.Frame):
19.     def __init__(self, master=None):
20.         super().__init__(master)
21.         self.master = master
22.         self.grid()
23.         self.create_widgets()
24.
25.
26.     def create_widgets(self):
27.         self.menubar = tk.Menu(self.master)
28.         self.fileMenu = tk.Menu(self.menubar, tearoff=0)
29.         self.fileMenu.add_command(label='Open', command=self.load_file)
30.         self.menubar.add_cascade(label='File', menu=self.fileMenu)
31.         self.master.config(menu=self.menubar)
32.
33.         self.ellipse_var = tk.StringVar()
34.         self.ellipse_entry = tk.Entry(self, textvariable=self.ellipse_var)
35.         self.ellipse_entry.grid(row=1, column=1)
36.         self.ellipse_label = tk.Label(self, text="Ellipse parameters (e.g., 1
37.         .5,0.2):")
38.         self.ellipse_label.grid(row=1, column=0)
39.
40.         self.domain_var = tk.StringVar()
41.         self.domain_entry = tk.Entry(self, textvariable=self.domain_var)
42.         self.domain_entry.grid(row=2, column=1)
43.         self.domain_label = tk.Label(self, text="Domain parameters (e.g., 1,-
44.         1,-0.1,82,40.5,0.1):")
45.         self.domain_label.grid(row=2, column=0)
46.
47.         self.generate_button = tk.Button(self, text="Generate code", command=
48.         self.generate_code)
49.         self.generate_button.grid(row=3, column=0, columnspan=2)
50.
51.         ##
52.         def define_target(self):
53.             self.target_path = filedialog.askopenfilename()
54.             self.save_config()
55.
56.         def run_program(self):
57.             subprocess.run([self.target_path])
58.
59.         def save_config(self):
60.             with open('venv/config.json', 'w') as f:
61.                 json.dump({'target_path': self.target_path}, f)
62.
63.         def load_config(self):
64.             try:
65.                 with open('venv/config.json', 'r') as f:
66.                     config = json.load(f)
67.                     self.target_path = config.get('target_path', '')
68.             except FileNotFoundError:
69.                 self.target_path = ''
70.
71.         def load_file(self):
72.             self.file_paths = filedialog.askopenfilenames() #askopenfilename() >>
73.             > askopenfilenames()
74.
75.         def generate_code(self):
76.             domain_params = list(map(float, self.domain_var.get().split(',')))
77.             ellipse_params = list(map(float, self.ellipse_var.get().split(',')))
78.
79.             for idx, file_path in enumerate(self.file_paths):
80.                 df = read_file(file_path)
81.                 output_path = os.path.join(os.path.dirname(file_path), f'Yarn{idx
82.                 }.py')
83.                 with open(output_path, 'w') as f:

```

```

78.         f.write("""# Create a textile
79. Textile = CTextile()
80.
81. # Create a python list containing yarn
82. Yarns = [CYarn()]
83. """)
84.
85.         # Loop over the rows of the dataframe
86.         for _, row in df.iterrows():
87.             x = row['X']
88.             y = row['Y']
89.             z = row['Z']
90.             f.write(f"Yarns[0].AddNode(CNode(XYZ({x},{y},{z})))\n")
91.
92.         # Add the second part of the code
93.         f.write(f"""
94. # Loop over all the yarns in the list
95. for Yarn in Yarns:
96.     # Set the interpolation function
97.     Yarn.AssignInterpolation(CInterpolationLinear())
98.     # Assign a constant cross-section all along the yarn of elliptical shape
99.     Yarn.AssignSection(CYarnSectionConstant(CSectionRectangle({ellipse_params
[0]}, {ellipse_params[1]})))
100.    # Ellipse, Rectangle section
101.    # Set the resolution of the surface mesh created
102.    Yarn.SetResolution(40)
103.    #assign material property
104.    Yarn.SetYoungsModulusX(39000*10**(-6))
105.    Yarn.SetYoungsModulusY(9000*10**(-6))
106.    Yarn.SetYoungsModulusZ(9000*10**(-6))
107.    Yarn.SetShearModulusXY(15000*10**(-6))
108.    Yarn.SetShearModulusXZ(3461*10**(-6))
109.    Yarn.SetShearModulusYZ(3461*10**(-6))
110.    Yarn.SetPoissonsRatioX(0.3)
111.    Yarn.SetPoissonsRatioY(0.3)
112.    Yarn.SetPoissonsRatioZ(0.3)
113.    # Add the yarn to our textile
114.    Textile.AddYarn(Yarn)
115.# Create a domain and assign it to the textile
116.Textile.AssignDomain(CDomainPlanes(XYZ({domain_params[0]}, {domain_params[1]
}, {domain_params[2]}), XYZ({domain_params[3]}, {domain_params[4]}, {domain_p
arams[5]})))
117.Textile.SetMatrixYoungsModulus(3000*10**(-6))#automatically turned to Pa
118.Textile.SetMatrixPoissonsRatio(0.37)
119.# Add the textile with the name "test"
120.AddTextile("New-hole-{idx}", Textile)
121.
122.         """)
123.         messagebox.showinfo("Success", f"Code written to Yarn{idx}.py")
124.
125.root = tk.Tk()
126.app = Application(master=root)
127.app.mainloop()

```

A.5 Voxel Mesh Post Processor

```

1. # Used to modify the voxel mesh generated from Texgen
2.
3. # *****
4. # After use,
5. # 1. modify the name of the input .ori file in the .inp file.

```

```

6. # 2. And delete the unknown number under *elset
7. # *****
8.
9. import os
10. import tkinter as tk
11. from tkinter import filedialog
12. import re
13. import math
14. import tkinter.messagebox as messagebox
15.
16. def generate_sequence(sequence):
17.     output = [(sequence[0], sequence[0])]
18.     for i in range(1, len(sequence)):
19.         output.append((sequence[i], output[i-1][1]+1))
20.     return output
21.
22. #def delete_nodes_and_elements(filepath, N, radius=5):# modify the radius to
    create the through hole region
23. def delete_nodes_and_elements(filepath, N, radius=3.0): # modify the radius
    to create the through hole region
24.     with open(filepath, 'r') as f:
25.         lines = f.readlines()
26.
27.         output_lines = []
28.         deleted_nodes = []
29.         deleted_elements = []
30.         #center_x, center_y = 11.25, 8.25 # 19.75, 20.25
31.         center_x, center_y = 18, 18 # 19.75, 20.25
32.         #center_x, center_y = 19.75, 20 # 19.75, 20.25
33.         #center_x, center_y = 60, 20 # 19.75, 20.25
34.         section = None
35.         node_mapping = {}
36.         element_mapping = {}
37.
38.         for line in lines:
39.             stripped_line = line.strip()
40.             if stripped_line.startswith('*Node'):
41.                 section = 'node'
42.                 output_lines.append(line) # Add the *Node line to output without
modification
43.             elif stripped_line.startswith('*Element, Type=C3D8R'):
44.                 section = 'element'
45.                 output_lines.append(line) # Add the *Element line to output with
out modification
46.             elif any(stripped_line.startswith(f'*ElSet, ElSet=Yarn{i}') for i in
range(N)): # Adjust the conditional
47.                 section = 'elset'
48.                 output_lines.append(line)
49.             elif stripped_line.startswith('*ElSet, ElSet=AllElements, Generate'):
50.
51.                 section = 'all_elements'
52.                 output_lines.append(line)
53.             elif stripped_line.startswith('*NSet, NSet=AllNodes, Generate'):
54.                 section = 'all_nodes'
55.                 output_lines.append(line)
56.             elif stripped_line.startswith('*'):
57.                 section = None
58.
59.             if section == 'node':
60.                 data = list(map(float, re.findall(r"[-
+]?\\d*\\.\\d+|\\d+", stripped_line)))
61.                 if len(data) == 4:
62.                     index, x, y, _ = data
63.                     if math.sqrt((x - center_x)**2 + (y - center_y)**2) <= radius
:
deleted_nodes.append(int(index))

```

```

64.                 continue
65.             else:
66.                 node_mapping[index] = len(node_mapping) + 1
67.                 output_lines.append(f"{node_mapping[index]}, {x}, {y}, {_
}\n")
68.
69.             elif section == 'element':
70.                 data = list(map(int, re.findall(r"[-
+]?\\d*\\.\\d+|\\d+", stripped_line)))
71.                 if len(data) == 9:
72.                     element_index, *nodes = data
73.                     if any(node in deleted_nodes for node in nodes):
74.                         deleted_elements.append(element_index)
75.                         continue
76.                 else:
77.                     element_mapping[element_index] = len(element_mapping) + 1
78.
79.                     nodes = [node_mapping[node] for node in nodes]
80.                     output_lines.append(f"{element_mapping[element_index]}, {
', '.join(map(str, nodes))}\\n")
81.
82.             elif section == 'elset':
83.                 data = list(map(int, re.findall(r"[-
+]?\\d*\\.\\d+|\\d+", stripped_line)))
84.                 data = [element_mapping[element] for element in data if
85.                     element in element_mapping.keys() and element not in dele
ted_elements]
86.                 output_lines.append(', '.join(map(str, data)) + '\\n')
87.
88.             elif section == 'all_elements':
89.                 data = list(map(int, re.findall(r"[-
+]?\\d*\\.\\d+|\\d+", stripped_line)))
90.                 if len(data) == 3:
91.                     start, end, step = data
92.                     new_sequence = [element_mapping[i] for i in range(start, end
+ 1, step) if i not in deleted_elements]
93.                     if new_sequence:
94.                         output_lines.append(f"{new_sequence[0]}, {new_sequence[-
1]}, {step}\\n")
95.                 continue
96.
97.             elif section == 'all_nodes':
98.                 data = list(map(int, re.findall(r"[-
+]?\\d*\\.\\d+|\\d+", stripped_line)))
99.                 if len(data) == 3:
100.                     start, end, step = data
101.                     new_sequence = [node_mapping[i] for i in range(start, end +
1, step) if i not in deleted_nodes]
102.                     if new_sequence:
103.                         output_lines.append(f"{new_sequence[0]}, {new_sequence[-
1]}, {step}\\n")
104.                 continue
105.
106.
107.             elif section is None:
108.                 output_lines.append(line)
109.             # After the loop where output_lines is populated:
110.             dirname, filename = os.path.split(filepath)
111.             new_filename = os.path.join(dirname, filename.split('.')[0] + '_modified
.inp')
112.             with open(new_filename, 'w') as f:
113.                 f.writelines(output_lines)
114.
115.             return deleted_elements, element_mapping
116.

```

```

117.
118.
119. def modify_file(file_type, filepath, deleted_elements, element_mapping):
120.     with open(filepath, 'r') as f:
121.         lines = f.readlines()
122.
123.         output_lines = []
124.         for line in lines:
125.             if line.startswith(","):
126.                 output_lines.append(line)
127.                 continue
128.
129.             data = re.findall(r"[-+]?[d*\.d+e?[-
+]?\d*|\d+", line.strip()) # Capture numbers in scientific notation too
130.
131.             if len(data) >= 6:
132.                 element_index = int(float(data[0]))
133.
134.                 if element_index in deleted_elements:
135.                     continue
136.                 else:
137.                     new_index = element_mapping.get(element_index, element_index
)
138.                     data[0] = str(new_index) # Convert back to string after the
operation
139.                     output_lines.append(', '.join(map(str, data)) + '\n')
140.                 else:
141.                     output_lines.append(line)
142.
143.         dirname, filename = os.path.split(filepath)
144.         new_filename = os.path.join(dirname, filename.split('.')[0] + '_modified
.' + file_type)
145.         with open(new_filename, 'w') as f:
146.             f.writelines(output_lines)
147.
148.
149. def open_files(file_type):
150.     filepaths = filedialog.askopenfilenames(filetypes=(("inp files", "*.in" +
file_type), ("all files", "*.*")))
151.     return filepaths
152.
153. def start_process():
154.     try:
155.         N = int(num_yarns_entry.get()) # Get the number of yarns from the e
ntry
156.     except ValueError:
157.         tk.messagebox.showinfo("Invalid Input", "Please enter a valid number
of yarns.")
158.         return
159.
160.     inp_filepaths = open_files('inp')
161.     processed_files_count = 0
162.     for inp_filepath in inp_filepaths:
163.         deleted_elements, element_mapping = delete_nodes_and_elements(inp_fi
lepath, N)
164.
165.         # Find and modify the corresponding .ori and .eld files
166.         base_filepath = os.path.splitext(inp_filepath)[0]
167.         for file_type in ['ori', 'eld']:
168.             corresponding_filepath = base_filepath + '.' + file_type
169.             if os.path.exists(corresponding_filepath):
170.                 modify_file(file_type, corresponding_filepath, deleted_eleme
nts, element_mapping)
171.                 processed_files_count += 1
172.         else:

```

```

173.             print(f"No corresponding .{file_type} file found for {os.pat
    h.basename(inp_filepath)}.")
174.
175.     # Show a message box after processing all files
176.     tk.messagebox.showinfo("Process Complete", f"All tasks completed. Total
    files processed: {processed_files_count}")
177.
178.
179.root = tk.Tk()
180.root.title("File Modifier")
181.frame = tk.Frame(root)
182.frame.pack()
183.
184.# Add an entry to specify the number of yarns
185.num_yarns_label = tk.Label(frame, text="Number of Yarns(real number):")
186.num_yarns_label.pack(side=tk.LEFT)
187.num_yarns_entry = tk.Entry(frame)
188.num_yarns_entry.pack(side=tk.LEFT)
189.
190.start_button = tk.Button(frame, text="Start Process", command=start_process)
191.start_button.pack(side=tk.LEFT)
192.
193.root.mainloop()

```

Appendices B ABAQUS Macro Script

B.1 TexGen voxel mesh import

```
1. RangeA = 0
2. RangeB = 24
3. def A_ImportINP():
4.     import section
5.     import regionToolset
6.     import displayGroupMdbToolset as dgm
7.     import part
8.     import material
9.     import assembly
10.    import optimization
11.    import step
12.    import interaction
13.    import load
14.    import mesh
15.    import job
16.    import sketch
17.    import visualization
18.    import xyPlot
19.    import displayGroupOdbToolset as dgo
20.    import connectorBehavior
21.    for i in range(RangeA,RangeB,1):
22.        a = mdb.models['Model-1'].rootAssembly
23.        mdb.ModelFromInputFile(name='F'+str(i),
24.                                inputFileName=
25.
26.        a = mdb.models['F'+str(i)].rootAssembly
27.        a = mdb.models['Model-1'].rootAssembly
28.
29.
30. def A_RenameCopy():
31.     import section
32.     import regionToolset
33.     import displayGroupMdbToolset as dgm
34.     import part
35.     import material
36.     import assembly
37.     import optimization
38.     import step
39.     import interaction
40.     import load
41.     import mesh
42.     import job
43.     import sketch
44.     import visualization
45.     import xyPlot
46.     import displayGroupOdbToolset as dgo
47.     import connectorBehavior
48.     for i in range (RangeA,RangeB):
49.         part_name='PART-1'
50.
51.         p = mdb.models['F'+str(i)].parts[part_name]
52.
53.         p1 = mdb.models['F'+str(i)].parts[part_name]
54.
55.         mdb.models['F'+str(i)].parts.changeKey(fromName=part_name, toName='F'+
+str(i))
56.
57.         mdb.models['F'+str(i)].sections.changeKey(fromName='Section-2-
YARN0',
```

```

58.         toName='Section-F'+str(i))
59.         a = mdb.models['F'+str(i)].rootAssembly
60.         a.regenerate()
61.
62.         mdb.models['F'+str(i)].rootAssembly.features.changeKey(fromName=part_
name+'-1',
63.             toName='F'+str(i))
64.         p1 = mdb.models['F'+str(i)].parts['F'+str(i)]
65.
66.         mdb.models['F'+str(i)].discreteFields.changeKey(
67.             fromName=part_name+'_TEXGENORIENTATIONVECTORS',
68.             toName='F'+str(i)+'_TEXGENORIENTATIONVECTORS')
69.         import part
70.         import assembly
71.         import material
72.         import section
73.         import interaction
74.         mdb.models['Model-
1'].Part('F'+str(i), mdb.models['F'+str(i)].parts['F'+str(i)])
75.         mdb.models['Model-
1'].copySections(sourceModel=mdb.models['F'+str(i)])
76.         mdb.models['Model-
1'].copyDiscreteFields(sourceModel=mdb.models['F'+str(i)])
77.
78. def A_FieldSectionRename():
79.     import section
80.     import regionToolset
81.     import displayGroupMdbToolset as dgm
82.     import part
83.     import material
84.     import assembly
85.     import optimization
86.     import step
87.     import interaction
88.     import load
89.     import mesh
90.     import job
91.     import sketch
92.     import visualization
93.     import xyPlot
94.     import displayGroupOdbToolset as dgo
95.     import connectorBehavior
96.     for i in range(RangeA,RangeB):
97.         p1 = mdb.models['Model-1'].parts['F'+str(i)]
98.         mdb.models['Model-
1'].parts['F'+str(i)].materialOrientations[0].setValues(
99.             orientationType=FIELD, fieldName='F'+str(i)+'_TEXGENORIENTATIONVE
CTORS',
100.             localCsys=None)
101.         mdb.models['Model-1'].parts['F0'].sectionAssignments[0].setValues(
102.             sectionName='Section-
F0', offsetType=MIDDLE_SURFACE, offsetField='',
103.             offset=0.0)
104.
105.         mdb.models['Model-
1'].parts['F'+str(i)].sectionAssignments[0].setValues(
106.             sectionName='Section-
F'+str(i), offsetType=MIDDLE_SURFACE, offsetField='',
107.             offset=0.0)

```