

Thèse

Characterization and optimization of the forming behavior of the textile preforms assembled by tufting

Caractérisation et optimisation du comportement de formage des
préformes textiles assemblées par piquage

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General introduction

Continuous fiber-reinforced textile composites, such as glass fiber and carbon fibers, are valued for their high tensile strength, durability, low density, and corrosion resistance, which makes them applicable to numerous industries. The moldability of textile composites allows for the creation of complex shapes, which is especially advantageous in aerospace and automotive engineering, where there's a rising demand for light-weight and high-strength design.

The Liquid Composite Molding (LCM) process is widely recognized for its superior manufacturing capabilities in textile composites, valued for its high quality, durability, and cost efficiency. This process is particularly distinguished by its ability to produce shaped components with uniform fiber distribution. However, despite its advantages, the preforming process introduces several challenges that frequently lead to forming defects such as wrinkling, buckling, and yarn misalignment, all of which can significantly compromise the structural integrity and mechanical properties of the final composite product. Therefore, this study aims to investigate the forming mechanisms of these defects, identify key influencing factors, and propose optimization strategies to minimize their occurrence. My research works in the past three years can be briefly divided into three principal aspects:

At first, systematically investigating the influence of slit and tufted configurations on the in-plane shear response of glass woven fabrics through standardized picture frame test. Optical measurement based on vision algorithms is employed to quantitatively characterize deformation mechanisms at slit edges and tufted regions during progressive shear loading. Chapter 2 focuses on elucidating how controlled slitting process and tufting technology synergistically regulate continuous deformation field evolution in woven fabric.

Second, aims to investigate the evolution of in-plane shear stiffness and wrinkle formation across various slit and tufted structures. This will enhance our understanding of selecting appropriate slit and tufted configurations. Slitting is carried out to disrupt

the continuous shearing field, while tufting is used to replace yarn tension with in-plane shearing, thereby preventing further damage caused by slitting. Chapter 3 and Chapter 4 aims to investigate the impact of changes in the continuous deformation field on the forming behavior of woven preforms.

Finally, two types of fabric scraps with distinct geometries (rectangular and triangular) were assembled by tufting process into square preforms, followed by hemispherical forming. The formability behaviours were systematically analysed through materials draw-in, in-plane shear angle and wrinkles to investigate the consistency of patch geometry and forming behavior. These establish a basic understanding for converting fabric scraps into functional preforms, advancing sustainable composite manufacturing through reusing of offcuts.

1. State of art

1.1 Continuous fiber-reinforced composite materials

Continuous fiber-reinforced composite materials have emerged as a cornerstone of advanced engineering applications due to their exceptional strength-to-weight ratios, tailored anisotropic mechanical properties, and resistance to environmental degradation [1–3]. These materials, characterized by the incorporation of high-performance continuous fibers (e.g., carbon, glass, or aramid) within polymeric, metallic, or ceramic matrices, enable the design of lightweight structures with superior load-bearing capabilities. For instance, carbon fiber-reinforced composites exhibit exceptional specific strength and stiffness, attributable to continuous carbon fibers embedded in epoxy or thermoplastic matrices [4]. Meanwhile, glass fiber-reinforced composites (GFRCs) offer a balance of cost-effectiveness, moderate tensile strength, and corrosion resistance, utilizing E-glass or S-glass fibers in polyester or epoxy systems [5].

The versatility of continuous fiber-reinforced composites has driven their widespread adoption across diverse industries. In the aerospace industry, CFRCs reduce airframe weight by 20 - 50%, improving fuel efficiency in aircraft such as the Boeing 787 (Figure 1-1) [6]. Within the automotive sector, CFRCs are utilized for high-performance chassis and electric vehicle components. In contrast, GFRCs are widely used in marine structures (e.g., boat hulls), automotive body panels, and civil infrastructure applications, such as pipes and rebars [5,7]. Wind energy systems utilize carbon and glass fiber composites to produce lightweight turbine blades and spars, while emerging applications include biomedical implants and space exploration equipment.

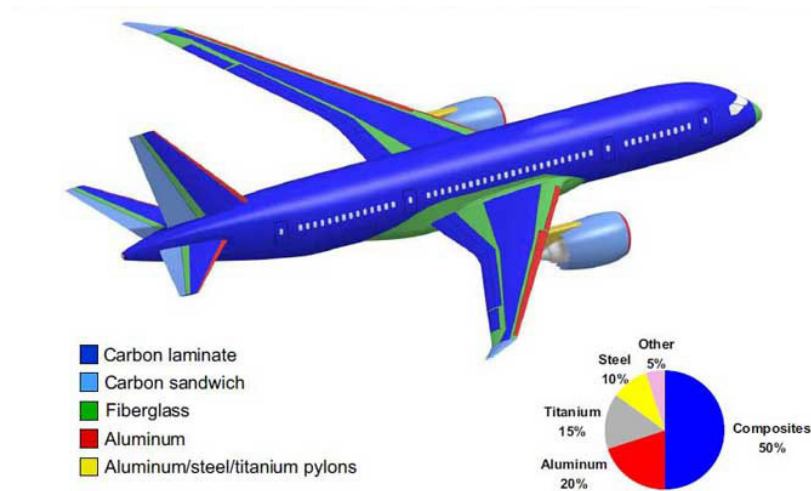


Figure 1-1 Material used in the Boeing 787 [6].

Recent advancements in manufacturing techniques have enhanced design flexibility and production scalability for continuous fiber-reinforced composites. These include automated fiber placement (AFM) [8], resin transfer molding (RTM) [9], 3D printing [2], and additive manufacturing (AM) [4]. Parallel advancements in computational modeling, such as multi-scale simulations and machine learning-driven optimization frameworks, have significantly improved the prediction accuracy of complex nonlinear behaviors, particularly damage initiation and fatigue resistance. However, persistent challenges include achieving robust interfacial bonding, minimizing process-induced defects, and ensuring long-term durability under multiaxial thermo-mechanical loading conditions.

1.1.1 Tufted fiber-reinforced composite materials

The tufting process is a one-sided stitching technique that inserts fibrous reinforcements through the thickness of multiple plies in composite laminates. Tufting process can be complete on the machine directly, which is particularly useful when working with thicker or more intricate composite structure [10]. Tufting enables flexible manufacturing of intricate 3D structures. By integrating Z-fibers into laminated composites, it offers distinct advantages over traditional 3D weaving or 3D braiding techniques [11,12]. This technology supports reinforcement of components with diverse geometries, rendering it suitable for industrial and aerospace applications. By

introducing tufting yarns in the thickness direction, tufting effectively enhances interlaminar strength, damage tolerance, delamination resistance, and impact performance in composites [13–16].

Tufting directly reinforces dry fabrics and helps maintain the geometric shape of preforms and prepregs [17–19]. The tufting yarn helps keep the layers stable and prevent deformation or misalignment during handling, moulding and curing, ensuring that the final composite part maintains the desired geometry and integrity [19]. Meanwhile, the presence of tufting yarns reduces defects during shaping and forming processes [17,18]. Moreover, the tufting technique offers significant flexibility in arranging through-thickness reinforcement (TTR) by varying parameters such as density, pattern, spacing and yarn type [20]. Consequently, tufted composites have broad applications across various sectors, as illustrated in Figure 1-2, including aerospace, aviation, automotive, marine, and civil infrastructure [21–24].

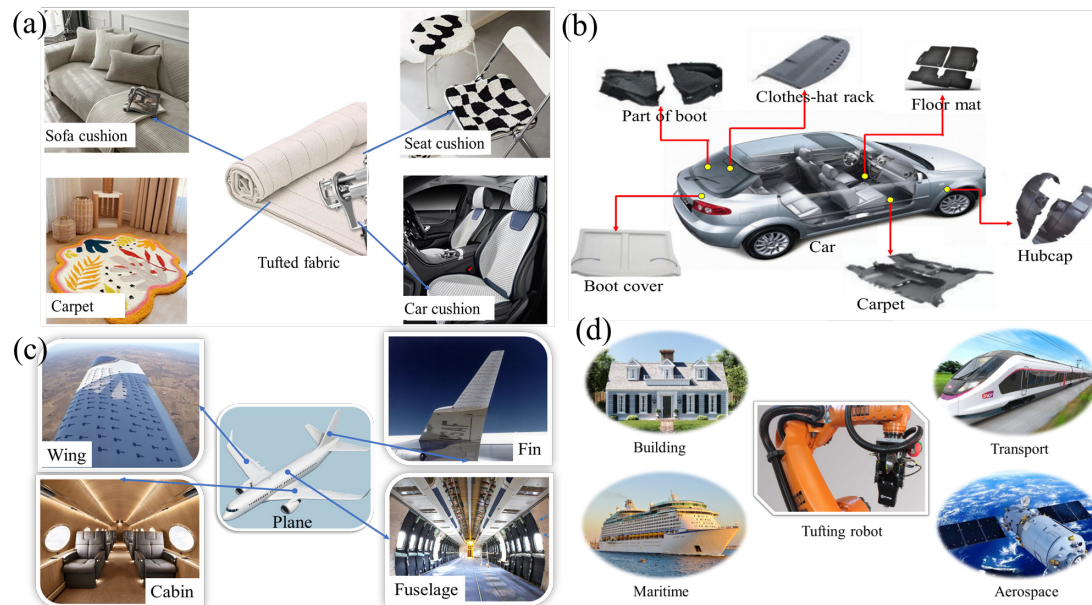


Figure 1-2 Tufted composites and related application [22–24]: (a) Tufted fabric; (b) Car; (c) Plane; (d) Other fields.

Tufting directly reinforces dry fabrics while ensuring structural stability in preforms and prepregs [25–27]. Tufting yarn stabilizes the layers, preventing deformation or misalignment during handling, molding, and curing processes. This ensures the final

composite retains its intended geometry and structural integrity. Furthermore, tufting yarns mitigate defects during shaping and forming process [17,18]. The tufting technique also enables precise tailoring of through-thickness reinforcement (TTR) through adjustments in tufting density, tufting pattern, tufting space, and tufting yarn type [20].

In the Mercedes SLR, tufting integrates I-stiffeners with braided oval crash tubes during frame rail production, significantly improving energy absorption during collision events [28]. Laourine et al. [29] utilized tufting to fabricate a complex 3D composite undercarriage demonstrator, overcoming spatial constraints that rendered conventional methods impractical. Aerospace research demonstrates that tufting effectively bonds T-stiffeners and J-stiffeners to composite skins, tripling the load-bearing capacity prior to structural failure. Stickler et al. [30–34] developed partially tufted T-shaped composite butt joints. Their results indicated that a 20% increase in maximum tensile strength and 25% enhancement in axial displacement for tufted single-lap joints relative to non-tufted counterparts. Verma et al. [35] reinforced a full-scale carbon-epoxy T-joint (representative of aircraft wing interiors) using Kevlar tufts, achieving notable toughening effects. This approach yielded a 24% rise in ultimate load capacity and a 120% increase in joint toughness. Notably, the majority of published studies on tufted structures concentrate on aircraft joint applications [36]. Tufting effectively enhances damage tolerance and delamination resistance in glass and carbon fiber-reinforced composites [37–39]. Consequently, tufting is ideally suited for components demanding high impact resistance and fatigue durability, including aerospace, automotive, and marine structures.

1.1.2 Assembled fiber-reinforced composite materials

Assembled fiber-reinforced composite materials (AFRCMs) represent an innovative advancement in materials engineering. They involve the systematic integration of discrete fiber-reinforced modules or hierarchical architectures to achieve customizable mechanical, thermal, and functional properties [40]. In recent decades, AFRCMs have

garnered significant attention due to their exceptional mechanical performance, lightweight nature, and adaptability across various engineering applications. These materials consist of high-strength fibers embedded in polymer, ceramic, or metallic matrices, offering superior performance compared to conventional monolithic materials. Within the broader category of fiber-reinforced composites, AFRCMs stand out as an advanced class distinguished by tailored structural configurations and enhanced mechanical capabilities.

The flowchart detailing the assembly process for fiber-reinforced thermoplastic composites is illustrated in Figure 1-3 [41]. Compared to metal manufacturing, this process enables the fabrication of composites with enhanced mechanical performance, complex geometries, shorter production cycles, fewer components, and significantly reduced weight. These attributes are ideal for mass production [41]. AFRCMs are manufactured via systematic assembly processes that precisely control fiber alignment, distribution, and interfacial bonding, resulting in enhanced load-bearing capacity and damage tolerance. In contrast to conventional unidirectional or woven composites, AFRCMs utilize multi-scale hierarchical architectures to achieve tailored functional and structural properties. These include laminates, braided structures, and hybrid reinforcements. These strategies allow AFRCMs to achieve exceptional strength-to-weight ratios, impact resistance, and fatigue durability, rendering them ideal for high-performance aerospace, automotive, and civil engineering applications.

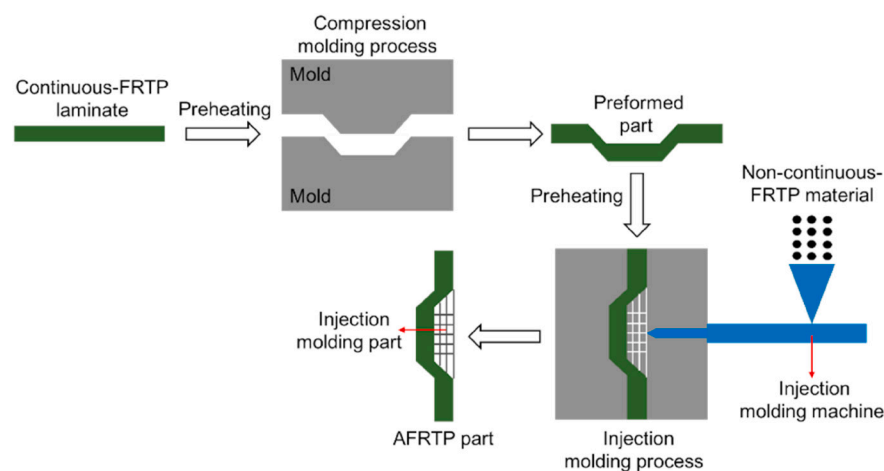


Figure 1-3 Assembly fiber reinforced thermoplastic plastics process flowchart [41].

The development of AFRCMs is further propelled by innovations in advanced manufacturing techniques, including automated fiber placement, additive manufacturing, 3D printing, and tailored fiber preforming [42]. These techniques enable precise control of fiber orientation and composite microstructure, thereby improving mechanical performance and production efficiency. Kroll et al. [40] investigated bonding strength and process parameters for integrating injection-molded short fiber-reinforced ribs with continuous fiber-reinforced thermoplastics. This approach aims to develop structurally rigid assembled composites suitable for industrial-scale production. Their findings demonstrate that optimized process parameters significantly reduce cycle times for producing assembled composite components.

1.2 Manufacturing of tufted reinforcements composite materials

1.2.1 Tufting technology

As illustrated in Figure 1-4, the tufting process involves inserting a tufting needle (such as a hollow needle) through the thickness of the reinforcement and retracting it along the same path. When the tufting needle retracts from the fabric, the tufting yarn was retained in the reinforcement by friction between tufting yarn and reinforcement/supporting materials, and held by the supporting material (e.g. high-density supporting foam). This creates a free loop on the bottom of reinforcement [25,43,44]. Alternatively, the loop can be fully embedded within the reinforcement to meet specific application requirements, such as tufting on reinforcements positioned on rigid molds [45–47]. The process utilizes a single needle to insert tufting yarn with minimal tension, effectively minimizing degradation of the reinforcement's in-plane mechanical properties.

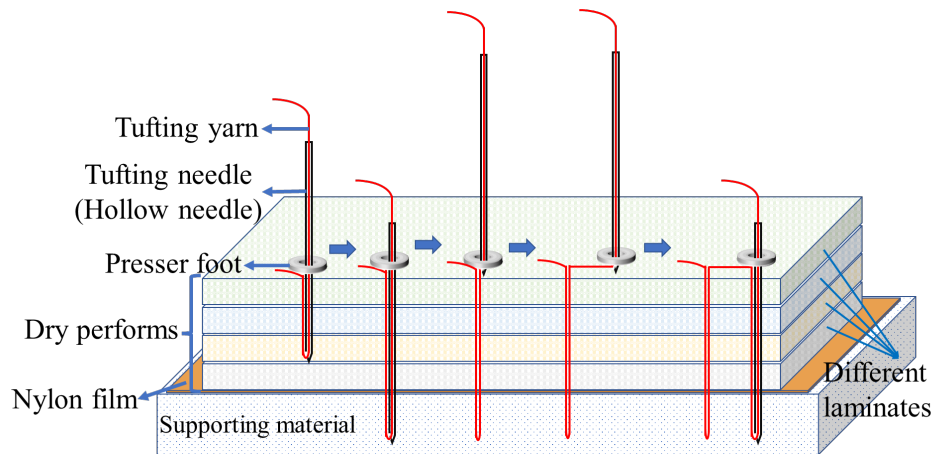


Figure 1-4 Schematic of tufting process.

Tufting equipment typically comprises four primary systems: tufting head system, yarn feed system, movement system, and supporting system. Each system performs distinct functional roles, collectively ensuring process efficiency and operational reliability. The tufting head system is the core mechanism, driving tufting needles through the reinforcement to form loops via the supporting system. It precisely controls needle trajectories to insert tufting yarn at varying depths, while pressure modulation through a presser foot prevents yarn degradation. This mechanism ensures consistent yarn retention, which is essential for maintaining geometric accuracy and process repeatability. The yarn feed system regulates yarn delivery, maintaining precise tension and length consistency throughout the process. This system is crucial for achieving uniform tufting quality by ensuring optimal yarn pretension and length. The movement system facilitates multi-axis positioning of the tufting head, enabling programmable control over tufting density, orientation and pattern. The supporting system stabilizes the reinforcement substrate and secures the yarn within the supporting material. Modern tufting machines combine mechanical linkages, cam mechanisms, and programmable electronic controls to synchronize subsystem operations, ensuring precise stitch characteristics [48–51]. Advanced systems integrate the tufting head with robotic manipulators or CNC platforms, enabling the creation of complex 3D geometries through synchronized multi-axis motion. They also incorporate automated, computer-integrated controls for programmable pattern generation and real-time

parameter optimization [52].

1.2.2 Tufting equipment

(a) Tufting head system

The tufting head system functions as the central component of tufting equipment, executing the tufting operation through the integration of needles, a presser foot, and a multi-shaft drive mechanism [53]. In early-generation tufting heads (e.g., the KSL KL150 in Figure 1-5a), a single motor-driven crank mechanism synchronized needle strokes, presser foot motion, and main shaft oscillation. This mechanism stabilized the presser foot and maintained needle alignment during fabric penetration, ensuring precision in tufts formation [54]. The internal mechanics of the instrument precisely coordinate the relative movements of various components. The tufting speed of these machines reaches up to 500 tufts per minute [12,55]. In contrast, modern tufting head models, such as the KSL RS522 (Figure 1-5b), have replaced belt-driven mechanisms with fully geared systems, where the needle, presser foot, and shafts are independently controlled by three electronic motors. This configuration enables more precise tuft placement and delivers greater power during insertions [56]. These advanced systems can tuft through 10 mm thick, bindered, and highly consolidated fabric, which was previously impossible to penetrate automatically [12].

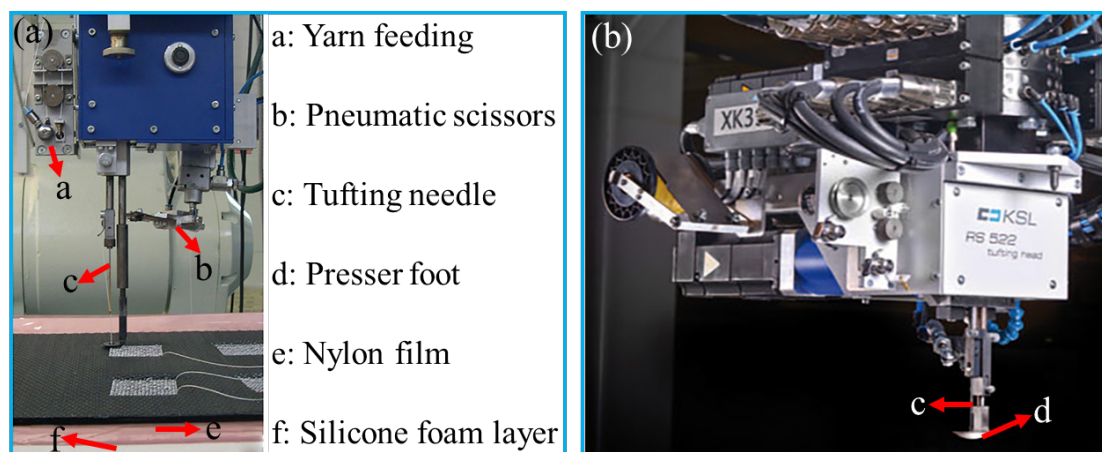


Figure 1-5 Different tufting heads: (a) KSL KL150 [65]; (b) KSL RS522 [75].

(b) Yarn feed system

The yarn feed system consists of yarn guides, tensioners, and feeding mechanisms designed to enhance operational efficiency and process reliability. Before reaching the needle, the yarn follows an extended pathway. Therefore, variations in the needle-to-reinforcement distance cause cyclic flexural deformation in the yarn along its pathway during tufting process [45,53]. Figure 1-6 depicts the cyclic flexural deformation of the yarn pathway during tufting. As the needle advances toward and retracts from the reinforcement, dynamic variations in yarn path length and tension induce cyclic flexural strain. A critical role of the system is to regulate yarn tension, preventing overstretching and loosening, ensuring consistent tufts formation. Precise control of yarn length prior to each tuft insertion is vital for maintaining consistent tuft geometry and reproducible composite quality.

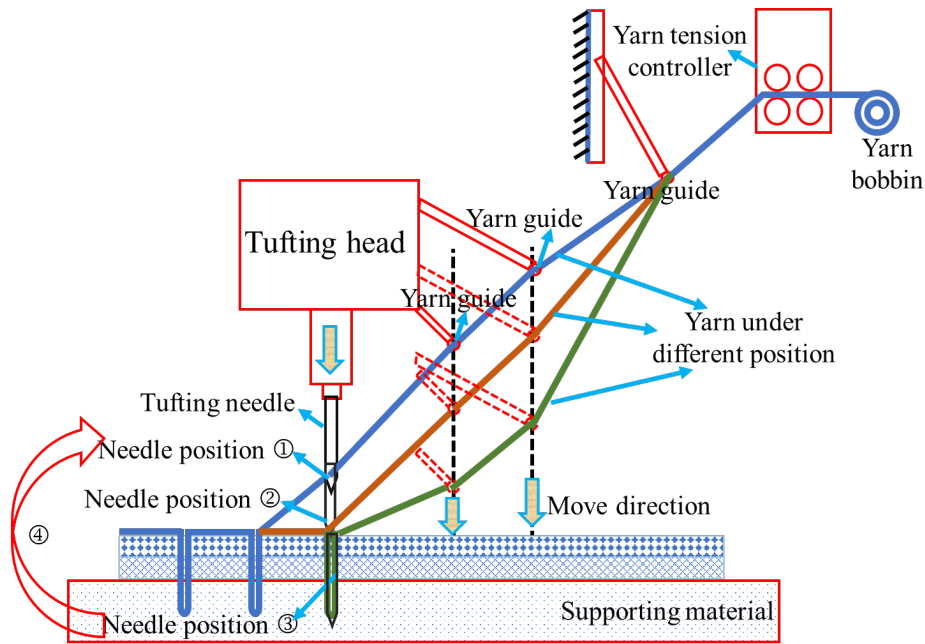


Figure 1-6 Yarn flexing in the yarn path [50].

(c) Movement system

Driven by industrial demand for cost-effective manufacturing solutions, the tufting process has undergone extensive mechanization and automation. Initially, the German Aerospace Centre, in collaboration with industrial partners EADS and KSL, pioneered proprietary tufting head technology for integration into CNC machinery [25].

Following this innovation, CNC machines equipped with tufting heads underwent rapid development. Fig. 9 depicts a modern intelligent CNC tufting machine designed for carpet production [57]. The three-axis gantry design provides a stable operational framework: the X and Y axes facilitate precise spindle positioning, while the Z axis regulates yarn insertion depth [52]. This configuration enables uniform yarn insertion across large fabric surfaces, ensuring consistent production of high-quality tufted textiles. Modern three-axis CNC tufting machines incorporate advanced automation, including automated color change, yarn cutting, and adaptive pattern design systems [44]. These advancements significantly enhance productivity while minimizing manual intervention.



Figure 1-7 Modern carpet CNC tufting machine [57].

For compatibility, precision, and tolerance requirements in aerospace structural composite manufacturing, an automated robotic tufting process has been developed. KSL pioneered the integration of tufting systems with industrial robots, markedly enhancing process efficiency. Coupling KSL's tufting heads with six-axis robotic systems achieves superior flexibility and precision, broadening the scope of tufting applications. These systems are now extensively deployed in laboratory and industrial environments, with tufting operations governed by custom machine language and software protocols. As shown in Figure 1-8a, researchers integrated the KSL RS522 tufting head with a Kuka KR 240-2 robotic arm, employing a fully geared mechanism driven by three servo motors to independently actuate the needle, presser foot, and drive

shafts [12,38]. This configuration ensures micron-level tuft accuracy and delivers enhanced thrust during penetration cycles, significantly improving process efficiency and repeatability. Figure 1-8b demonstrates an industrial application of robotic tufting for bonding stiffeners to carbon fiber reinforced polymer panel. This system integrates tufting into the robotic head and couples it with a multi-axis robotic platform, eliminating geometric constraints on reinforcement dimensions. Under robotic control, these systems achieve tufting angles of 45° - 135° , speeds of 500-1000 tufts per minute, and maximum penetration depths of 40-60 mm [25]. The synergy between tufting heads and robotic systems enhances both process efficiency and precision while enabling novel solutions for manufacturing complex geometries and advanced high-performance materials [11,12,25,55,58].

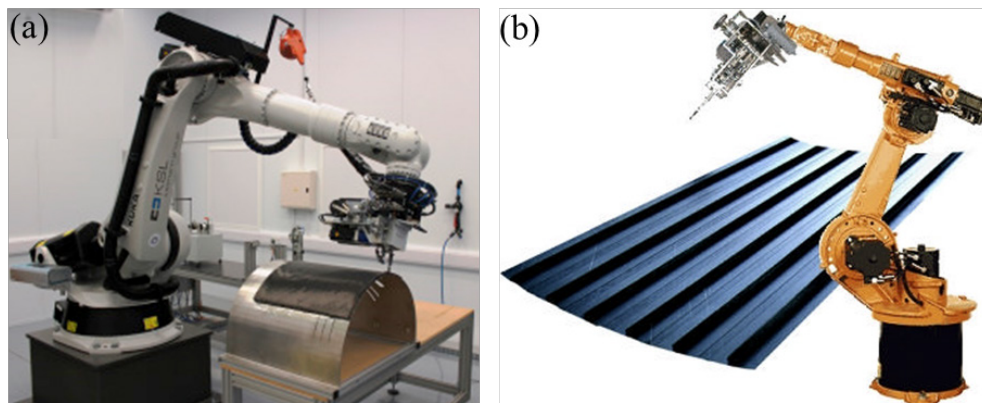


Figure 1-8 Robotic arm: (a) KSL RS522 tufting head and Kuka KR 240-2 robotic arm [12]; (b) Industrial application with a tufting robot to bond stringer on carbon fiber reinforced polymer panels [25].

KSL has pioneered modular functional heads that, when integrated with robotic systems, enable advanced 3D textile processing. As demonstrated in Figure 1-9, the KL 504 model epitomizes KSL's state-of-the-art tufting technology, incorporating multi-axis control and adaptive stitching protocols. The system integrates a KUKA industrial robotic unit within a gantry structure, featuring a six-axis robot with a payload capacity of 6-210 kg and a reach capacity of 0.9-3.1 m. It incorporates supplementary X- and Y-axis positioning units, expanding the operational workspace (X-axis = 6 m; Y-axis = 3.5 m), and integrates a tool-changing system [59]. The system accommodates

lockstitch or two-thread chain-stitch technologies and supports ultrasonic cutting heads for dry fabrics/prepregs, alongside auxiliary heads for metrology and material handling.

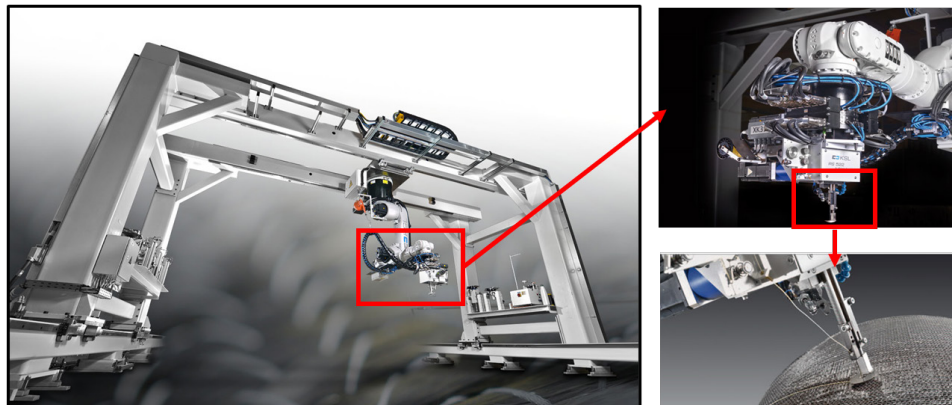


Figure 1-9 Tufting machine based on combinations framework and robotic arm [59].

(d) Supporting system

The supporting system serves to provide stability and support to the entire tufting setup, securely holding the tufting head system, tufting yarn feed system, control panels, and any other necessary components in place during operation. An essential component of the supporting system is the supporting materials, rigid supporting mould and soft supporting moulds, which primarily provide friction to form the tufting loops.

Rigid supporting molds serve as a stable platform for securing base fabrics during tufting operations. Their geometry (flat or curved) is determined by structural design requirements. Flat molds are employed for planar geometries (Figure 1-10a), whereas curved molds accommodate complex 3D contours (Figure 1-10b). These molds ensure precise alignment of the tufting head, enhancing positional accuracy and reducing process deviations. Fabricated from high-strength materials such as steel or aluminum, these molds resist needle penetration forces while preserving dimensional stability. However, their elevated machining costs, stringent maintenance requirements, and restricted design adaptability impose significant economic constraints. Nevertheless, their exceptional wear resistance ensures extended operational longevity, rendering them particularly suitable for high-volume industrial applications.

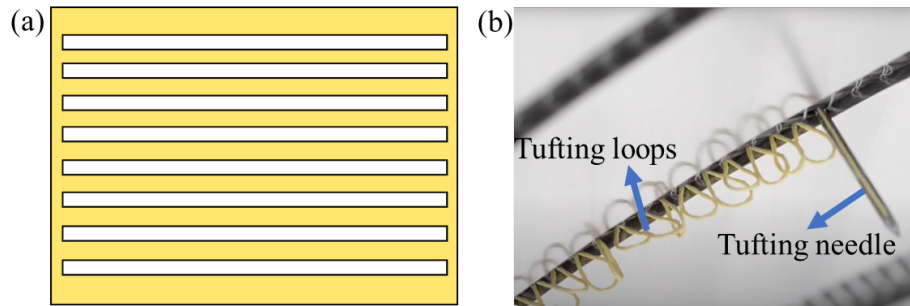


Figure 1-10 Rigid supporting mould: (a) Flat moulds; (b) Back of curved moulds [59].

Figure 1-11 illustrates the soft supporting molds commonly used in the tufting process, including foam, felt, rubber, and silicone. The exceptional elasticity of these materials enables multiple reuses of a single pad due to self-healing puncture closure upon needle retraction [12]. A nylon film placed between the backing layer and the preform facilitates the removal of loops once thread insertion is complete. The pad is typically discarded after without elasticity due to the numerous needle-punched holes created during the process. Careful selection of backing materials is critical, as incompatibility with the tufting yarn/preform system may result in irregular loop geometry or failed stitch insertion. Inadequate interfacial adhesion in the backing substrate can cause yarn retraction post-insertion, producing void regions devoid of loops [12].

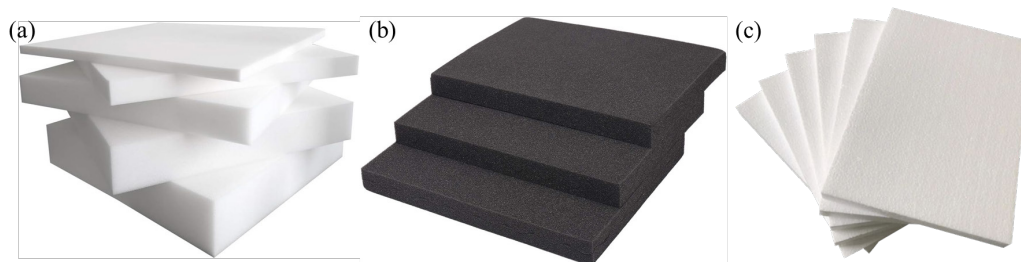


Figure 1-11 Supporting foam: (a) Rigid polyurethane foam sheets; (b) Eggshell foam black sheets; (c) Normal polyurethane foam sheets.

1.2.3 Parameters of tufting process

Tufting parameters are critical factors governing the fabrication of tufted composites. They determine the material's aesthetic, structural, and mechanical properties. These key parameters play a fundamental role in determining the composite material's

performance characteristics. These include tufting spacing and density, tufting pattern, tufting angle and length, as well as tufting loop [60].

(a) Tufting space and density

Tufting space refers to the gap or distance between individual tufts in a tufted reinforcement, which is the measure of the distance between two tufting points on the surface [36]. Figure 1-12a illustrates a schematic representation of various tufting spacings. This parameter is crucial in tufting processes, as it significantly impacts the overall appearance, durability, and performance of the tufted reinforcement. The tufting seam refers to the yarn visible on the reinforcement surface, forming a loop on one side between two tufting points. Typically, the tufting seam is longer than the tufting spacing due to the bending of the tufting yarn. The distinction between tufting seam and tufting spacing is depicted in Figure 1-12b. Therefore, position the tufting seam as close as possible to the fabric substrate.

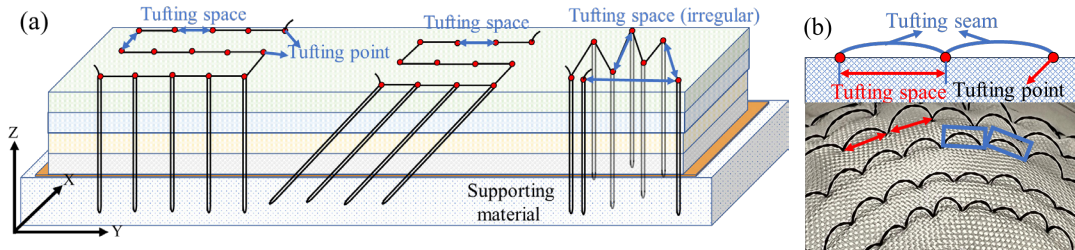


Figure 1-12 The schematic of tufting space: (a) Tufting space; (b) Tufting seam.

Tufting spacing directly governs the areal density of the tufted textile. This relationship exhibits an inverse proportionality: increased tufting spacing reduces tufting density. Normally, manufacturers strategically modulate tufting space to achieve target tufting density thresholds aligned with performance. Tufting density is defined as the tuft count per unit area, expressed in tufts per square centimeter (tufts/cm²) or tufts per square meter (tufts/m²). Critically, this metric refers exclusively to the tufted regions, excluding non-tufted areas. The Tufting density is calculated as follow the Eq.(1-1):

$$\text{Tufting density} = \frac{\text{Total number of tufts}}{\text{Tufting area}} \quad (\text{tufts/m}^2) \quad (1-1)$$

(b) Tufting pattern

The tufting pattern is defined by the orientation and alignment of tufting yarns on the textile surface [17]. It determines the arrangement of yarns during the tufting process, influencing the visual appearance and texture of the final product or reinforcement. Variations in tufting direction depend on design considerations, production techniques, and aesthetic preferences. Common tufting directions include straight, random, and spiral tufting, as illustrated in Figure 1-13. Tufts may be arranged in diverse patterns such as geometric or floral motifs. This flexibility allows for the creation of intricate, customized designs with specific tufting patterns. Additionally, a multidirectional tufting pattern enhances composite stability by promoting a more uniform distribution of deformation within the material [61].

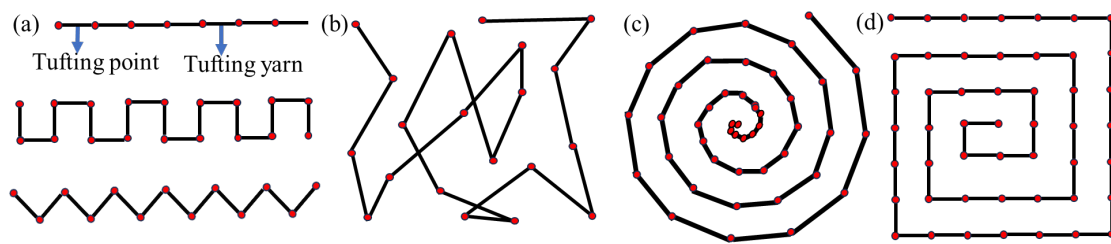


Figure 1-13 Tufting patterns: (a) Straight tufting; (b) Random tufting; (c) Circle spiral tufting; (d) Square spiral tufting.

(c) Tufting angle and length

The tufting angle refers to the angle at which tufts or loops are inserted into the reinforcement and support materials during the tufting process. It represents the angle of penetration by the tufting needles into the support material. This angle defines the orientation of the tufting loops. Figure 1-14 illustrates the tufting angles along the Y-Z axis. When the needle is inserted in the direction opposing the tufting process, the tufting angle equals the angle between the needle and the reinforcement's normal plane [62]. Conversely, when aligned with the process direction, the tufting angle equals the sum of 90° and the angle between the needle and the normal plane. This difference in angle calculation, based on the needle's insertion direction, is essential to comprehend how its movement relative to the process influences the resulting angle.

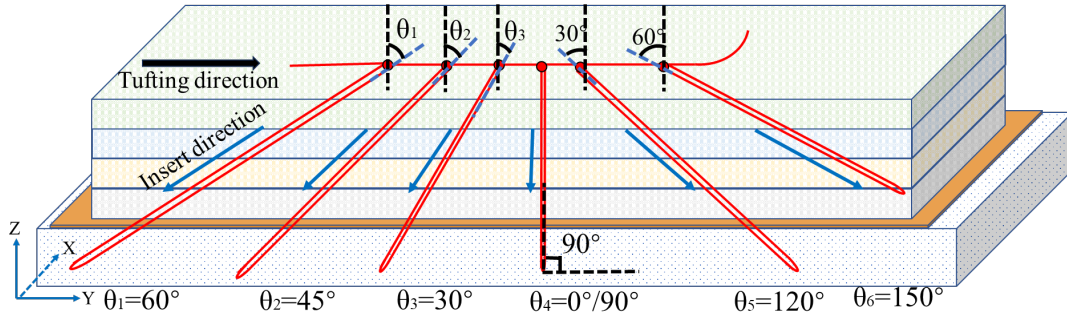


Figure 1-14 Different tufting angles in the tufting process.

Tufting length indicates the height of the tufts or yarn loops projecting from the support material in a tufted composite. It differs based on tow insertion method: full insertion (Figure 1-15a) or partial insertion into the reinforcement (Figure 1-15b). In full insertion, the tufting yarn creates a loop on the underside, anchored by the support material. Consequently, tufting length comprises the reinforcement thickness plus the loop length. In contrast, with partial insertion, tufting length corresponds to the tow length, yet is less than the reinforcement thickness. With an introduced tufting angle, tufting length matches the thread length within the reinforcement, as illustrated in Figure 1-15c.

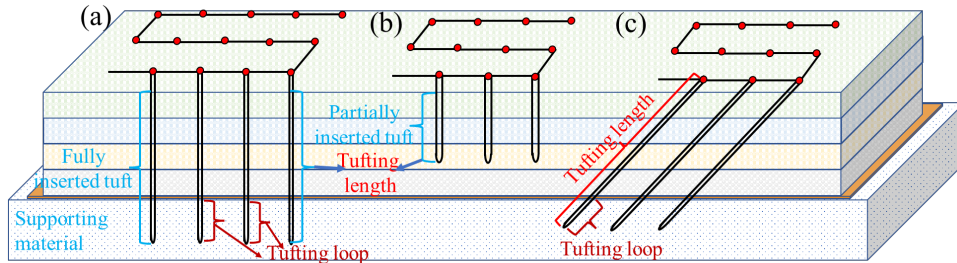


Figure 1-15 Tufting length: (a) Fully inserted tuft; (b) Partially inserted tuft; (c)

Tufting length with a tufting angle.

(d) Tufting loops

In the tufting process, loops are created by passing tufting yarn through a supporting material using tufting machines equipped with tufting needles. This results in loops embedded within the supporting material, as shown in Figure 1-16a. There are two primary types of tufting loops. In the first type, loops remain intact, forming a continuous pattern across the textile surface, as illustrated in Figure 1-16b. This method

produces a textured surface. In the second type, loops formed during the process are cut to create individual tufts, as shown in Figure 1-16c, resulting in a softer, plush surface with a thick pile. Figure 1-16d presents the underside of a tufted reinforcement after the loops have been cut.

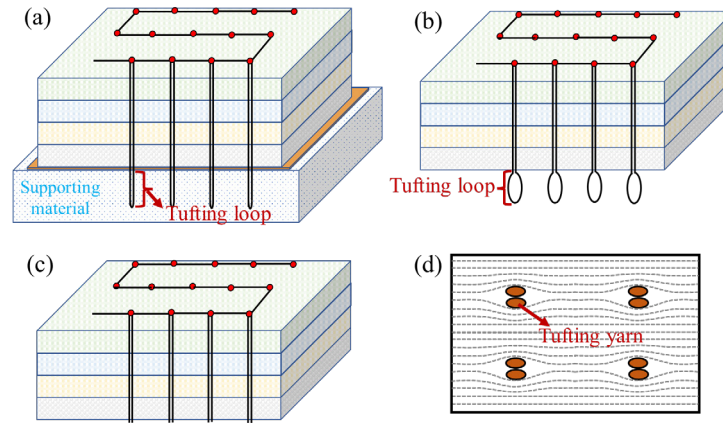


Figure 1-16 Tufting loop: (a) Tufting loops in the supporting material; (b) Loop pile; (c) Cut pile; (d) The bottom of cut pile.

Tufting loops may be extracted prior to resin infusion or preserved, based on the composite's intended application. The length of the tufting loop depends linearly on needle penetration depth, irrespective of whether the loop is formed within the preform thickness or the support material. Greater needle penetration depth results in longer tufting loops. Dell'Anno et al. [45] demonstrated that retained tufting loops produce a resin-rich layer (< 0.5 mm thick) containing flattened loops on cured panels, possibly affecting bending stiffness. Conversely, Hertley et al. [63] and Hu et al. [36] demonstrated minimal effects of loop length variation (assessed under quasi-static and dynamic compression) or loop removal on energy absorption and fracture strength, respectively. Together, these findings indicate that tufting loops exert limited mechanical influence, emphasizing their contribution to application-specific design factors (e.g., durability, aesthetics) rather than structural properties, thus informing industrial selection of loop or cut pile methods.

1.3 Tufting-induced damage

Tufting effectively enhances the mechanical properties of composites in the through-

thickness direction. However, the tufting process often causes damage to the fabric and tufting yarn. Such damage compromises the mechanical performance of both the tufted composite and preform. This section examines the damage resulting from the tufting process.

1.3.1 At the fabric scale

During the tufting process, multiple types of fabric damage may arise, impacting the quality and properties of the final composite. In dense fabrics, puncture holes created by the tufting needle may enlarge if the needle is overly sharp or the fabric is thin, resulting in noticeable defects. Additionally, the tension from the tufting yarn may stretch the fabric near tufted areas, producing an uneven surface and possibly altering the pattern, as presented in Figure 1-12a. On the underside of the preform, the tufting puncture hole exhibits a markedly irregular surface and greater fiber breakage relative to the upper side (Figure 1-12b). High yarn tension can cause localized damage, such as tears or strain, at the thread anchorage points. Furthermore, the insert of tufting yarn into the composite's upper surface causes crimping in the outer fabric plies, with warp angles up to 6.5° from the surface plane. This inconsistent tension and pressure during tufting may distort the fabric, further undermining structural integrity.

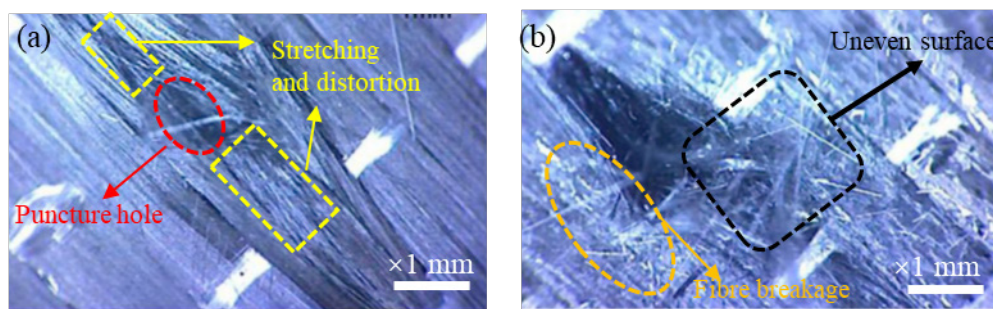


Figure 1-17 Typical image of damage in the carbon preforms [64]: (a) Yarn on the upper tufted reinforcement; (b) Yarn on the underside tufted reinforcement.

When loosely woven dry preforms are employed, needle size exerts little influence on fiber breakage, as the fibers can displace to accommodate the needle, damaging only a few filaments. However, substantial fiber damage is probable when tufting densely binded preforms, potentially diminishing the strength of the final composite [12,65].

However, reveal variability in findings across different studies, varying from reported strength reductions to no discernible change, with some studies claiming increases of 15–20% [66].

The tufting needle's design is crucial for minimizing fabric damage. A sharp and smooth needle tip effectively reduces friction with reinforcement fibers during insertion. It also limits in-plane fiber damage by sliding through fibers rather than piercing them, thereby maintaining the reinforcement's structural integrity. The needle tip wears with repeated insertions. Thus, prompt replacement of worn needles is vital to ensure the quality of tufted reinforcements, particularly with thicker and denser materials.

1.3.2 At the yarn scale

During the tufting process, tufting yarn may sustain various forms of damage, impacting its integrity and the material's quality. Common damage includes breaking, wearing, and untwisting [49,61]. Breaking frequently occurs, particularly with thicker preforms or dull needles, leading to tufting yarn rupture. For example, carbon yarn may experience localized breaking under high curvature within the needle eye due to the brittleness of carbon filaments, especially in densely packed fabric reinforcements [55]. The small tufting needle tip requires the tufting yarn to resist bending without damage. Fragile carbon fibers may fracture at the needle tip. Carbon yarn damage was noted at both noncritical surface loops (Figure 1-18a) and the needle entry point, as shown in Figure 1-18b [55]. Additionally, wearing results inevitably from friction between the tufting yarn and the needle or preform. That's leading to the yarn strength and durability decline as preform thickness increases. Lastly, untwisting may occur as tufting yarn is drawn through, leading to irregular yarn and loops that undermine the uniformity and structural integrity of the tufted composite [48].

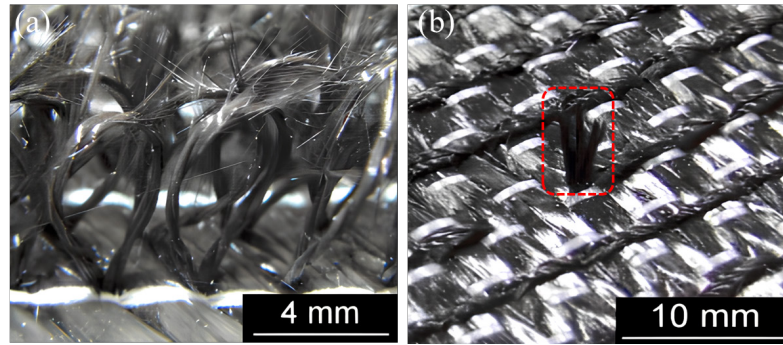


Figure 1-18 Tufting defects of tufting yarn [12]: (a) Yarn damage in tufting loops; (b) Yarn rupture in tufting seam.

The potential degradation of tufting yarn due to interfacial friction was investigated by Liu et al. [67] and Rudov-Clark et al. [68], they suggested that such damage could compromise the strength of tufted composites. To mitigate this, Chan et al. [48] introduced a two-step tufting method using a guide needle for pre-insertion (two-step tufted), significantly reducing yarn damage. Figure 1-19a illustrates the differences between non-inserted, inserted, and two-step tufted yarn at a 3.0 mm tufting density, while Figure 1-19b confirms the method's effectiveness in minimizing degradation. Strategies to further reduce damage include optimizing needle design, such as adjusting diameter and tip geometry, to enhance penetration and reduce breakage. Additionally, selecting yarns with high tensile strength and abrasion resistance, such as synthetic or treated natural fibers, can help improve durability. Moreover, controlling tufting speed and tension is essential to limit elongation and breakage. And a compact yarn structure via twisting also enhances resistance to friction and abrasion.

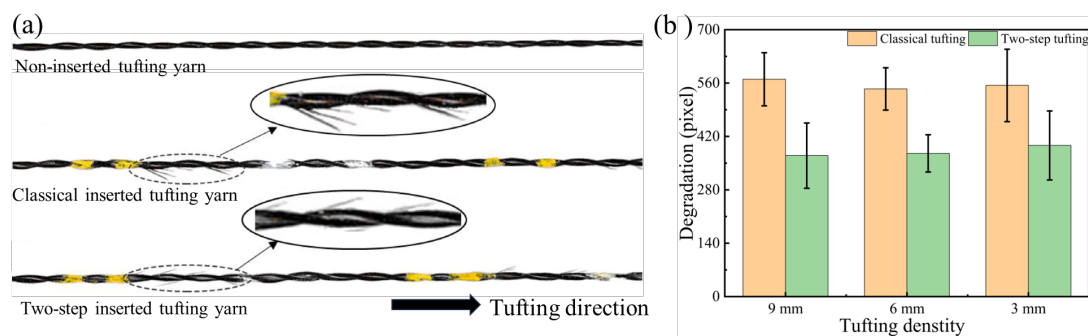


Figure 1-19 Improvement of tufted yarn [48]: (a) Two-step tufting method; (b) Comparison of the tufting yarn degradation.

1.4 Forming of tufted preforms

The main objective of textile forming is to convert fabric into 3D shapes, typically accomplished via processes like stamping and compression forming. This chapter seeks to provide an overview of the tufting processes applied on textile forming.

1.4.1 Textile reinforcements forming process

Textile forming denotes the process of shaping textile reinforcements into targeted shapes or structures. During forming, textile reinforcements are manipulated using mechanical force, heat, pressure, or their combination to achieve the desired shape or structure. The primary objective of forming is to create preforms with specific shapes, properties, and functionalities tailored to their intended applications [69–71]. The formability of reinforcement, which is influenced by its material composition, structural configuration, layer count and so on [72,73]. The parameters of the forming process are also important factors influencing the formability of reinforcement, such as punch geometry, forming pressure, tension and speed [74–76]. These factors are also influenced by additional variables, making the formability more complex. For example, the punch geometry comprises edge radii, inclination, curvature, and other related factors [77–79]. Figure 1-20 depicts the textile forming devices in the laboratory. Producing defect-free complex preforms remains challenging [37,80,81]. Despite numerous studies that have been carried out, completely eliminating defects in complex shape forming remains difficult. Forming defects, such as wrinkling, buckling, and yarn sliding, readily occur during high-curvature forming processes. Thus, investigating reinforcement forming processes enhances understanding of defect mechanisms.

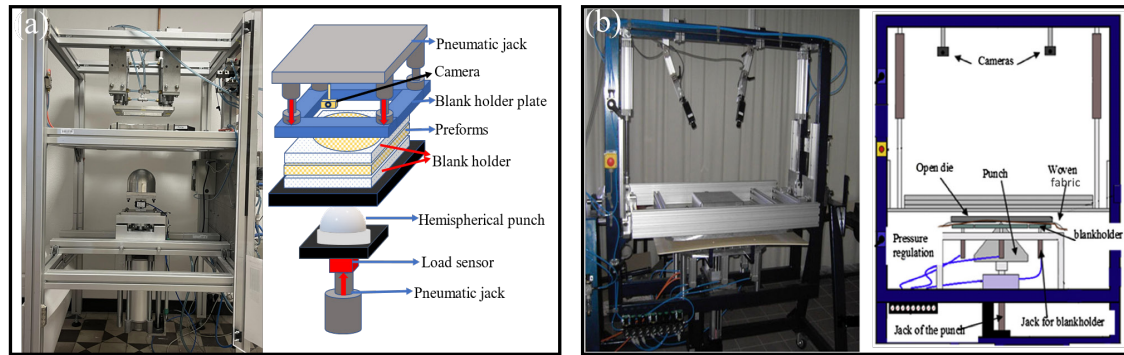
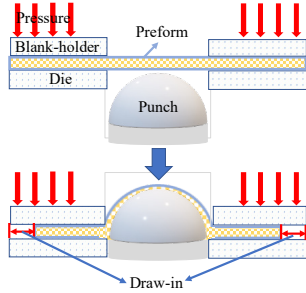
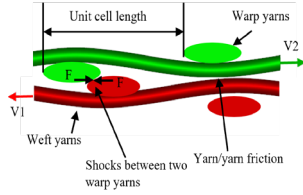
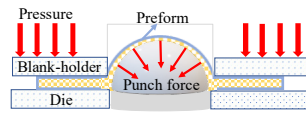
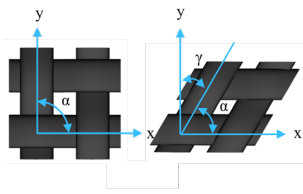


Figure 1-20 Forming device: (a) GEMTEX laboratory [82]; (b) University of Orléans [83].

1.4.2 Deformability of tufted preforms

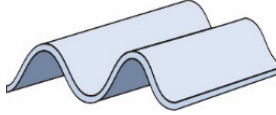
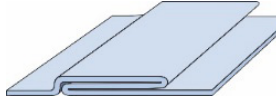
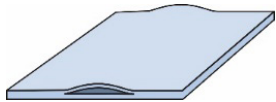
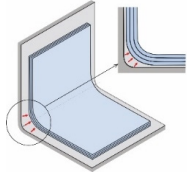
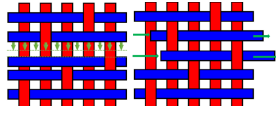
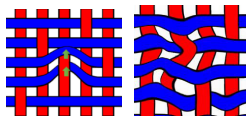
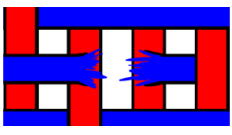
Assessing forming performance is critically important, as precise characterization provides key insights for optimizing textile forming processes. Extensive research has significantly improved forming defect mitigation, particularly in wrinkles [84,85]. However, the complete elimination of forming defects remains neither feasible nor economically viable. Systematic defect characterization supports the establishment of robust acceptance-rejection criteria for composite components with imperfections [17,86,87]. Currently, establishing a reasonable tolerance for wrinkles is considered a more practical approach, as it balances manufacturing efficiency, cost-effectiveness, and product performance [88]. However, tufting demonstrates an alternative pathway by directly modifying the formability of tufted preforms and actively removing/ameliorating forming defects [17,18]. Table 1-1 summarizes key performance indicators, defect evaluation frameworks, and tufting-induced effects on forming outcomes.

Table 1-1 Evaluation of forming performance

Characterizes	Definition	Schematic	Influence by tufting
Material draw-in [76]	When the fabric deforms out-of-plane taking the shape of a waved curve that can vary in length, number and magnitude.		The material draw-in decreases with the increasing of tufting points [18].
Inter-layer sliding [89]	When the fabric deforms into an out-of-plane curved shape, similar to the described wrinkles mechanism, the two sides of the curve overlap, locally multiplying the fabric's thickness.		The inter-layer sliding can be much reduced owing to the increase of tufting points (tufting density).
Punch force [18]	The punch force is captured by a load sensor, which can be confirmed by the observation of the punch load to describe the preform deform.		The preforms become more rigid and are more difficult to be deformed along with the increase of tufting points [18].
Shear angle [90]	When forming a curved concave form, the material retreats in a corner and the fabric is no longer in contact with the shaping form and stay suspended mid-air.		Tufting influences the shear angle by restricting shear deformation, increasing in-plane shear stiffness, altering shear angle distribution [90].

The inextensibility of preforms along the fiber direction complicates forming complex shapes without inducing distortions or out-of-plane buckling, known as wrinkling. Diverse forming defects may compromise preform structural uniformity, potentially impairing the composite material's performance through localized heterogeneities. Optimizing the forming process to reduce defects occurrence is a widely studied aspect of composite manufacturing. Hence, understanding the types and causes of forming defects is essential. Forming defects are categorized into two primary types based on their scale: out-of-plane defects [91,92] and in-plane defects [83,93–95]. Table 1-2 presents the definitions, schematics of these defects and influence by tufting.

Table 1-2 Forming defects

Terminology	Definition	Schematic	Influence by tufting
Out-of-plane defects			
Wrinkling [92,95,96]	When the fabric deforms out-of-plane taking the shape of a waved curve that can vary in length, number and magnitude.		The shape of wrinkles was more regular and the size of wrinkles was strongly reduced.
Folding [97,98]	When the fabric deforms in an out-of-plane curved form, identical to the “wrinkling” mechanism described, the two sides of the curves will fall, one on the other, multiplying the thickness of the fabric locally.		Almost avoid folds
Buckling [99,100]	When the shifting of the fibre position out-of-plane is randomly creating an irregular yarns pattern distribution in the multi-layer preform.		Reducing the buckles and decreasing the length of buckles
Bridging [79,101]	When forming a curved concave form, the material retreats in a corner and the fabric is no longer in contact with the shaping form and stays suspended mid-air.		Reducing the curved degree of bridging
In-plane defects			
Yarn sliding [79]	The yarns slide from their initial position to another following their longitudinal or perpendicular direction.		Reducing the yarn sliding with the increase of tufting density
Yarn misalignment [79]	When the yarns are curved locally in plane, and the yarns are unparallel		Reducing the yarn misalignment
Yarn rupture [79]	By applying high tensile stress on the yarn, higher than its maximum resistant stress, it will break the fibre.		Increasing the yarn rupture due to the insertion of tufting yarn

Tufting reduces wrinkles and inter-layer sliding by enhancing through-thickness reinforcement, where tufting yarns fix fiber crossover points to stabilize fabric deformation [18,82,102,103]. This process improves formability through controlled shear resistance (regulated by tufting density/yarn fineness) and optimized buckling control when tufting patterns align with punch geometry. While effective for wrinkle suppression and void elimination between tufting points (Figure 1-21a and Figure

1-21b), improper patterns may induce corner buckling in angular shapes. The technique's defect mitigation relies on strategic parameter selection: tufting density, thread material, and tufting pattern (Figure 1-21c) critically balance in-plane/out-of-plane performance for uniform deformation [82].

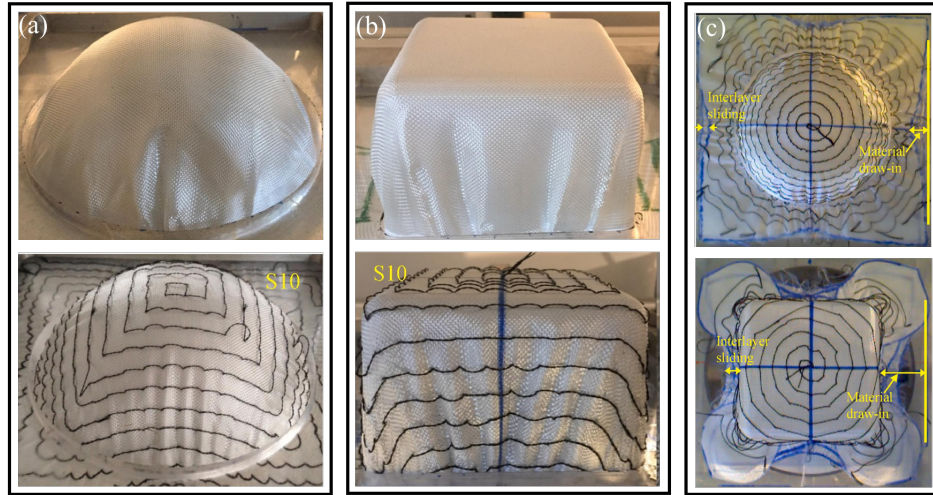


Figure 1-21 Deformed tufted preforms after forming [18]: (a) Hemispherical forming; (b) Square-box forming; (c) Tufting reduce the interlayer sliding.

1.4.3 Mechanical characterization of tufted preforms

Significant efforts have been devoted to quantifying the mechanical properties of textile preforms to investigate the influence factors of forming defects. The ability of textile reinforcements to form complex shapes mainly depends on the in-plane shear stiffness, bending stiffness and tension, which collectively influence wrinkle formation [76,90]. Furthermore, friction between textile preforms and the mold, encompassing fabric-to-fabric and fabric-to-tool interactions, markedly affects forming quality. Figure 1-22 presents a schematic of the mechanical properties addressed in the literature for the selected macroscopic model. The precision of forming simulations hinges on the model's comprehensiveness. Incorporating more forming parameters and material characteristics enhances the detail and precision of simulation outcomes [77,104]. Table 1-3 summarizes the experimental methods used to characterize materials in simulations, providing insights into preform mechanical properties.

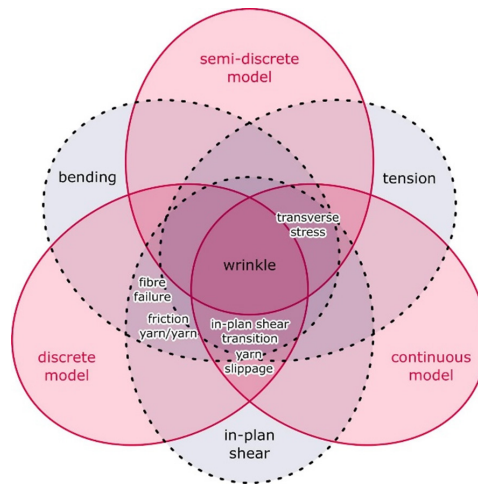
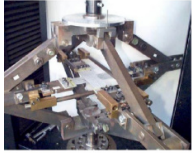
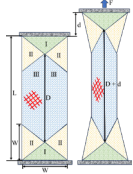
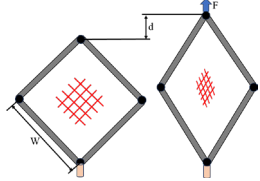
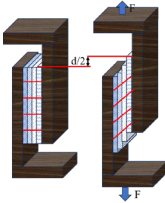
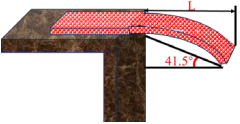
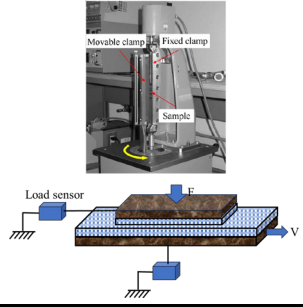


Figure 1-22 View of the considered behaviors in the literature regarding the chosen macroscopic model [104].

Table 1-3 Material characterization for preforms

Properties	Test	Description of test	Picture
In-plane tension	Uniaxial tensile test [105]	To characterize the coupling between warp and weft yarn directions, biaxial tension tests are performed using a device capable of simultaneously stretching in both directions.	
	Bias extension test [72]	A rectangular sample is clamped at both ends, with the warp and weft yarns oriented at a 45° relative to the direction of the applied tensile load.	
In-plane shearing	Picture frame test [106]	The picture frame is made with a deformable frame that (ideally) prescribes a uniform shear strain field. The textile sample is clamped into the frame.	
	Uniaxial tensile test [107]	Two parallel plates were fixed to the sample and pure shear strain was imposed on the specimen. The transverse shear strain energy density function then was built based on the transverse shear strain.	
Bending behaviour	Three-point bending test [108]	The sample involves applying a load at a single central point on a material sample supported at two ends.	
	Standard cantilever test [109]	The fabric is cantilevered under gravity and the overhang length is usually determined by the bending angle, which is 41.5°.	

	Kawabata bending test [110]	The sample was clamped between a fixed and movable clamp. During the test, the movable clamp rotates around the fixed clamp to impose a pure bending on the sample.	
Friction	Pull-out friction test [111]	Reinforcement was clamped between two heated pressure plates and then pulled out.	

Current research remains sparse on the mechanical characterization of tufted preforms prior to resin infusion. Shen et al. [90] systematically investigated the in-plane shear behavior during the forming of tufted carbon woven fabrics, as presented in Figure 1-23. Their findings demonstrated that vertical tuft alignment (parallel to tensile loading), higher tuft density, and larger yarn diameters significantly enhance in-plane shear resistance. Furthermore, the study identified a measurable impact of tufting parameters on bending behavior. Higher tufting density was shown to elevate flexural rigidity, effectively mitigating wrinkle formation during forming. Critically, the bending response of tufted preforms exhibits nonlinear behavior, diverging fundamentally from non-tufted 2D textile architectures.

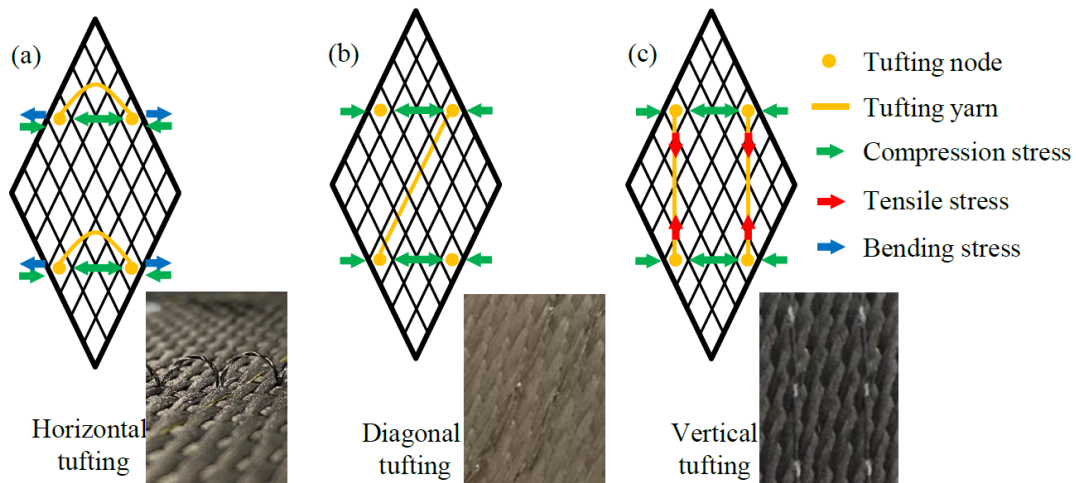


Figure 1-23 Schematic of mechanical mechanisms in tufted fabrics [90]: (a) Horizontal tufting; (b) Diagonal tufting; (c) Vertical tufting.

1.4.4 Numerical simulation of tufted 3D preforms' forming

Numerical simulation of textile reinforcement forming is widely utilized, as it significantly reduces both the time and cost associated with optimizing processing

parameters [77]. Forming simulation plays a crucial role in predicting changes in fabric orientation and detecting potential forming defects. Simulation models operate across three distinct scales: microscopic (fiber scale), mesoscopic (yarn scale), and macroscopic (fabric scale). Among these, the macroscopic scale is the most commonly employed for forming simulations. Macroscopic model simulations are instrumental in analyzing dry fabric behavior under in-plane deformations (tension, compression, and shear) and out-of-plane deformation (bending) [112,113]. Additionally, both microscopic and mesoscopic models are used to simulate changes in fiber orientation, yarn sliding, wrinkling and shear angle. Table 1-4 provides references to recent textile forming simulations, focusing on methods for analyzing wrinkle appearance and reduction. This focus is essential for identifying the underlying factors contributing to wrinkle formation and developing effective mitigation strategies, thereby improving the quality and consistency of textile composite materials.

Table 1-4 Simulation of various fabrics during the forming process

Preforms	Scales	Constitutive laws	Finite element types	Characterizations	Validation shape
Glass plain weave Fabric [114,115]	Mesoscopic	Hypoplastic	Three node shell + inter-yarn contact	Tension, in-plane shear, bending stiffness	Cylindrical, tetrahedron
Woven fabrics [116]	Macroscopic	Non-linear hyperelastic	Stress-strain shell	Biaxial tension, compression, normal strain-dependent shear behaviour	Generic double dome
Woven continuous carbon fabric [117]	Macroscopic	Hypoelastic + hysteretic	Shell + rotation-free element of type S3 + specific deformation modes	In-plane shear stiffness, out-of-plane bending stiffness	Hemisphere, Four-branch cross shape, T-shape
Carbon reinforcement fabric [118]	Macroscopic + Mesoscopic	Hypoelastic	Stress resultant shell+ specific deformation modes+inter-layer contact algorithm	Bending stiffness, tension and in-plane shear, bending stiffness	Tetrahedral, hemispherical
Non-orthogonal braided fabrics [119]	Macroscopic + Mesoscopic	Hyperelastic	Strain shell+ specific shear angle algorithm	Tensile tension, in-plane shear stiffness	Bias-extension test, hemispherical

Stitched biaxial fabrics [120]	Macroscopic + Mesoscopic	Fabric: hyperelastic Stitching thread: elastic	Shell+Rod+inter-layer contact algorithm +fabric-thread contact algorithm	Fabrics: tension, in-plane shear, friction Stitching thread: tensile stiffness Fabrics: tension, stress, transverse in-plane compression loading, in-plane shear, bending stiffness	Hemispherical
Stitched unidirectional non-crimp fabrics [121]	Macroscopic	Non-linear elastic	Shell + Rod + inter-layer contact algorithm + fabric-thread contact algorithm	Fabrics: tension, in-plane compression loading, in-plane shear, bending stiffness	Hemispherical
Tufted multilayer composite preform [19]	Macroscopic + Mesoscopic	Fabrics: hyperelastic Tufting yarn: elastic	Fabrics: stress resultant shells + rod Tufting yarn: rod +Sliding thread method)	Fabrics: tension, in-plane shear, bending, friction Tufting yarn: tension, bending	Hemispherical

Existing simulations focus predominantly on stitched composites rather than tufted preforms [122,123]. Limited studies specifically address tufted preform forming simulations, which need to consider the deformation brought by the presence of the tufting yarns and their possible slippage [19]. Developing accurate tufted preform models also requires accounting for bending stiffness and tension of tufting yarn. Integrated simulation-experimental analysis enables parameter optimization to prevent forming defects while balancing structural performance.

1.5 Conclusion

Continuous fiber-reinforced composite materials have emerged due to their exceptional strength-to-weight ratios, tailored anisotropic mechanical properties, and resistance to environmental degradation. LCM process is widely recognized for its superior manufacturing capabilities in continuous fiber-reinforced composite materials. Forming or preforming is the first step for the LCM process, which often lead to forming defects including wrinkling, buckling, and yarn misalignment, decreasing the structural integrity and performance of composites. Fortunately, tufting demonstrates an alternative pathway by directly modifying the formability of tufted preforms and actively removing/ameliorating forming defects.

Chapter 2 specifically focuses on elucidating how controlled slitting and tufting

synergistically regulate continuous deformation field evolution in woven fabric. This study systematically investigates the influence of slitting configuration and tufting patterns on the in-plane shear response of glass woven fabrics through standardized picture frame test.

Chapter 3 aims to investigate the evolution of in-plane shear stiffness and wrinkle formation across various slitting structures. This will enhance our understanding of selecting appropriate slitting positions and optimizing the preforming process. Various slitting locations, corresponding with ply orientations, were assessed to determine their influence on preform formability.

Chapter 4, slitting is carried out to disrupt the continuous shearing field, while tufting is used to replace yarn tension with in-plane shearing, thereby preventing further damage caused by slitting. this chapter aims to investigate the impact of changes in the continuous deformation field on the forming behavior of woven preforms.

Chapter 5, to evaluate the feasibility of fabric scrap assembly by tufting, two types of fabric scraps with distinct geometries (rectangular and triangular units) were assembled into square preforms, followed by hemispherical forming. The forming behaviours were systematically analysed through punch force, materials draw-in, in-plane shear angle and wrinkles amplitude.

2. Investigation of in-plane shear deformation mechanisms

2.1 Introduction

A large number of composite products are manufactured through the forming process due to the efficiency and stability. Textile composites have demonstrated their great potential as a viable alternative to metal sheet for high-strength and low-weight products [7,124–126]. Extensive research has systematically investigated both the intrinsic material properties and forming characteristics of these composites [17,77,127–129]. However, the complexity arising from the diversity of materials, fabric architectures, and the evolution of properties induced by processing necessitates the adoption of advanced design methods [83,130]. Simulations serve as pivotal tools for manufacturing optimization via parametric studies of tooling designs, material selections, and operational parameters [19,92,108,115]. As know, the reliability of these simulation hinges on the input of a proper material constitutive law and the associated parameters. Incorporating more forming parameters and material characteristics enhances the detail and precision of simulation outcomes [104]. This makes standard material testing methods essential to understanding the effects of material and process variables (e.g., weave pattern, temperature, rate, binder pressure) on formability, and to providing input data and validation data for simulations [77].

During the forming stage, in-plane shearing of the textile is one of main deformation mode. A bias extension test and picture frame test are the two main experiments used to measure in-plane shear property for the textile [85,131–134]. The bias extension test is essentially a uni-axial extension test with the dimension of the test sample in the loading direction relatively greater than the width, and the yarns initially oriented at $\pm 45^\circ$ to the loading direction [72,90]. The advantage of picture frame test stems from generating controlled homogeneous shear strain fields while minimizing parasitic tensile effects. It also provides a more uniform in-plane shear deformation, minimizing edge effects and ensuring consistent fiber alignment [133,135]. Additionally, picture

frame test closely simulates the actual shear conditions experienced in composite manufacturing, making it a more representative and practical testing method [136]. Hence, the picture frame test provides a more reliable method for obtaining the pure in-plane shear behavior of textile. Therefore, this test will be the focus of the work presented here.

The slitting process involves creating geometrically controlled incisions in fabric materials to generate continuous linear discontinuities, enhancing localized flexibility and facilitating efficient shaping of structural components [137]. The determination of slitting positions requires strict adherence to deformation criteria ensuring edge integrity preservation in functional zones (useful zone) post-processing. Unconstrained slit edges in large-scale geometrically complex forming processes exhibit pronounced susceptibility to warp/weft directional elongation, compromising dimensional stability in functional zones. This limitation necessitates the implementation of edge constraint mechanisms during slitting process. Tufting technology has emerged as a promising method for pre-assembly processes and through-thickness reinforcement in composite manufacturing. Shen et al. [90] revealed that selecting appropriate in-plane tufting yarn directions and optimizing the number of tufting yarns per unit cell within the woven reinforcement effectively suppresses defect formation during in-plane shear deformation. Building upon these foundational studies, this chapter proposes an innovative methodology combining precision slitting and optimized tufting parameters to modulate in-plane shear behavior.

This chapter systematically investigates the influence of slitting parameters and tufting parameters on the in-plane shear properties of textile preforms, employing the picture frame test. The evolution of in-plane shear angles is quantified using optical measurement based on vision algorithms. Furthermore, elucidating the underlying mechanisms responsible for the observed variations in-plane shear response among specimens fabricated with distinct slitting and tufting configurations.

2.2 Materials and methods

2.2.1 Materials

The materials employed in this study include continuous E-glass fiber plain-woven fabric, which serves as the basic material, and twisted carbon filament yarn, used as the tufting yarn. The E-glass fabric features balanced orthogonal yarns with high in-plane stiffness and drapability, making it suitable for studying in-plane shear deformation. Further details of the materials present as follows:

- Glass fiber fabric (Figure 2-1a): an area weight of $153.06 \pm 5 \text{ g/m}^2$, a uniform warp/weft linear density of 11.5 yarns/cm, and a thickness of $0.15 \pm 0.02 \text{ mm}$.
- Tufting yarn (Figure 2-1b): A 67 Tex twisted carbon filament yarn, supplied by Tenax Corporation, is used as the tufting thread. This yarn exhibits a high tensile strength of approximately 4100 MPa.

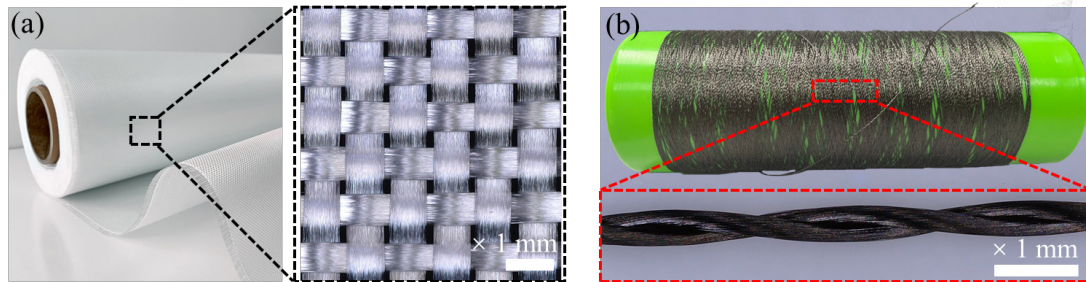


Figure 2-1 Raw materials: (a) Glass fiber woven fabric; (b) Carbon tufting yarn.

2.2.2 Picture frame test

In-plane shear characterization was conducted using a picture frame machine developed by LPMT laboratory (Université Haute Alsace, ENSISA), equipped with a 2000 N load cell. As shown in Figure 2-2a, the picture frame test device constructed with four equal-length articulated arms, which length is 400 mm, and enabling a maximum frame shear angle of 30° while accommodating specimens with shear angle up to 60° . Specimen mounting involved precise alignment of fabric yarns at $\pm 45^\circ$ relative to the loading axis, achieving a tensile-free initial state through a two-stage clamping pin: Initial fixing using clamping plate around the edges, then secondary fixing using clamping plate on the frame to eliminate border slippage. Testing was

conducted under standard laboratory conditions (23°C, 50% RH). Meanwhile, a load cell linked to the upper jaw permits to record the force of deformation and a constant displacement rate of 1.5 mm/s is applied on the specimens during the tests. The loading mechanism applies diagonal tension across the frame's opposing corners, inducing controlled kinematic transformation from square to rhomboid configuration.

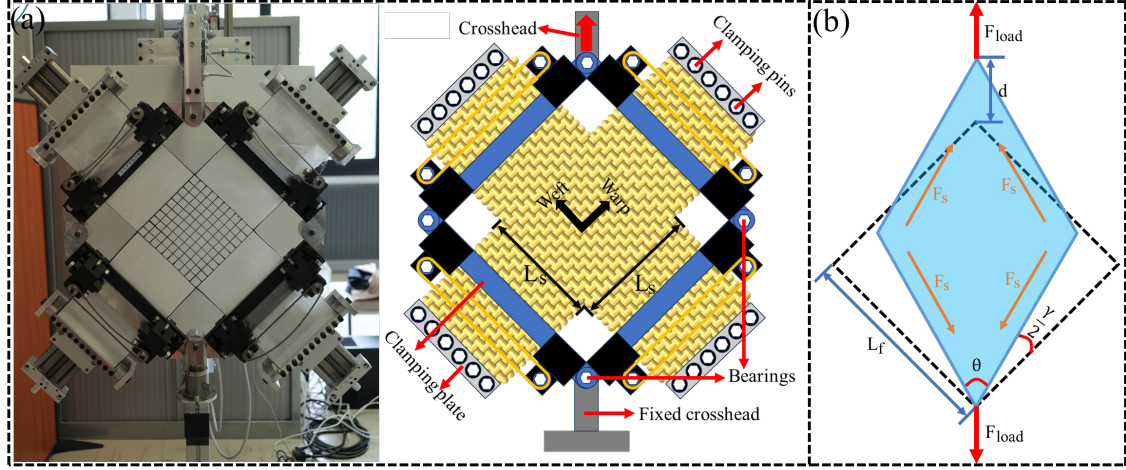


Figure 2-2 Picture frame test:(a) Description of the test machine; (b) Load on the picture frame.

For analyzing the picture frame test results, two important relations are necessary to be established. A kinematic relation is to link the in-plane shear angle to the extension of the specimen and a mechanical relation relates the shear stress in the fabric to the measured force on the tensile machine [135,138,139]. The normalized shear force-frame shear angle curves were calculated from the load-displacement curves. Through trigonometric relations, the frame angle (θ) is calculated by Eq.(2-1):

$$\theta = \cos^{-1} \left[\frac{1}{\sqrt{2}} + \frac{d}{2L_f} \right] \quad (2-1)$$

Where d is the displacement of the crosshead. L_f is the length of the picture frame.

The shear angle γ , (see in Figure 2-2b) was calculate by Eq.(2-2):

$$\gamma = \frac{\pi}{2} - 2\theta = \frac{\pi}{2} - 2 \cos^{-1} \left(\frac{1}{\sqrt{2}} + \frac{D}{2L_f} \right) \quad (2-2)$$

The shear force (F_s) can be calculated from the uniaxial load (F_{load}) applied along the diagonal of the sample as Eq.(2-3):

$$F_s = \frac{F_{load} - F_0}{2 \cos \theta} \quad (2-3)$$

Where F_0 is the fixture force without mounting a sample. For more general cases of comparing results from different specimen sizes and different frame sizes, the ratio of the loads can be expressed as Eq.(2-4) [21,24]:

$$\frac{F_f}{F_s} = \frac{L_f^2}{L_s^2} \quad (2-4)$$

Where L_s is the length of sample, as presented in Figure 2-2a. Therefore, the normalized shear force (F_n) of the corners cut-off sample can be using the following Eq. (2-5) [139]:

$$F_n = \frac{F_{load} - F_0}{2 \cos \theta} \left(\frac{L_f}{L_s} \right)^2 \quad (2-5)$$

2.2.3 Slitting process and slit specimens

The industrial slitting process, traditionally employed for material segmentation and excess removal, which is also adapted for controlled discontinuity engineering in forming process. The dimension of sample as follows the Figure 2-3a, undergoing no additional processing except for cutting to the required dimensions. The specimens had a cruciform geometry, cut from $800 \times 800 \text{ mm}^2$ fabric with $300 \times 300 \text{ mm}^2$ sections removed from each corner. This resulted in a central $200 \times 200 \text{ mm}^2$ cross-shaped test zone. Figure 2-3b and Figure 2-3c is subjected to controlled slitting parameters to examine the effects on in-plane shear distribution and deformation characteristics. Figure 2-3b featured a diagonal slit at 45° to the warp/weft directions, with a slit length of 60 mm, designed to evaluate the influence of fiber misalignment and off-axis discontinuity on shear behavior. Figure 2-3c contained a slit length of 60 mm away from the fabric edge, with a 40 mm slit along the warp/weft directions, to investigate the effect of edge-located discontinuities on shear force distribution and potential strain localization.

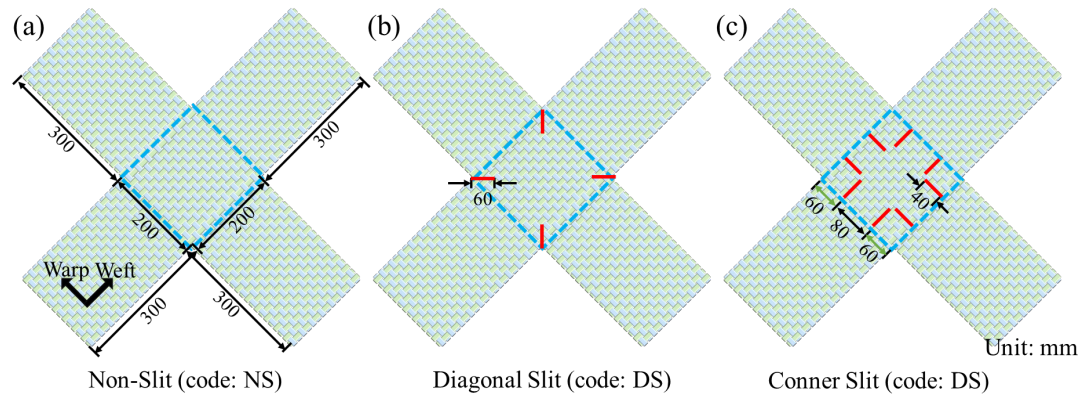


Figure 2-3 Prepared picture frame test specimen with different slitting configurations:

(a) Non-slit; (b) Diagonal slit; (c) Corner slit.

2.2.4 Tufting process and tufted specimens

The specimens were prepared using a programmable tufting machine developed by the GEMTEX laboratory (Université de Lille, ENSAIT), as illustrated in Figure 2-4a. The tufting machine comprises four major systems: tufting head system, tufting yarn feed system, movement system, and supporting system [53]. Tufting head system governs the insertion and retraction of a hollow needle (1.2 mm in diameter), as well as the synchronized motion of presser-foot, which applies a constant pressure of 0.5 MPa to provide an appropriate pressure around the tufting point, as shown in Figure 2-4b. A tufting yarn feed system enables continuous and real-time yarn delivery throughout the tufting process. The movement system digitally controls key tufting parameters such as tufting density, tufting pattern, and tufting direction with high precision. The supporting system ensures that the tufting yarn is securely retained within the supporting material (e.g. high-density supporting foam) through frictional interaction with the supporting materials. The tufting yarn is inserted into the fabric with a tufting depth of 15 mm.

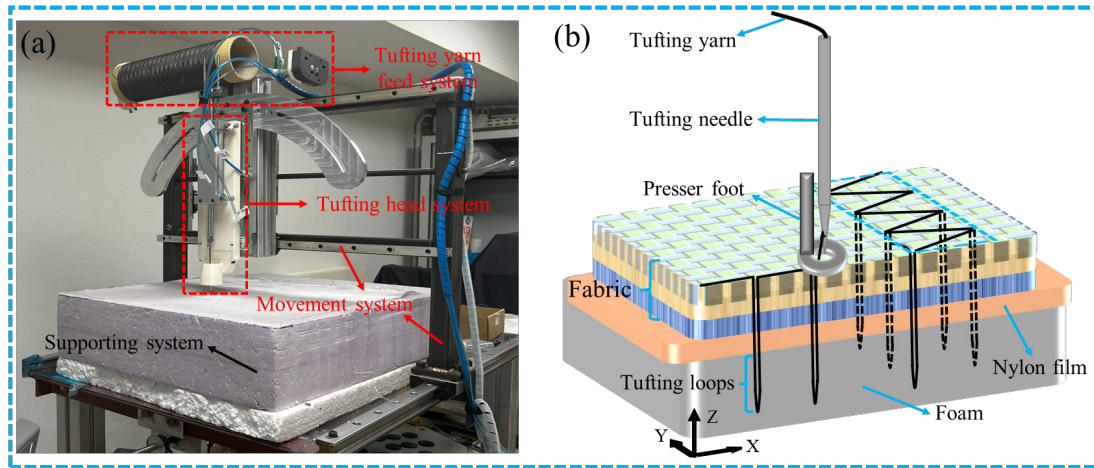


Figure 2-4 Tufting equipment: (a) Tufting system; (b) Schematic of tufting process.

To investigate the influence of tufting directionality on the shear behavior, two distinct tufting patterns were designed. The first configuration involved linear tufting yarns aligned either along the warp or weft direction, referred to as the rectangular tufting pattern (code: RT), as illustrated in Figure 2-5a. This pattern was intended to assess the effect of reinforcement aligned strictly with the principal material axes, thereby elucidating its role in stabilizing continuous shear deformation zones. The second configuration employed a zigzag tufting pattern (code: ZT), characterized by tufting yarns oriented at an angle of approximately 40° with respect to the warp and weft directions (Figure 2-5b). This off-axis arrangement was designed to examine its contribution to mitigating shear induced distortion.

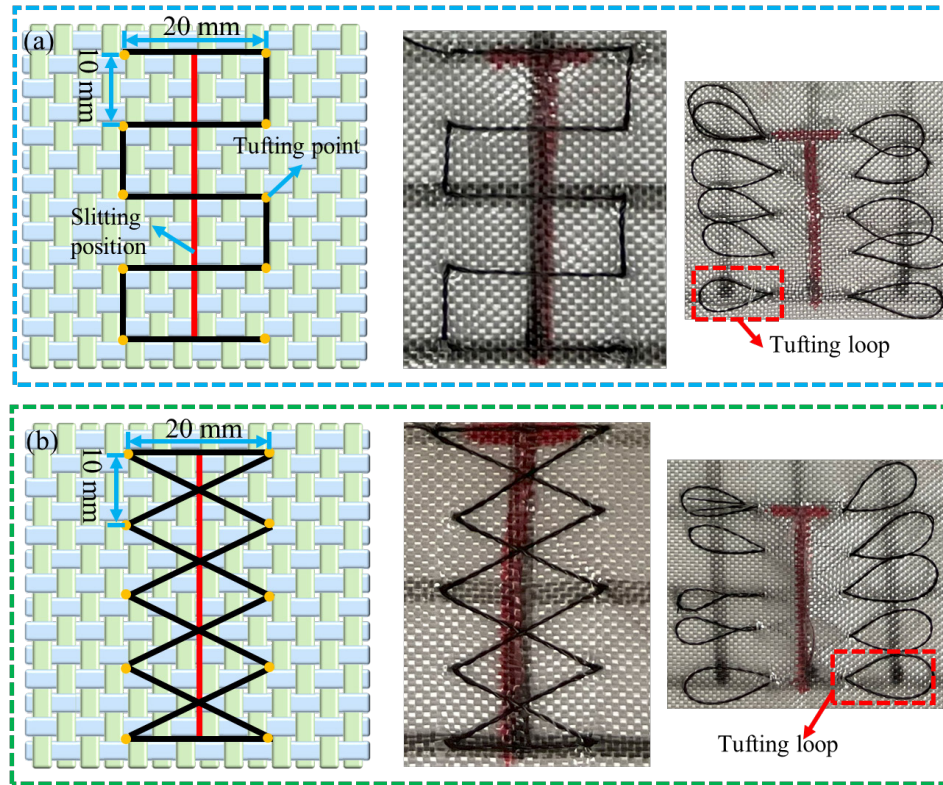


Figure 2-5 Schematic illustrations and macroscopic morphologies of tufted sample:

(a) Rectangular tufting pattern; (b) Zigzag tufting pattern.

A total of seven groups of specimens were prepared, encompassing three primary configurations involving different slitting configurations, along with four tufted configurations combining two tufting patterns (RT, ZT) with two slitting configurations (DS, CS). To evaluate repeatability, three specimens were tested for each group, and standard deviations are reported alongside the experimental results. The specimen naming convention reflects the slitting configurations followed by the tufting pattern. For instance, DS-ZT denotes a specimen with diagonal slit and zigzag tufting pattern.

2.3 Optical measurements based on vision algorithms

Previous studies have demonstrated that the theoretical shear angle in picture frame tests deviates from experimentally measured values [85,132]. These discrepancies primarily originate from operator errors during specimen installation, fixture misalignment, and inherent fabric non-uniformities [17,140,141]. Thus, it is important to take accurate measurements for the shear angle during picture frame test in the shear

zone. The experimental procedure followed a systematic approach: A high-resolution digital camera continuously recorded the entire picture frame test, ensuring comprehensive visual data acquisition. Specialized video analysis software was employed to extract representative still frames corresponding to distinct displacement phases with high precision. Every two adjacent images can be selected out as a reference image and a moving image, from a series of consecutive images recorded. Determine the in-plane shear angle by comparing the change in shear angle of the frame with the change in shear angle of the sample. Specifically, a set of black lines defined marker at shear regions of the sample were used to construct vectors representing yarn orientations, from which shear deformation could be quantitatively calculated. The shear angle datasets obtained from the analysis were further processed to statistical evaluation. This methodological framework provided a robust visual and analytical foundation for the subsequent interpretation of mechanical behavior and parametric characterization.

Figure 2-6 a-d shows the shear angle distribution at different crosshead displacements during the picture frame test. The results indicated that optical measurements based on vision algorithms method yields high accuracy when the specimen surface remains smooth and free of wrinkles. However, Figure 2-6e reveals that localized wrinkling induces yarn overlap and out-of-plane buckling, which significantly impairs optical tracking accuracy. Consequently, these surface irregularities cause substantial data loss in affected regions, indicating that measurement accuracy strongly depends on surface flatness.

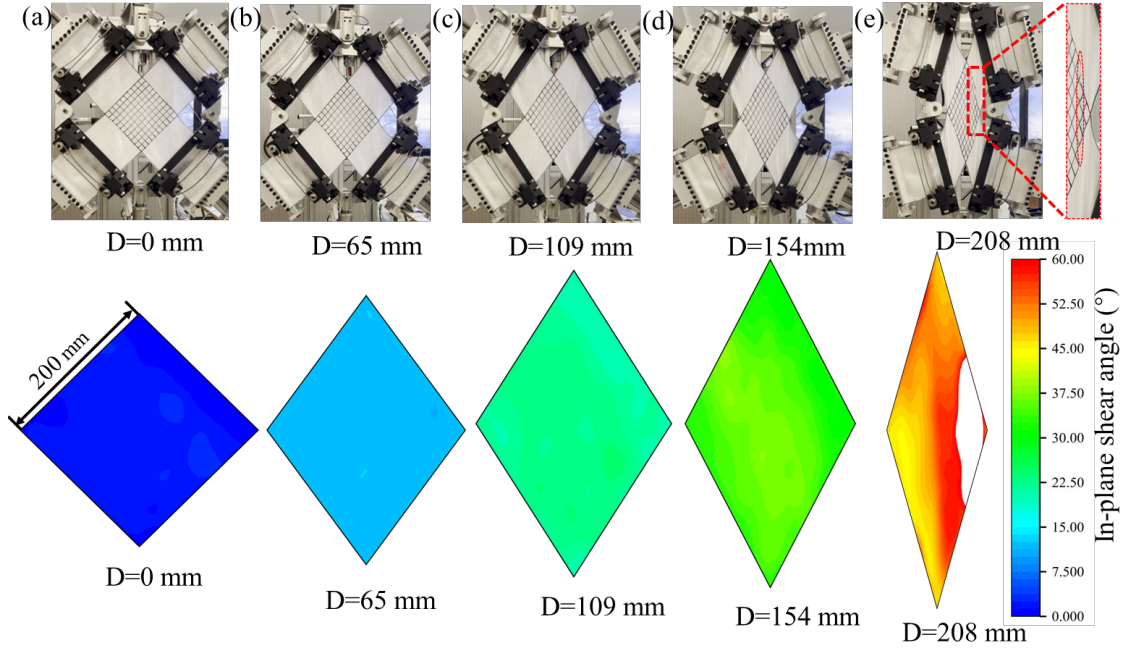


Figure 2-6 In-plane shear angle contours at different crosshead displacements.

Additionally, Figure 2-7 quantitatively compares the measured shear angle of frame and specimen shear angle against theoretical predictions derived from Eq. (2-2) for the NS-NT sample. The results indicate that the measured frame shear angle closely follows the theoretical predictions, with a maximum deviation of less than 1.5° , thereby confirming the reliability of the picture frame test method. However, as the displacement increases, the discrepancy between the frame shear angle and the specimen shear angle becomes more pronounced. At larger displacements, the measured shear angle tends to fall below that of the frame. This deviation is likely attributed to the formation of wrinkles, which interfere with accurate optical tracking and reduce the reliability of shear angle determination, as presented in Figure 2-6e. Therefore, the optical measurement method based on vision algorithms exhibits high accuracy in quantifying shear deformation under wrinkle-free conditions, highlighting its robustness during moderate deformations. Its limitations become evident when applied to scenarios involving significant wrinkling, where surface distortions compromise the precision of the optical measurements.

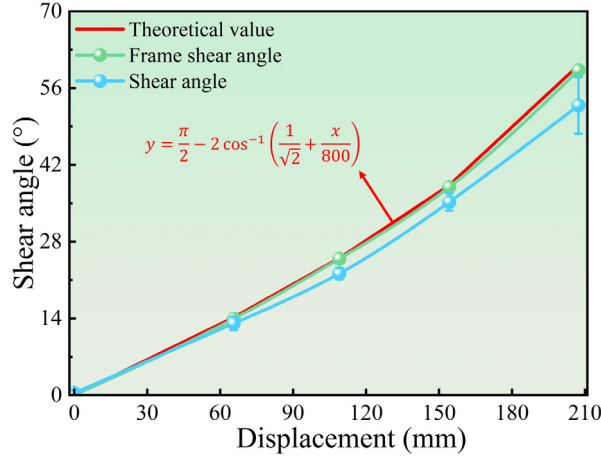


Figure 2-7 Comparison of theoretical value, frame shear angle and shear angle.

2.4 Results and discussion

2.4.1 Deformation mechanisms of slit specimen

After the slitting process, the continuity of certain yarns is disrupted, resulting in changes in the shear distribution within the shear zone and alterations in the effective area of the pure shear region. It is important to establish the relationship between slit parameters and shear distribution. Figure 2-8a illustrates the relationship between shear force (calculated from the Eq.(2-3)) and shear angle. In the initial stage of shear deformation (Figure 2-8c), discrepancies among the curves are minimal, and the shear force increases at a relatively low rate as shear angle increases. During this stage, pure shear deformation primarily governs the mechanical behaviour, as shown in Figure 2-8d. However, as the shear angle surpasses approximately 36° , the curves begin to diverge significantly, with a noticeably steeper shear force increase. This critical shear angle corresponds to the shear locking angle (see Figure 2-8e), a phenomenon examined in detail in section 4.3 and 4.4. Shear locking occurs when the fabric structure undergoes increasing constraints on further shearing due to geometric limitations from yarn interactions. At this stage, resistance to yarn rotation intensifies, leading to a sharp shear force increase, as shown in Figure 2-8a. This occurs due to the progressive alignment and densification of yarns, restricting relative movement, leading to increase shear rigidity [13], as shown in Figure 2-8f. This increase of shear stiffness leads to wrinkling

onset (see in Figure 2-6e).

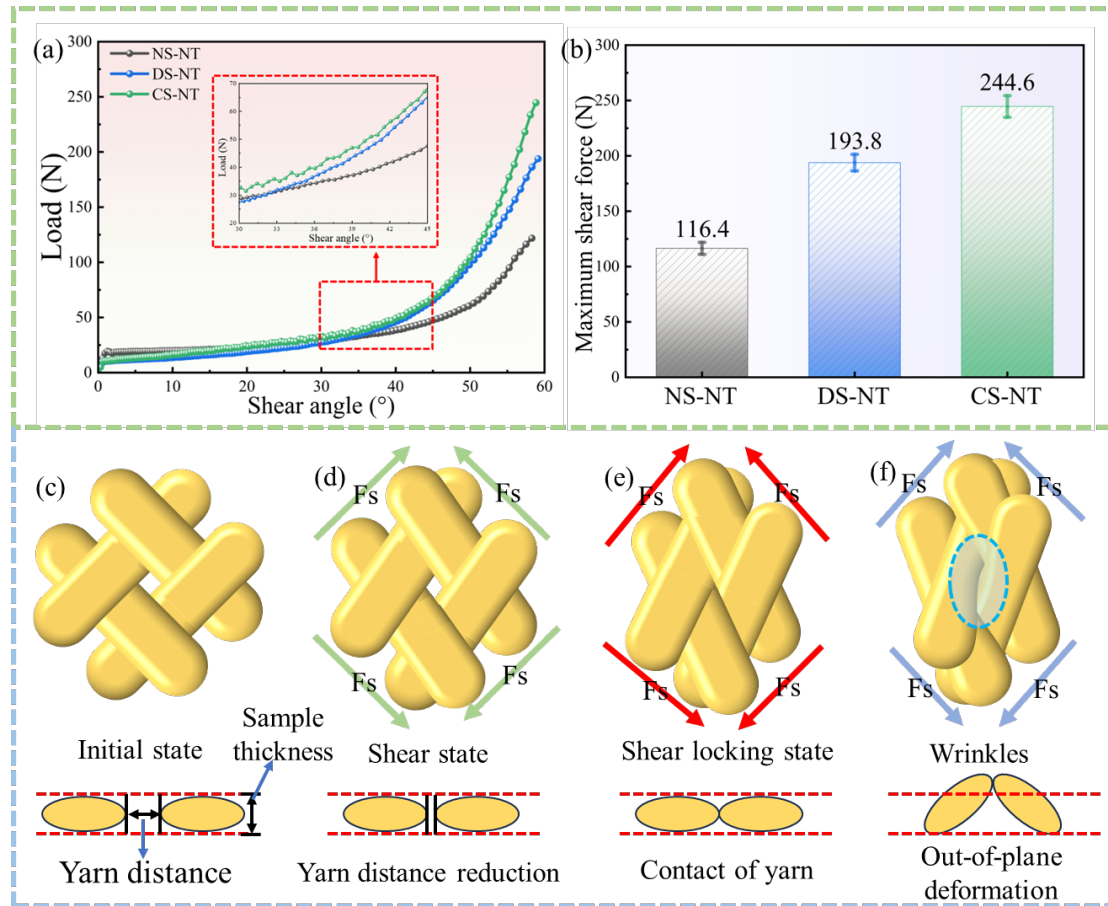


Figure 2-8 In-plane shear angle: (a) The applied load of slit specimens under different shear angle, (b) The maximum applied load of slit specimens, (c)-(f) The process of change in shear behavior during picture frame test.

Furthermore, it is observed that all slit specimens exhibit greater shear force resistance compared to their non-slit specimen, suggesting that the presence of a slit influences the shear response. The ranking of the three tested specimens in terms of increasing shear angle (beyond the shear locking angle) and applied load follows the order: CS-NT > DS-NT > NS-NT, as depicted in Figure 2-8b. Beyond the shear locking angle, the mechanical behavior undergoes significant changes, characterized by a sharp increase in shear stiffness, stress concentration at yarn intersections, yarn tension and reduced deformability. Initially, deformation is predominantly governed by the yarn frictional resistance at the interlacing points of warp and weft yarns (Figure 2-8c and Figure 2-8d). No significant yarn rotation is observed, and the fabric exhibits a nearly

linear elastic response. As the shear angle increases, static friction at the interlacing points is overcome, initiating compression and progressive reorientation of warp and weft yarns, as presented in Figure 2-8e. Beyond the shear locking angle, intensified transverse compressive stresses between warp and weft tows trigger out-of-plane buckling of yarns (see in Figure 2-8f, the blue zone), culminating in wrinkling. This reconfiguration forms localized shear bands, which drive a gradual accumulation of shear stress through kinematic adjustments in the fabric structure. Figure 2-8a (shear angle lower than 36°) shows that slitting has no significant effect on this process, as it does not alter static friction.

The state of the slit edge is also very important before reaching the shear locking angle. As shown in Figure 2-9, it can be observed that there is a significant difference in the variation of the various slit edges in the frame test at shear angle of 35° . In the DS configuration, the slit edge adopts a triangular profile wherein the central slit opening ($36.5^\circ \pm 3^\circ$) is substantially larger than both the upper and lower slit openings ($10^\circ \pm 2^\circ$), as quantitatively measured in Figure 2-9b. Additionally, the sample's contour undergoes noticeable deformation, implying that this slitting method may have a considerable impact on the structural integrity of the material. In contrast, Figure 2-9c illustrates the deformation behaviour of the CS configuration, where the slit edges evolve into elliptical morphologies. Notably, no significant out-of-plane contour deformation is observed across the specimen, indicating a localized deformation mode. The maximum lateral displacement at the centre of the slit edge is measured to be 1.3 ± 0.1 mm. This limited displacement and the uniform shape of the slit suggest that the structural integrity of the specimen is well preserved under this configuration, with minimal perturbation to the overall geometry. Therefore, the shear zone of CS can be considered to be all the area of sample.

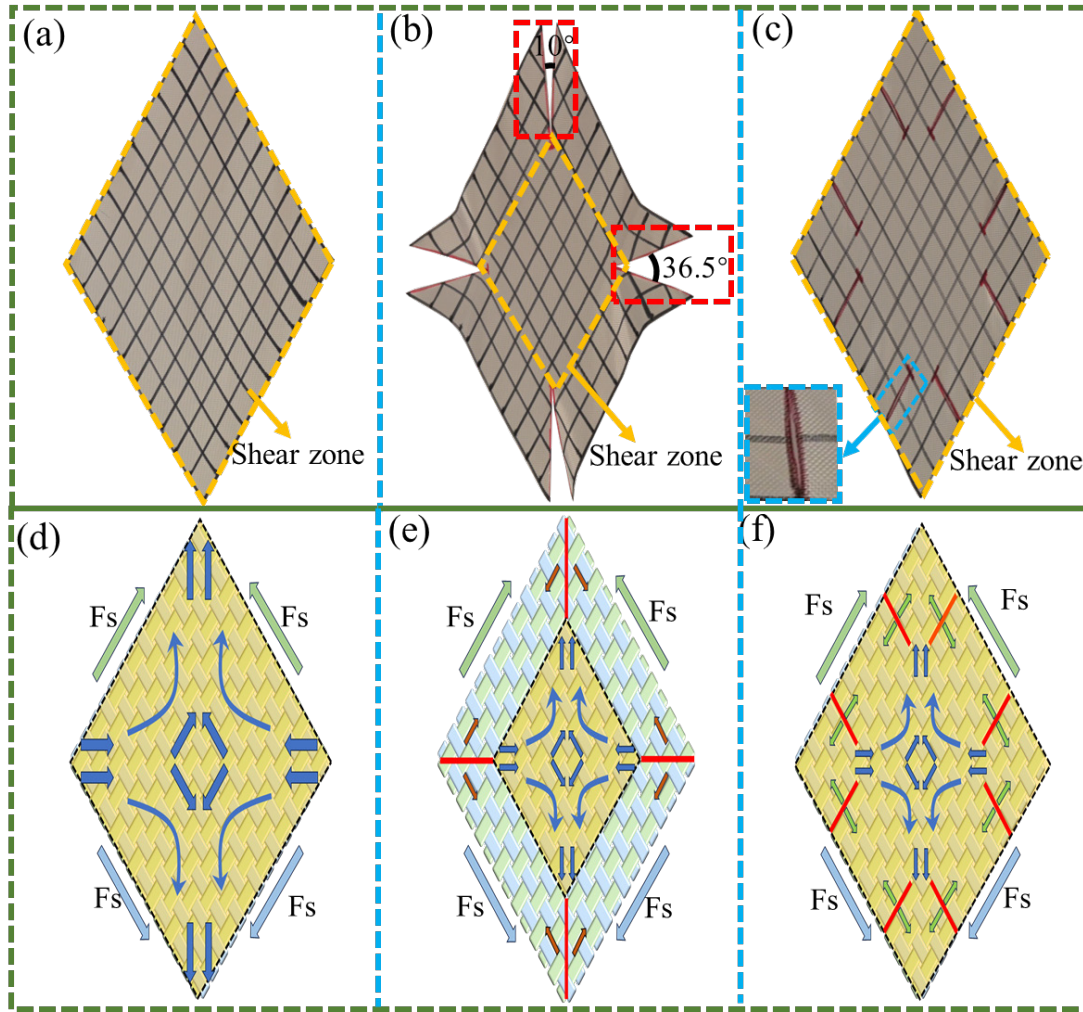


Figure 2-9 Deformation of slit edges at shear angle of 35° : (a) Non-slitting; (b) Diagonal slitting; (c) Corner slitting and close-up morphology of slit edge.

A typical experimental in-plane displacement field of a woven fabric under picture frame test as shown in Figure 2-9d [139]. Warp and weft yarns progressively rotate toward the principal shear direction (45° to loading axes). The presence of a slit alters the internal shear transfer path of the fabric, leading to shear stress concentration at the slit edges or surrounding areas, potentially increasing local shear deformation. Slit edges tend to propagate along the warp/weft directions under shear loading. This behaviour stems from the slit-induced discontinuity in in-plane displacement field, where localized shear forces near the slit edge are converted into tensile and bend forces that drive slit expansion. In the DS-NT configuration (see in Figure 2-9e), the slit alleviates spatial constraints on yarns at the in-plane displacement field periphery,

enhancing rotational freedom connected to the shear zone. Under the applied shear force, the middle region of the slit edge tends to open along the direction of shear deformation, whereas the upper/lower portions of the slit edge experience a degree of compression. As a result, the displacement or separation at the central slit edge is greater than that observed at the upper/lower edges. Meanwhile, the angle of central slit opening (36.5°) is similar to the shear angle (35°). This correspondence indicates that the slit edge propagates along the direction of maximum shear strain, forming a dominant opening aligned with the principal shear axis. This observation confirms that the slit edge in DS configurations is primarily governed by shear kinematics, which aligns with the principles of the picture frame test, where shear governs yarn reorientation. For CS-NT, slitting induces structural segmentation of warp and weft yarns, disrupting the continuous shear field and generating a discontinuous deformation field. This segmentation weakens mechanical coupling between adjacent yarns, thereby modifying local shear stress distribution and promoting heterogeneous shear behaviour. Under applied shear forces, slit edges exhibit pronounced outward expansion (Figure 2-9f), driven by yarn rotation and reduced in-plane constraints. The expansion magnitude correlates with the slit orientation relative to the shear load direction, governing yarn mobility gradients and localized shear deformation intensity.

2.4.2 Influence of tufting on shear deformation

Tufting pattern is another important parameter often studied for tufted fabrics [12]. Figure 2-10a and Figure 2-10b shows the shear force - shear angle curves for the slit specimens with different tufting patterns. These tufted specimens have the same number and position of tufting points, but the tufting yarns have a different connecting trajectory. Similarly, in the first stage, no apparent difference can be distinguished among these specimens. After a certain shear angle is reached, the resistance to shear in tufted specimens increases progressively. Moreover, the shear force-shear angle curve of the RT specimen increases more steeply than that of the ZT specimen.

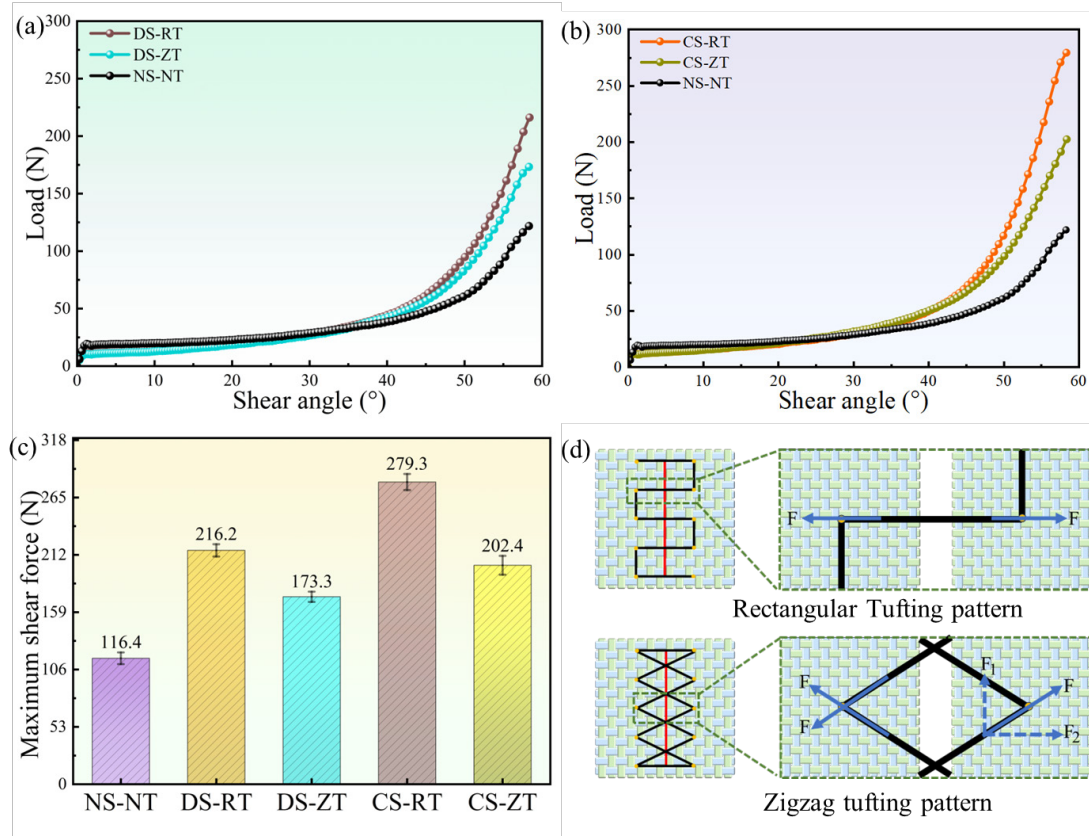


Figure 2-10 The influence of tufting pattern of the slit specimen: (a) Diagonal slitting, (b) Conner slitting, (c) Maximum shear force, (d) Schematic of the tensile of tufted yarn for deformed specimens with different tufting pattern.

The shear force of RT is consistently higher than that of ZT (see in Figure 2-10c), a behaviour primarily attributed to the differing in-plane tufting effects and their influence on tensile of yarn direction distribution. In RT specimens, the tufting yarns are aligned either perpendicular or parallel to the weft and warp directions, effectively connecting the slit edges, as presented in Figure 2-10d. This configuration effectively restricts the relative movement between yarns at the slit edge, thereby increasing resistance to both slit edge widening and shear deformation. As a result, more energy is required to facilitate slit edge expansion and material deformation. Figure 2-10d also shows the tensile of tufted yarn in ZT. The tufted yarns of ZT are oriented at an angle to the direction of warp/weft yarns, which results in a more distributed load transfer across the fabric structure. The tensile load within the yarns is redistributed along the warp and weft directions through the fabric's inherent load transfer mechanism, with

the normal stress components perpendicular to the slit edge serving as the dominant contributor to shear resistance by counteracting specimen deformation. The tufted yarn in ZT offer reduced resistance to shear deformation, resulting in a lower energy requirement to accommodate slit edge displacement. The loading mechanism of RT exhibits direct coupling with shear resistance enhancement, thereby achieving superior energy transfer efficiency compared to ZT configurations. These differences highlight the critical role of tufting pattern in mechanical performance of slit and tufted fabrics.

After the tufting process, the inserted tufting yarn stretches on the front surface of the fabric and forms a tufting loop on the opposite side at each tufting point (Figure 2-5c and Figure 2-5d). According to Figure 2-9, the change of the slit edges of CS-NT is not as obvious as those of DS-NT. Therefore, in order to show the deformation mechanisms of the tufted specimens more clearly, the changes of diagonal slitting are mainly discussed here. In the case of DS-RT and DS-ZT, the size of the slit edge varies between the top/bottom and the middle, as presented in Figure 2-11a and Figure 2-11b. Typically, the slit edge in the middle is larger than that at the top/bottom. For DS-RT and DS-ZT, the maximum opening distances at the middle slitting section are 42.8 ± 0.5 mm and 43.4 ± 0.4 mm, respectively, while the corresponding values at the top/bottom are 12.6 ± 0.2 mm and 11.9 ± 0.4 mm. The results illustrates that the two different tufting patterns have similar constraints on the slit edge. The constraining effect of tufting patterns on slit edges primarily originates from frictional resistance generated at each tufting point through yarn-substrate interactions. Although the tufting patterns vary between rectangular and zigzag configurations, both configurations maintain identical tufting points, which serves as a controlled variable to isolate the effect of pattern on shear behaviour.

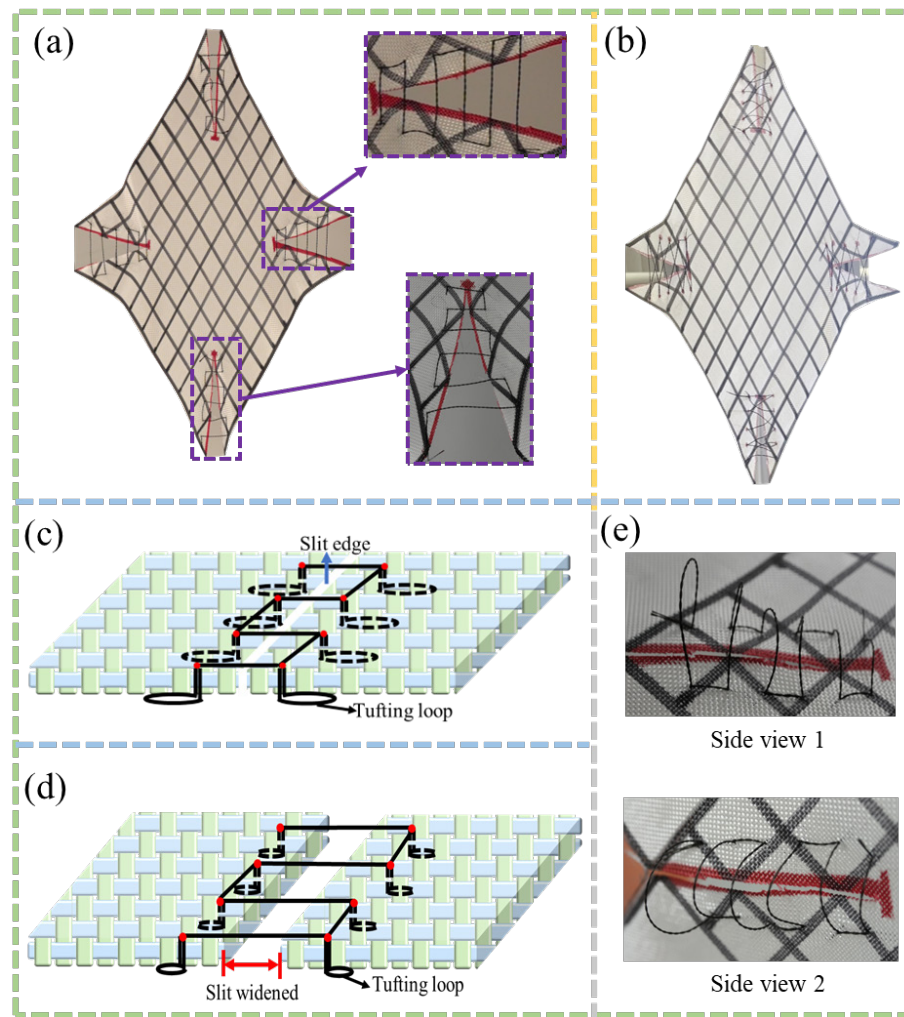


Figure 2-11 Deformation mechanisms of the tufted specimens: (a) DS-RT and close up of tufting yarn after deformation; (b) DS-ZT; (c) Tufting yarn before deformation; (d) Tufting yarn after deformation; (e) Tufting yarn recovered after picture frame test.

It has been demonstrated that the sliding of tufted yarns occurs during fabric extension. Given the inextensible nature of the inserted tufting yarns, their sliding in the longitudinal direction results in a pull-out effect. Figure 2-11c illustrates the initial state of the tufting yarn before deformation. As shown in Figure 2-11d, when the two sides of the slit edge move apart, the in-plane yarn stretches, causing the tufting yarn to slip and leading to changes in the tufting seam and tufting loops. At these tufting points, the tufting loops on the reverse side of the fabric are pulled out to the front surface. In other words, the length of the tufting seam will increase, while the length of tufting loops will correspondingly decrease. The increase in tufting seam length equals the total

reduction in tufting loop lengths from both sides. The slid length of tufting yarn is changed along with the shape of slit edge, their lengths at each tufting point are varying. Shen et al. [90] observed that the extent of tufting yarn pull-out increases with fabric extension in the bias-extension test. These findings highlight the critical role of fabric deformation in governing the structural stability and mechanical response of slit and tufted specimens. After completion of the shear loading, the crosshead returns to its initial position. However, due to frictional resistance at the tufting points, the stretched yarns are unable to recover to their original length. As a result, tufting seam with different lengths are formed, as illustrated in the Figure 2-11e.

2.4.3 Shear locking angle on the slit and tufted specimen

The textile reinforcements generally have a limit to the shear angle during the forming process [76,90,139]. Over a limit of the shear angle, often called “shear locking angle” and depending on the textile architecture [17,142]. According to the definition of the shear locking angle, which represents the critical angle at which the warp and weft yarns become interlocked due to their woven structure [131]. Consequently, the shear locking angle can be determined through either the second derivative extremum method or the tangent intersection method. The tangent intersection method is adopted to calculate the shear locking angle in this study [133,134]. As presented in Figure 2-12a, the calculated shear locking angle for the NS-NT, DS-NT, and CS-NT are 42.9°, 42.5°, and 42.9°, respectively. These results indicate that the slitting process has a negligible effect on the shear locking angle. This demonstrates that slitting does not alter the fabric’s intrinsic shear locking behaviour, which is primarily governed by the woven architecture and yarn interactions.

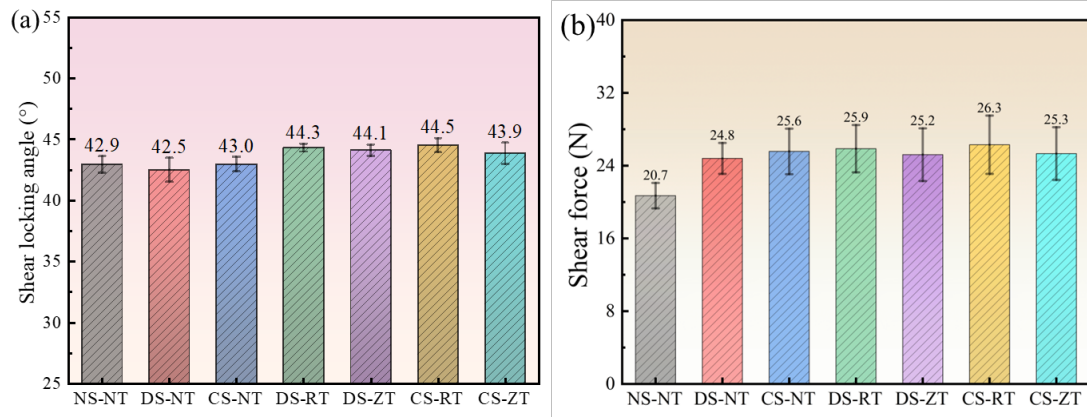


Figure 2-12 Shear locking angle with different configurations: (a) Shear locking angle; (b) Shear force at shear locking angle.

Furthermore, the shear locking angle for the tufted samples were calculated using the same methodology, as illustrated in Figure 2-12a. The results demonstrated that the shear locking angle of the different tufted samples are around 43.9° - 44.5° , which was slightly higher than that of NS-NT. The introduction of slits compromises the structural continuity of the fabric, enhancing localized yarn mobility within shear regions. This mechanism delays the onset of global shear locking, thereby enabling sustained deformation at elevated shear angles. Meanwhile, the in-plane tufting effect reinforces the load-bearing capacity of tufted specimens, which contributes to an increased shear force compared to non-tufted configurations. Meanwhile, slit and tufted specimens exhibited shear forces ranging from 24.8 N/mm to 26.3 N/mm at the shear locking angle. In contrast, non-tufted specimens demonstrated a lower shear force of approximately 20.7 N/mm at the same locking angle, as presented in Figure 2-12b. This indicates a slight enhancement in shear resistance attributable to the presence of slitting and tufting own to the delay of shear locking angle.

2.4.4 Shear angle distribution at the shear locking state

To further characterize the state of the shear region at the shear locking angle calculated from the shear force-shear angle curves, Figure 2-13 presents the shear locking angle of all test samples. The results indicate that slitting induces a localized reduction in shear angle around the slit position during the shear locking stage, while

exerting no significant influence on the overall shear zone (as shown in the blue box). For diagonal slitting, the reduction in shear angle is more pronounced along the diagonal region of the specimen (green section), reflecting the alignment of the slit with the principal shear deformation path. In contrast, for corner slitting, the decrease in shear angle is restricted to the immediate vicinity of the slit location (yellow section), with negligible impact on the surrounding areas. Furthermore, the tufting pattern shows no significant effect on the overall shear angle at the shear locking stage. Its primary role is to constrain the lateral expansion of the slit edges, while having minimal influence on the yarn slip or rotation within the fabric. This suggests that the in-plane deformation mechanisms, particularly yarn slippage and rotation, remain largely unaffected by the tufting pattern under shear locking conditions.

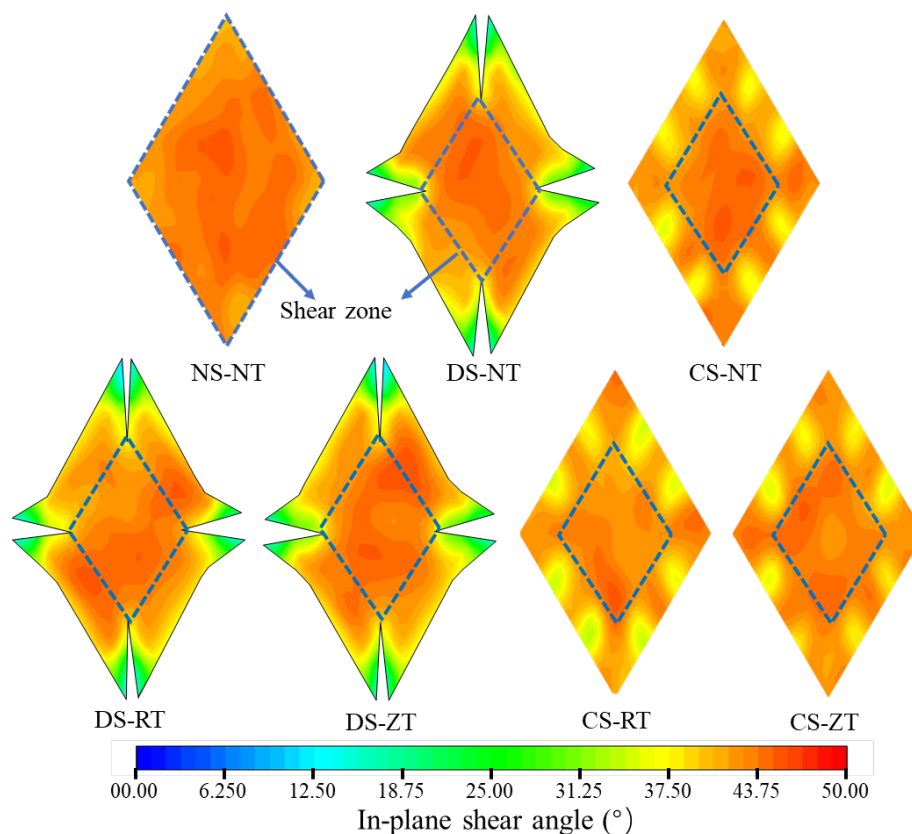


Figure 2-13 The in-plane shear angle disruption at the shear locking state.

Figure 2-13 also indicated that in the shear zone, most yarns have reached the shear locking state. However, a small portion of yarns have not yet attained the shear locking angle (color difference in shear zone), while others have exceeded it (represented in

orange). This uneven shear state may be attributable to the inherent angularity and friction of the warp and weft yarns in the woven glass fabric. The distance between neighboring warp and weft yarns is not exactly same. The friction between yarns affects shear deformation transmission, with higher friction areas requiring greater shear force to reach the locking angle, while lower friction areas may reach or exceed it earlier [72,141]. This uneven shear distribution underscores the limitations of the assumption of homogeneous shear in forming simulations, as even minor asynchronous yarn group movement can precipitate strain localization or premature wrinkling in practical textile forming scenarios [130].

2.5 Feasibility analysis of slitting and tufting in textile forming

This chapter presented herein elucidate the intricate interplay between slitting configurations, tufting patterns, and shear-induced deformation mechanisms in woven glass fiber fabrics. The experimental findings on shear locking modulation via slitting and tufting configurations provide actionable strategies to address longstanding challenges in textile forming processes, particularly in the manufacture of complex composite preforms. Textile forming processes often encounter wrinkling when shear angles exceed the locking threshold, leading to rejected parts or compromised mechanical performance. The delayed shear locking angle observed in slit and tufted specimens ($44.0 \pm 0.4^\circ$ vs. 42.9° for non-slit fabrics, Figure 2-12) suggests that strategic slit placement could extend the shear locking angle. The ability to manipulate shear stiffness through structural modifications provides designers with a means to achieve targeted deformation characteristics, thereby improving the feasibility of complex-shaped textile preforms. By treating slits as “controlled defects” and tufting as “targeted reinforcement”, manufacturers can tailor fabric shear ability and anisotropy to enhance material utilization and reduce defect rates.

2.6 Conclusion

In this chapter, the effects of different slitting configurations and tufting patterns on the in-plane shear deformation behavior of woven glass fiber fabrics were

systematically investigated using the picture frame test. The results provide new insights into the deformation mechanisms governing textile preforming. It was observed that all slit specimens exhibited higher shear force resistance compared to their non-slit specimens, indicating that the introduction of slits significantly influences in-plane shear response. Additionally, tufted specimens showed a continuous increase in shear force with increasing shear angle, and both slit and tufted samples demonstrated higher shear forces relative to non-slit specimens. Importantly, the slitting process showed negligible influence on the overall shear locking angle, as this critical threshold primarily governed by the intrinsic woven architecture. However, slitting did induce localized reductions in shear angle near the slit regions during the shear locking stage, without altering the deformation characteristics of the global shear zone. Furthermore, the experimental results reveal that not all warp and weft yarns within the shear zone simultaneously reach the shear locking state when the specimen approaches the calculated locking angle. This finding highlights the inherent non-uniformity of shear deformation in woven structures under large in-plane strains. Overall, these findings emphasize the need for careful selection and optimization of slitting and tufting parameters to improve fabric formability and reduce forming defects, aiming at enhancing both process stability and final product quality.

3. Experimental analyses on the precision slitting on the preform

3.1 Introduction

The LCM process is highly regarded for its advanced manufacturing capabilities in textile composites, offering high quality, durability, and cost-effectiveness [77,143,144]. It is particularly effective in producing complex components with uniform fiber distribution, a crucial factor for achieving optimal mechanical performance [144]. However, the preforming stage presents challenges that often lead to defects such as wrinkling [77,88,96], buckling [83,94,99], and yarn misalignment [17,79,83], all of which compromise the structural integrity and mechanical properties of the final composite [90]. To address these issues, extensive research has been conducted across various material systems to enhance product quality and structural performance.

Numerous studies have investigated fabric forming defects, emphasizing the susceptibility of composite materials to wrinkling under complex 3D deformations caused by interactions among tension, in-plane shear, and bending stiffness [92,115,145–147]. According to Kashani et al. [148], tension-shear coupling had the most significant influence on the preform effective mechanical properties, followed by shear-tension and tension-tension couplings. The balance between in-plane shear stiffness and out-of-plane tension is key to the formation and characteristics of wrinkles [93,112,122]. Optimizing key process parameters, including punch design, velocity, and sequence [73,147], as well as adaptive blank-holder systems [150,151], enhances defect mitigation. Multi-punch tools outperform single-punch methods in wrinkle suppression, while pressure-adjustable blank-holders improve strain distribution [83,147]. Simulations confirm that blank-holders effectively suppress wrinkles by regulating tension distribution [115]. Innovations such as tufting patterns enhance multi-layer formability but show limited effectiveness in single-layer applications [17,102]. Traditional slitting methods focus on edge geometry modification [130],

whereas this study proposes a novel approach that targets shear concentration zones in unformed regions, redistributing stress to mitigate defects. Despite advancements, research gaps remain in stress management within unformed regions and achieving complete wrinkle elimination [93,142,149,152].

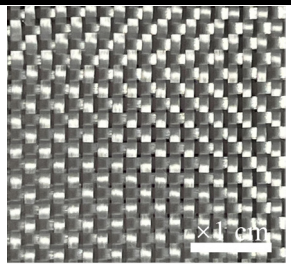
This chapter proposes a refined slitting method to regulate stress and strain in preforms by controlling local in-plane shear and minimizing defects. It investigates the relationship between in-plane shear stiffness and wrinkle formation across various slitting configurations, aiming to enhance slitting position selection and preforming process optimization. The impact of slitting locations, aligned with ply orientations, on preform formability was systematically evaluated in this chapter.

3.2 Materials and methods

3.2.1 Materials

The material employed was a continuous E-glass plain weave fabric, with key characteristics outlined in Table 3-1. The study analyzed a single ply at orientations of $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ relative to the warp or weft direction, facilitating a thorough evaluation of ply orientation effects. Each preform measured $280 \times 280 \times 0.15 \text{ mm}^3$.

Table 3-1 Main physical characteristics of the test fabric.

Parameter	Properties	Units	Fabric
Weave pattern	Plain weave		
Type of yarn	E-glass fiber		
Area density	153.06 ± 5	g/m^2	
Warp/ Weft density	11.5	yarns/cm	
Weight distribution (warp/weft)	50/50	%	
Thickness	0.15 ± 0.02	mm	

3.2.2 Forming process

The forming device integrates a mechanical component, a video camera, two linear infrared arrays, and a load sensor, as depicted in Figure 1-20a and Figure 3-1a. The mechanical component includes a punch/open-die system paired with a conventional blank-holder system. Figure 3-1a also displays the slit preform on the blank-holder and die. During forming, the load sensor measures punch force variations. A digital camera

positioned above the specimen continuously captures the forming process. Furthermore, linear infrared arrays track surface changes on the preform. Forming experiments utilized a hemispherical punch, as shown in Figure 3-1b. Figure 3-1c depicts the punch dimensions and hemispherical forming process. The blank-holder exerted pressures of 0.05 MPa and 0.20 MPa on the blank's outer region during forming. The punch executed a vertical displacement at a constant rate of 7.72 mm/s, with a load force of 0.15 MPa.

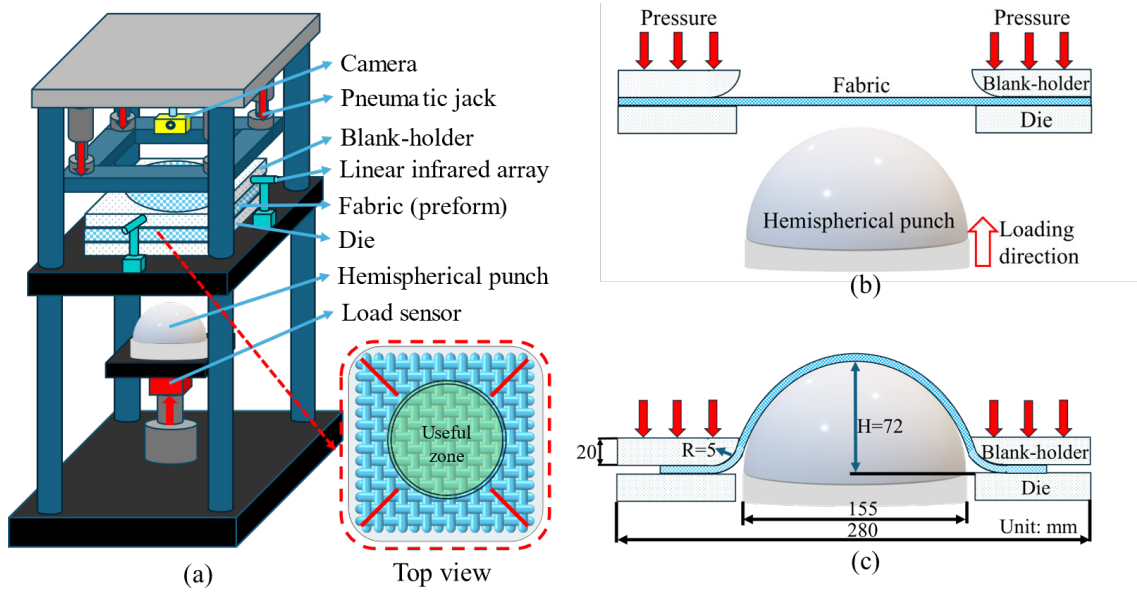


Figure 3-1 (a) Schematic of forming device; (b) before forming and (c) after forming.

3.2.3 Slitting process

The slitting process entails creating a continuous, narrow incision at a designated location in materials like fabric or similar substances. This technique enhances flexibility in the targeted region and facilitates efficient shaping of designated sections [137]. For the $[0^\circ/90^\circ]$ ply, slitting is conducted along the fabric's central axis with a length of 30 cm, to reduce and uniformly distribute in-plane shear forces, as shown in Figure 3-2b (denoted as MS). Alternatively, the preform can be slit diagonally across the fabric, as illustrated in Figure 3-2c (labeled DS). Additionally, a configuration with slits at two distinct locations within the in-plane strong shear zone has been adopted to regulate its dimensions, termed CS, as depicted in Figure 3-2d. The labeling scheme for the $[-45^\circ/45^\circ]$ ply adheres to the same convention, as outlined in Figure 3-2. Slitting

position criteria mandate that slit edges maintain the integrity of the functional area post-deformation. Moreover, slit edges should be positioned as near as possible to the useful zone to reduce their separation. This ensures the functional area remains intact during slitting, thereby preserving its utility.

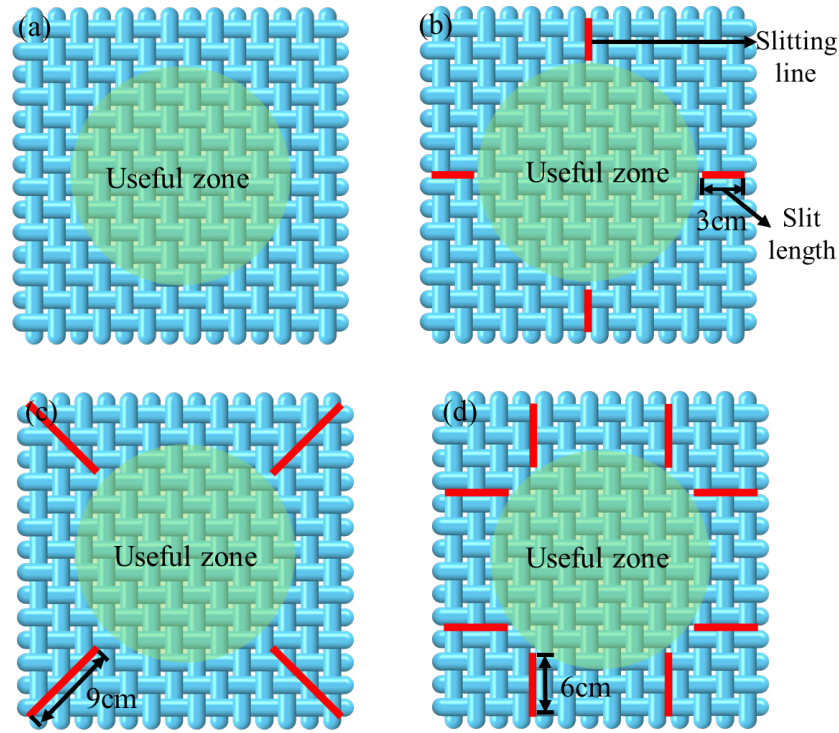
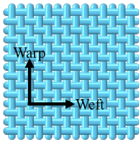
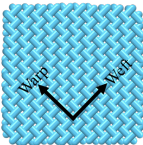


Figure 3-2 Schematic description of different slitting positions on $[0^\circ/90^\circ]$ ply as an example: (a) Non-Slitting (NS); (b) Middle Slitting (MS); (c) Diagonal Slitting (DS); (d) Corner Slitting (CS).

Table 3-2 details the key slitting parameters of the fabric employed in this chapter. Sample naming conventions are based on layer sequence, slitting position, and blank-holder pressure, in that order. For example, the 90-NS-0.05 denote the layer sequence of $[0^\circ/90^\circ]$, non-slitting and the blank-holder pressure of 0.05 MPa, respectively. Pre-marked fabrics were placed on the die and then slit at designated locations indicated in Figure 3-2. After slit, the fabrics were carefully transferred to the forming device. Next, the blank-holder was applied to secure the fabric, initiating the forming process.

Table 3-2 Main paraments of the slit fabrics in forming tests.

Fiber directions	Blank-holder pressure (MPa)	Ref. of sample	Slitting position	Slitting length (cm)	Total slitting length (cm)
 [0°/90°]	0.05	90-NS-0.05	NS	0	0
		90-MS-0.05	MS	3	12
		90-DS-0.05	DS	9	36
		90-CS-0.05	CS	6	24
	0.20	90-NS-0.20	NS	0	0
		90-MS-0.20	MS	3	12
		90-DS-0.20	DS	9	36
		90-CS-0.20	CS	6	24
 [-45°/45°]	0.20	45-NS-0.20	NS	0	0
		45-MS-0.20	MS	4	12
		45-DS-0.20	DS	8	32
		45-CS-0.20	CS	6	24

3.2.4 Measurement of in-plane shear angle

To analyze fabric deformation, a rigorous methodology was implemented, beginning with careful fabric sample preparation. Black reference lines were drawn along the warp and weft directions at 20 mm intervals to serve as reference markers for tracking fabric deformation and calculating shear angles, as shown in Figure 3-3a. The sample was formed into a hemisphere shape, and then high-resolution photographs were taken from multiple perpendicular angles to comprehensively record warp and weft distortions. These images were then imported into ImageJ, a precise image processing tool, to measure shear angle based on changes in the black reference lines. For a shear unit (e.g., a black square marked on a woven fabric), the shear deformation can be characterized by the change in its internal angles. If the two opposite interior angles are measured as θ_1 and θ_2 (see in Figure 3-3b), the in-plane shear angle θ_s of the unit can be calculated using the Eq.(3-1):

$$\theta_s = \frac{\pi}{2} - \frac{\theta_1 + \theta_2}{2} \quad (3-1)$$

Simultaneously, the black reference line of the preform surface was extracted to establish a Cartesian coordinate system. The data was processed and visualized using

Python to create an accurate representation of shear angle distributions. This data was then used to develop a 3D contour map, providing a spatial view of shear angle variations across the fabric surface. The 3D map provides an intuitive view of fabric deformation, highlighting shear angle concentration areas and supporting a detailed understanding of fabric behavior under stress.

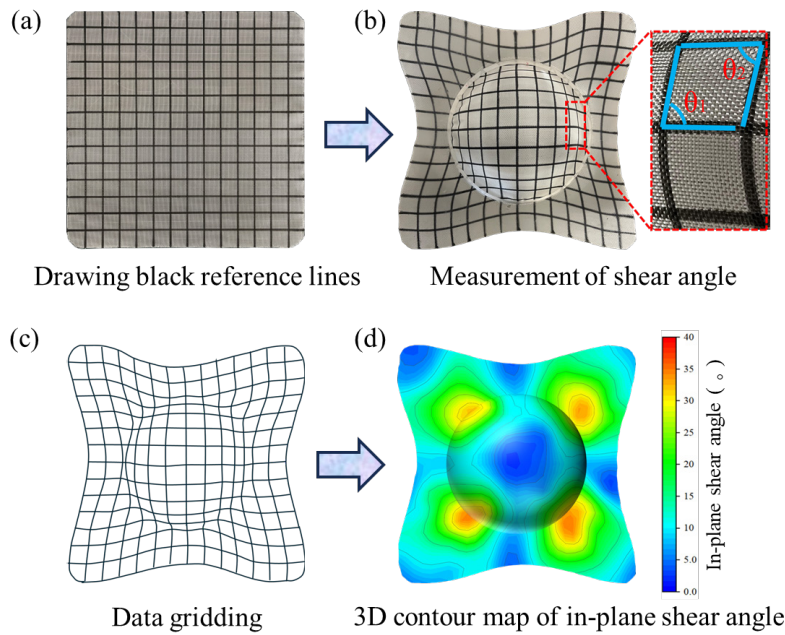


Figure 3-3 Measurement of in-plane shear angle.

3.2.5 Characterization of wrinkles

In this chapter, the effective wrinkle observation area lies above the blank-holder, as shown in Figure 3-4a [88]. A red line marks the wrinkle test position, located on the blank-holder. The experiment commenced with uniform illumination of the sample via two linear infrared arrays, improving wrinkle visibility. A high-resolution camera, positioned directly above the sample center, captures wrinkles from a top-down view. Images are also captured from various angles around the preform. This configuration ensures clear detection of changes in the linear infrared array's path. The camera's positioning reduces distortion and provides accurate recording of the linear infrared array's behavior, as illustrated in Figure 3-4b. Surface waviness was evaluated over a 120 mm length along the bottom profile. The raw image was then transferred to a computer for processing, as shown in Figure 3-4c [88].

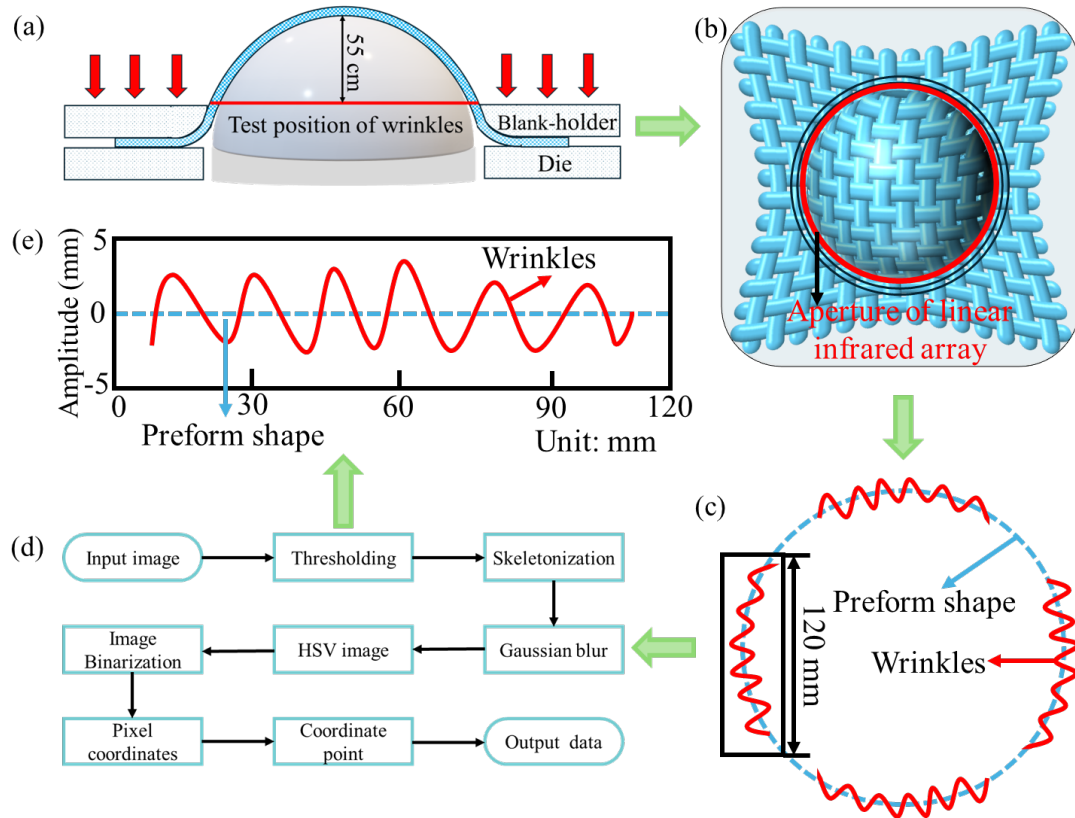


Figure 3-4 Characterization of wrinkles: (a) Initial setup for wrinkles positioning; (b) Top view of wrinkles positioning; (c) Presentation of wrinkling test results; (d) Data extraction from wrinkling results using Python; (e) Graphical representation of wrinkling data.

As shown in Figure 3-4d, the primary emphasis was on cropping the image to highlight wrinkles, eliminating extraneous lines or background noise that might impair observation clarity. The refined image was then imported into the PyCharm Integrated Development Environment (IDE). Within PyCharm, custom Python scripts were used to derive quantitative data from the image. These scripts analyzed pixel values associated with wrinkles, transforming visual data into quantitative metrics. This analysis culminated in plotting the extracted data, as illustrated in Figure 3-4e. A positive value indicates a protrusion wrinkle, while a negative value signifies a recessed wrinkle.

3.3 Forming results

Figure 3-5 depicts deformed preforms with varying slitting positions. Fiber

orientation influences the deformability and final shape of textile preforms [88]. In theory, hemispherical forming of woven fabrics yields quasi-symmetric outcomes due to the symmetry of punch and the intrinsic properties of woven materials. However, achieving perfect symmetry in practice is difficult due to fabric asymmetry and uneven pressure distribution from the blank-holder. Additionally, slitting significantly affects deformation in the unformed zone of preform. This deformation modifies the surface of preforms' appearance. This effect highlights the impact of slitting positions on the preforms' physical properties during forming. Formability was assessed by analyzing parameters like material draw-in, punch force, shear angle and wrinkles as indicators of overall and localized deformation. Material draw-in affects fabric tension and deformation. Insufficient draw-in leads to excessive tension and wrinkling, while excessive draw-in induces buckling and localized wrinkles [153]. Excessive punch force increases fabric tension, heightening stresses and inducing localized instability, potentially worsening wrinkling in the useful zone [154]. As the shear angle approaches or exceeds the shear locking angle, the preform stiffens, resisting further deformation and elevating wrinkling risk [142].

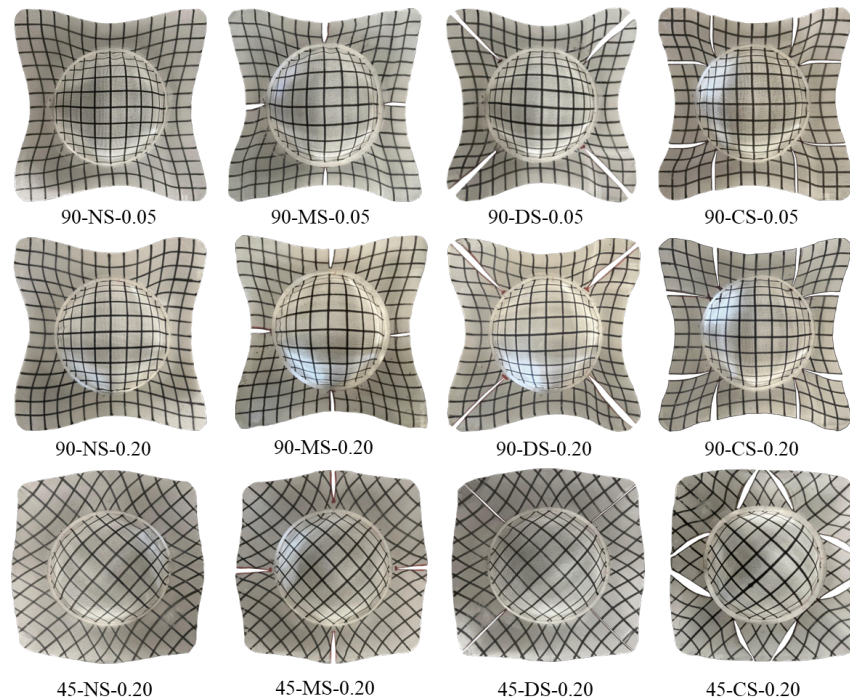


Figure 3-5 Observation of deformed slit preforms under 0.05 and 0.20 MPa blank-holder pressure.

Forming results revealed that certain preforms, such as 90-NS-0.05 and 90-MS-0.05, displayed prominent wrinkles. In contrast, other samples, such as 45-MS-0.20 and 45-CS-0.20, exhibited minimal to no visible wrinkles. Fig. 6 depicts the 90-NS-0.05 and 45-MS-0.20, emphasizing variations in wrinkle formation. Furthermore, wrinkles are clearly visible in top and side views but less discernible in the front view. These wrinkles possess 3D complexity that photographs struggle to capture due to their 2D nature. The depth and contours critical to wrinkles often diminish in 2D images, underscoring the limitations of this medium for representing 3D forms. Wrinkling is more prevalent in $[0^\circ/90^\circ]$ plies than in $[-45^\circ/45^\circ]$ plies. Future analysis will examine the forming behavior of various slit preforms, focusing on assessing the effects of different slitting positions. This will involve evaluating shear angles and wrinkles, which are critical to understanding preform formability and manufacturing processes.

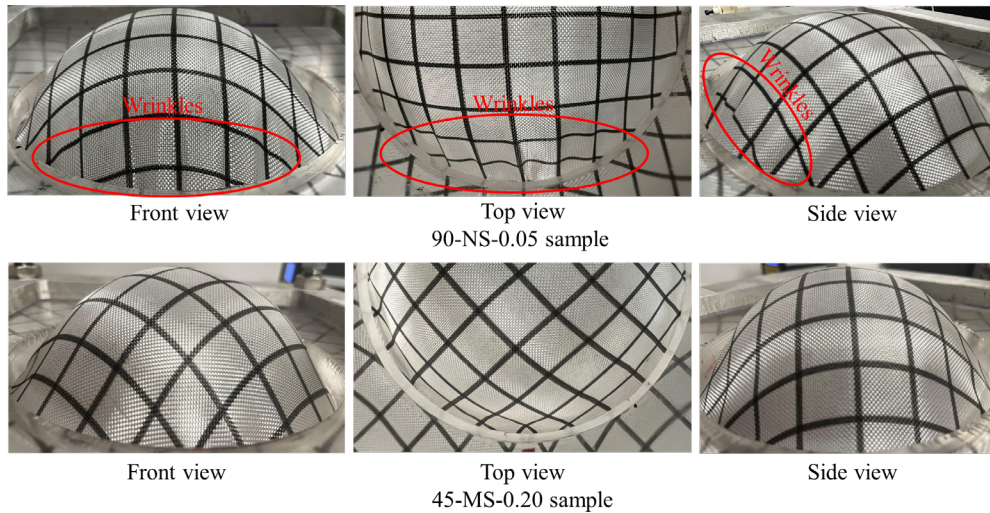


Figure 3-6 Wrinkles on the different slit preforms over the three-view drawing.

3.3.1 Punch force of deformed preform

During the forming process, the preform is subjected to punch and blank-holder pressures [150]. Punch pressure compels the preform to conform to the mold, inducing internal stresses and promoting sliding and extension. Meanwhile, blank-holder pressure stabilizes the periphery, ensuring uniform deformation. The interaction of these forces is crucial for forming defects prevention. Figure 3-7a illustrates the effect of different slitting positions on the punch force required to maintain the preform's final

shape. Quantitative analysis indicates that the punch force remains relatively stable across different slitting positions for the $[0^\circ/90^\circ]$ ply. Specifically, it varies from 6.4 ± 0.5 N at 0.05 MPa to 34.4 ± 1.5 N at 0.20 MPa. In contrast, for the $[-45^\circ/45^\circ]$ ply, DS results in the lowest punch force, approximately 20% lower than that of NS. The punch force in the CS configuration is reduced by 16% compared to NS. These findings suggest that slitting positions, particularly DS and CS, exert a more significant influence on punch force in the $[-45^\circ/45^\circ]$ ply than in the $[0^\circ/90^\circ]$ ply.

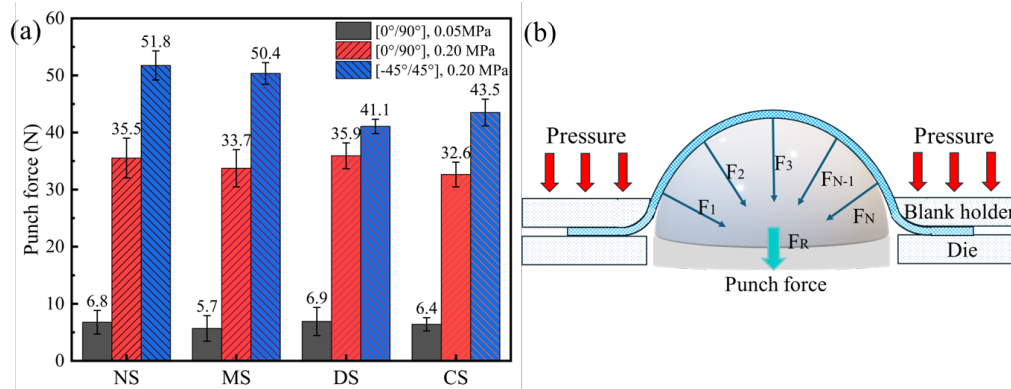


Figure 3-7 Punch force: (a) Under various slitting positions; (b) Punch force distribution.

For the $[0^\circ/90^\circ]$ ply, different slitting positions have little effect on the punch force distribution across the useful zone. Figure 3-7b shows the stress distribution of punch under the useful zone. Slitting also does not influence the material region beneath the blank-holder. In this ply, the fibers are aligned with the applied forces during forming. This alignment minimizes the influence of slit edges on the required punch force. Consequently, the punch force remains relatively consistent irrespective of the NS, DS, CS configurations. In contrast, for the $[-45^\circ/45^\circ]$ ply, DS reduces the punch force compared to the NS. This reduction reflects its ability to modify stress distribution under the blank-holder. The substantial decrease in punch force indicates that DS and CS configurations mitigate stress concentrations and ensure uniform force distribution across the material. These findings highlight the importance of selecting an appropriate slitting configurations based on fiber orientation.

3.3.2 Deformation of preform contours

Material draw-in denotes the process whereby textile materials (e.g., fibers, yarns, or

fabrics) are pulled into the mold from their initial position during forming, resulting in deformation and a mechanical response [153]. Preform contour deformation can be quantified through material draw-in. Quasi-symmetric deformation in hemispherical forming permits measurement of one-quarter of the hemisphere's deformation during material draw-in, as shown in Figure 3-8. Different slitting positions do not significantly alter the preform's deformation characteristics. Furthermore, the location of maximum material draw-in remains uniform across varying slitting positions. Tests indicate that maximum draw-in distances differ by less than 5% across positions, confirming the material's uniform deformation behavior under diverse conditions. The material maintains a uniform outline across varying slitting positions, suggesting that slitting position variations do not substantially affect yarn distribution in the useful zone. Figure 3-8b-d demonstrated a positive correlation between slit edge distance and blank-holder pressure. This suggests that higher blank-holder pressure corresponds to greater slit edge distances, critical for stabilizing slit edges during forming. Increased pressure further constrains slit edges, preventing their displacement during deformation. Consequently, higher blank-holder pressures impede material movement into the mold, leading to increased slit edge distances.

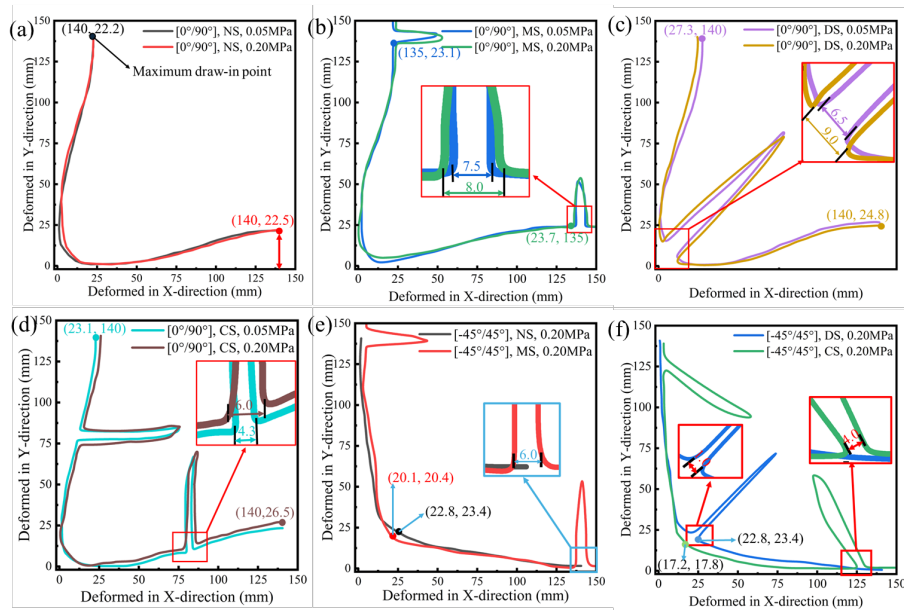


Figure 3-8 The material draw-in in X and Y directions shown on the quarter-deformed fabric

The maximum draw-in locations, central points of the $[0^\circ/90^\circ]$ ply and corners of the $[-45^\circ/45^\circ]$ ply [102], remain unchanged regardless of the slitting method applied. This finding indicates that the structural geometry of the preform and the directional properties of the ply predominantly dictate the maximum draw-in location, rather than the slitting technique. However, different slitting positions influence the extent of maximum draw-in, especially CS and DS in the $[0^\circ/90^\circ]$ ply. Analysis reveals that DS increases the maximum draw-in range from 11.7% to 22.9% relative to NT samples. The DS configuration may enhance material draw-in during the hemispherical forming process, potentially altering mechanical properties such as tensile strength, in-plane shear, and bending stiffness. The observed variations in maximum draw-in with CS and DS highlight their specific interaction with the material. Furthermore, increased blank-holder pressure likely intensifies friction between the preform and blank-holder during the forming process, consequently widening the distances between slit edges.

3.3.3 In-plane shear angle

Figure 3-9 presents the in-plane shear angles under different slitting positions. For the $[0^\circ/90^\circ]$ ply, increasing the blank-holder pressure has minimal impact on the shear angle of single ply, as evidenced by the similar maximum shear angles in configurations of 90-NS-0.05 (35.9°) and 90-NS-0.20 (36.5°). MS modifies the strong in-plane shear zone relative to NS. Furthermore, MS significantly increases the shear angle within the preform. The in-plane shear angles with MS exceed those observed with NS, as reflected in the maximum values for 90-MS-0.05 (39.2°) and 90-MS-0.20 (39.7°). In contrast, DS results in lower maximum shear angles than NS under blank-holder pressures of 0.05 MPa (35.0°) and 0.20 MPa (34.6°). Thus, DS decreases in-plane shear angles by minimizing regions of high shear concentration. CS shifts the maximum shear angle toward the corners of preform, expanding the concentration zone in unformed regions while reducing it in the useful zone. This redistribution of shear angles enhances wrinkle mitigation by improving control over shear angle distribution.

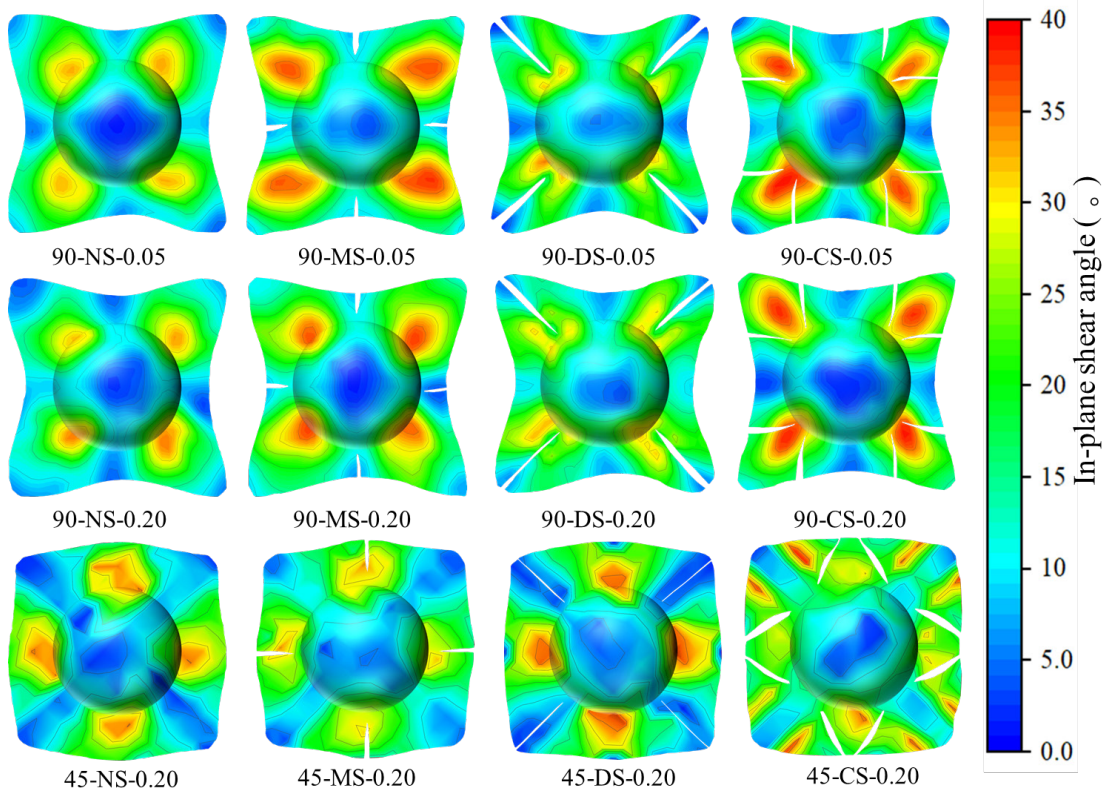


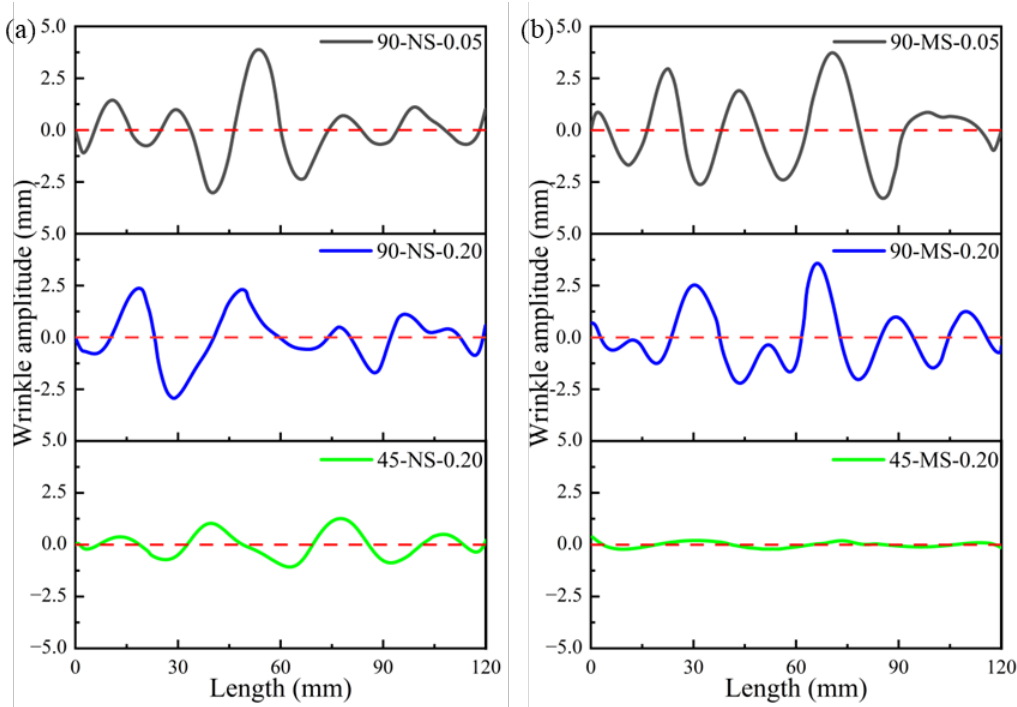
Figure 3-9 The change of in-plane shear angle under different slitting positions.

The shear behavior in the $[-45^\circ/45^\circ]$ ply differs from that in the $[0^\circ/90^\circ]$ ply. MS (45-MS-0.20) effectively reduces the shear angle of the slit preform. Its maximum shear angle remains lower than that of 45-NS-0.20, confirming enhanced efficiency in minimizing shear concentration. DS has a negligible effect on the shear angle within the shear angle concentration zone. CS decreases the shear angle concentration zone but raises the maximum shear angle in the unformed region, where the maximum shear angle is 35.8° in NS and 38.6° in CS. Simultaneously, the maximum shear angle in the useful zone is decreases, and the yellow or orange zones in this region vanish, as illustrated in 45-CS-0.20 in Figure 3-9.

Slitting in shear angle concentration zones is a highly effective approach for minimizing shear angles, regardless of preform ply orientations. Furthermore, managing shear angle concentration zones via CS effectively reduces shear angles in the useful area. Varying slitting positions and ply orientations markedly affect the distribution and magnitude of shear angles in preforms, with strategic slitting positions either increasing or decreasing shear angles in specific regions.

3.3.4 Wrinkling defects

Due to the quasi-symmetric deformation in hemispherical forming, wrinkle characterization can be efficiently analyzed using a representative quarter-hemisphere surface area. As shown in Figure 3-4, wrinkles along the bottom profile measure 120 mm. Wrinkles characterization via waveforms for varying slitting positions is depicted in Figure 3-10. Analysis of wrinkles after forming shows significant influences from ply orientation, blank-holder pressure, and slitting positions. At a blank-holder pressure of 0.20 MPa, $[-45^\circ/45^\circ]$ ply typically display reduced wrinkle amplitudes compared to $[0^\circ/90^\circ]$ ply (see red and blue lines in Figure 3-10), highlighting the critical influence of weave fabric orientation on wrinkle formation. Shen et al. [88] and Boisse et al. [92] noted fewer wrinkles in the $[-45^\circ/45^\circ]$ ply than in the $[0^\circ/90^\circ]$ ply, attributed to heightened sensitivity to shear deficiencies along warp and weft directions. Furthermore, increased blank-holder pressure consistently reduces wrinkle amplitudes across all slitting positions. This effect likely stems from enhanced force fostering uniform material deformation and diminishing localized stress concentrations that induce wrinkles [150].



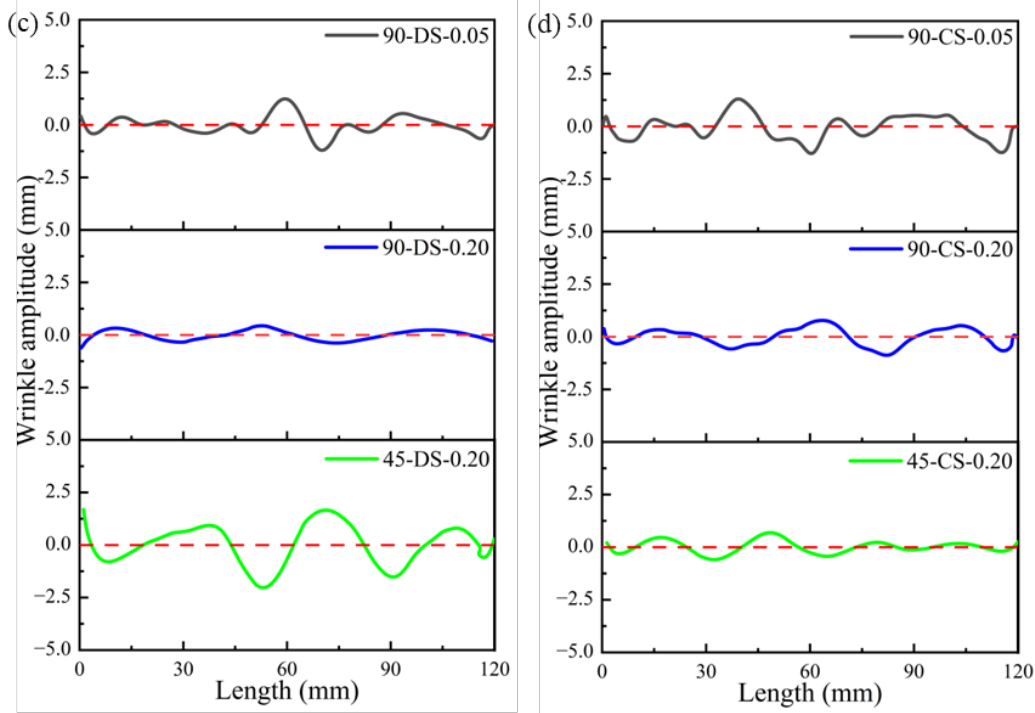


Figure 3-10 Wrinkle amplitude in different slit preforms:(a) NS; (b) MS; (c) DS; (d) CS.

For the $[0^\circ/90^\circ]$ ply, MS exhibits only moderate improvement in wrinkle reduction, as evidenced by comparable wrinkle amplitudes between the black and blue lines relative to NS. DS achieves the most significant reduction in wrinkling across all slitting configurations. Specifically, DS exhibits substantially lower amplitudes at both pressure levels compared to NS and MS, particularly at 0.20 MPa, where the blue line demonstrates a significant reduction in amplitude magnitude (Figure 3-10c). CS also reduces amplitudes in the $[0^\circ/90^\circ]$ ply, though less effectively than DS, as CS samples retain higher wrinkle amplitudes. As shown in Figure 3-10b, MS (green line) produces smoother surfaces in the $[0^\circ/90^\circ]$ ply, with fewer and less pronounced peaks, suggesting effective wrinkle suppression. In contrast, DS exhibits no notable reduction in wrinkling for this ply, while CS shows limited improvement compared to MS. In summary, DS demonstrates the greatest wrinkle mitigation in the $[0^\circ/90^\circ]$ ply, whereas MS achieves substantial wrinkle reduction in the $[-45^\circ/45^\circ]$ ply; these findings are analyzed in detail in Chapter 3.4.2.

3.4 Discussion

3.4.1 Correlation between slitting positions and in-plane shear angle

The orientation of warp and weft yarn governs the deformation mode of the preform, as shown in Figure 3-11. Variations in deformation modes lead to distinct shear angle concentration zones. During woven textile deformation, in-plane shearing serves as the primary deformation mechanism due to the nearly inextensible nature of fiber tows and potential inter-tow sliding [17,18]. In the $[0^\circ/90^\circ]$ ply, fiber tows experience pronounced shear deformation at the corners, as indicated by the red line in Figure 3-11a, which illustrates yarn deformation in the unformed region. This orientation aligns fibers along the principal tension and compression axes during forming. Consequently, the fabric exhibits reduced adaptability to complex geometries, increasing susceptibility to localized shear and stress concentrations [44]. Conversely, the $[-45^\circ/45^\circ]$ ply aligns fibers diagonally relative to the primary load paths typically encountered in the forming process. Shear deformation occurs predominantly along the mid-sections of the four sides, with minimal deformation at the corners. Yarn deformation in the unformed region is depicted in Figure 3-11b. This inherent alignment enhances shear deformability, enabling the fabric to accommodate complex geometries without localized stress concentrations. Thus, slitting positions exert minimal influence on material draw-in, as yarn orientations primarily dictate preform contours and draw-in behavior.

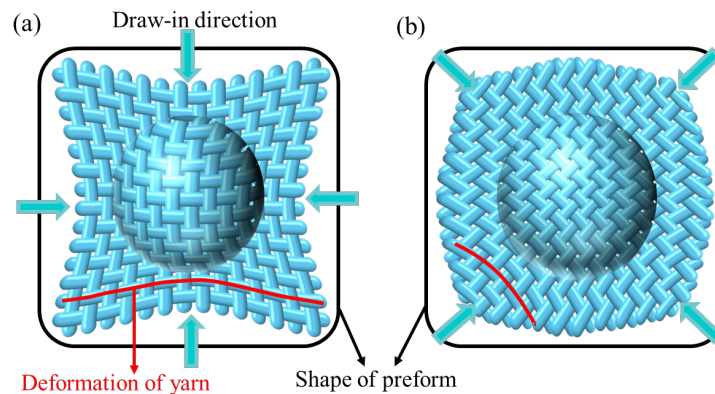


Figure 3-11 In-plane shear deformation mechanism of woven fabric: (a) $0^\circ/90^\circ$ ply; (b) $[-45^\circ/45^\circ]$ ply

To assess variations in shear angle across slitting configurations, shear angles were quantified at identical measurement locations for each preform (Figure 3-12a). The measurement location corresponds to either the X or Y direction, as marked by the red line, as shown in Figure 3-12a. In the $[0^\circ/90^\circ]$ ply (Figure 3-12b and Figure 3-12c), MS and CS exhibit higher shear angles relative to NS. Conversely, DS demonstrates distinct behavior, characterized by a reduced maximum shear angle and a divergent curve profile. DS modifies the shear angle concentration zone, lowering the maximum shear angle in the unformed region. As shown by the blue line in Figure 3-12b and Figure 3-12c, under blank-holder pressures of 0.05 MPa and 0.20 MPa, maximum shear angles in this zone measure were 31.2° and 30.1° , respectively.

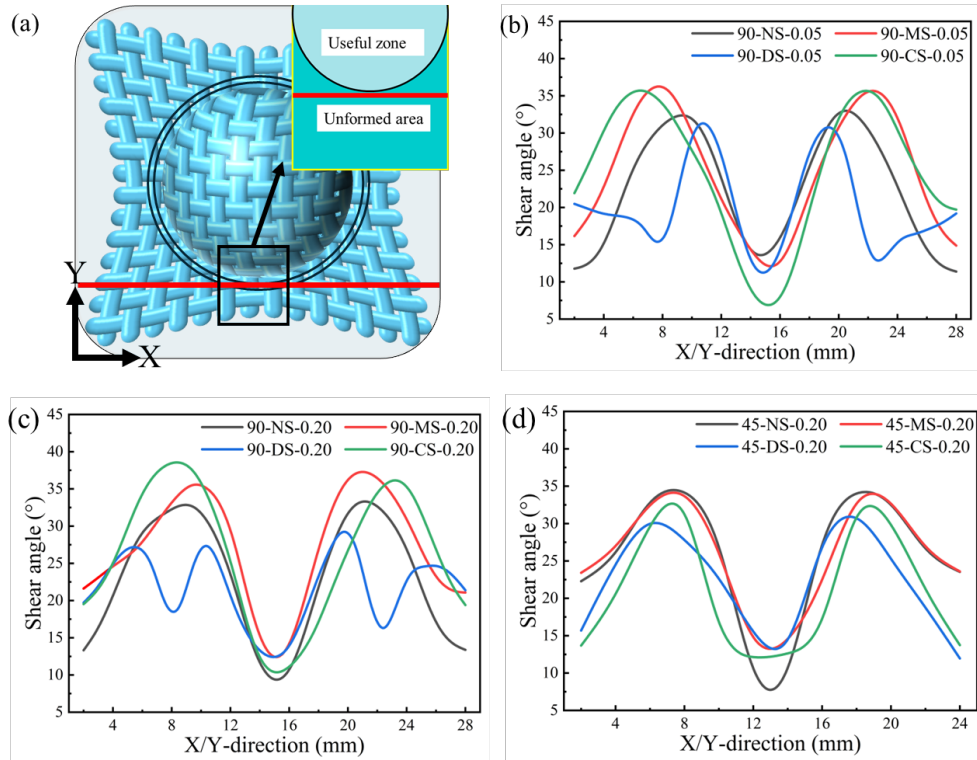


Figure 3-12 Shear angle: (a) The test position of shear angle; (b) $[0^\circ/90^\circ]$ ply under 0.05 MPa; (c) $[0^\circ/90^\circ]$ ply under 0.20 MPa; (d) $[-45^\circ/45^\circ]$ ply under 0.20 Mpa.

In the $[-45^\circ/45^\circ]$ ply (Figure 3-12d), MS exhibits a reduced maximum shear angle of 32.4° , which effectively suppresses wrinkle formation. However, the shear angle distribution profiles in this ply remain consistent across slitting configurations. Notably, the maximum shear angle in the useful zone is lower than that in the unformed region,

with values ranging from 30.2° to 32.2° and 35.8° to 39.7°, respectively. These observations align with simulations and experimental findings reported by Guzman-Maldonado et al. [93]. Precision slitting of the high shear angle concentration zone thus significantly reduces maximum shear angles of preform, mitigates the risk of wrinkle formation.

3.4.2 Consistency between slitting positions and wrinkles

To analyze the consistency between slitting positions and wrinkles, the parameters of W_a , W_t , and W_d are introduced to characterize the variation of the waveform, respectively. For more details information on the equation can read the reference [88]. The Eq.(3-2) for W_a is presented below:

$$W_a = \frac{1}{L} \int |Z| dx \cong \frac{1}{N} \sum_{i=1}^N |Z_i| \quad (3-2)$$

Here, W_a is the arithmetic mean of the absolute values of the vertical deviation from the mean. L is the length of the waveform. Z represents the waveform. N indicates the entire number of measurements, and Z_i denotes the height of the waveform. The equation of W_t can be expressed as Eq.(3-3):

$$W_t = Z_{max} - Z_{min} \quad (3-3)$$

Where W_t is defined as the sum of the largest profile peak height and the largest profile valley depth within the evaluation length. Z_{max} and Z_{min} represent the maximum and minimum values of the waveform, respectively. The equation defining W_d are shown as follows the Eq.(3-4):

$$W_d = \frac{1}{L} \int \frac{d^2z/dx^2}{[1+(dz/dx)^2]^{3/2}} dx \cong \frac{1}{L} \int \left| \frac{d^2z}{dx^2} \right| dx \cong \frac{1}{N-2} \sum_{i=2}^{N-1} \left| \frac{2Z_i - Z_{i-1} - Z_{i+1}}{\Delta x^2} \right| \quad (3-4)$$

Where W_d is the arithmetic mean of the absolute value of the waveform.

Owing to the inherent symmetry of the hemispherical geometry, the influence of ply orientation on surface waviness was systematically evaluated. Figure 3-13 summarizes the waviness parameters for all slitting configurations. Comparative analysis of wrinkling indices W_a , W_t , and W_d indicates that DS yields consistently lower values than other configurations for the [0°/90°] ply under equivalent blank-holder pressures.

Specifically, 90-DS-0.20 exhibits reductions of 78.8%, 80.2%, and 88.9% in W_a , W_t , and W_d , respectively, relative to 90-NS-0.20. For the $[-45^\circ/45^\circ]$ ply, W_a , W_t , and W_d values for MS measure 0.11, 0.59, and 0.01 mm, respectively, which are markedly lower than those of other configurations. The 45-MS-0.20 preform demonstrates the smoothest surface morphology with minimal wrinkle severity. These findings collectively confirm the superior performance of DS and MS in mitigating wrinkling within their respective ply orientations, corroborating the conclusions outlined in Chapter 3.3.4.

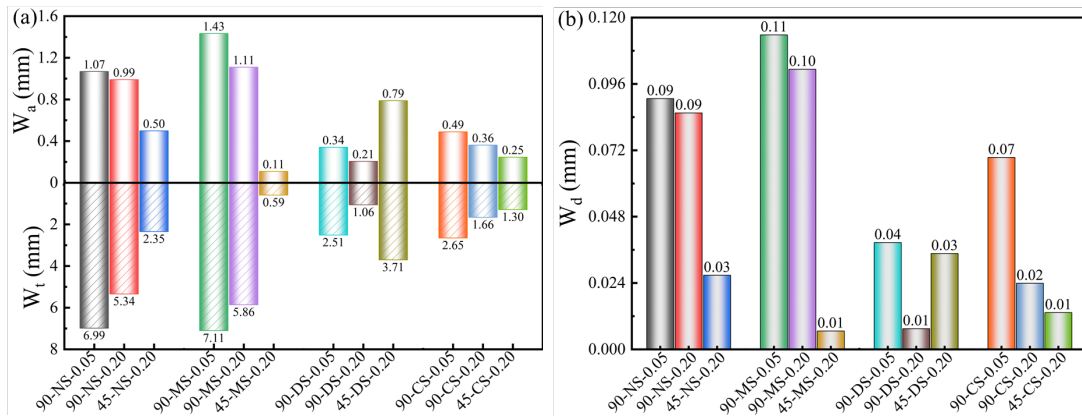


Figure 3-13 Waviness parameters of wrinkles: (a) The value of W_a and W_t ; (b) The value of W_d .

DS mitigates wrinkling by dispersing in-plane shear and forming forces, achieving more uniform stress distribution within the $[0^\circ/90^\circ]$ ply. As illustrated in Figure 3-14a, slit edges reorient toward the maximum draw-in region (preform center), facilitating uniform material flow and stress redistribution during forming. The expansion of slit edges along the warp/weft directions reduces diagonal pull-in and compressive forces between central yarns. Additionally, DS shortens yarns adjacent to the useful zone, enhancing inter-yarn slippage. These mechanisms collectively minimize shear concentrations and suppress wrinkles, improving preform quality and structural integrity. While CS also reduces waviness, its efficacy is inferior to DS. In the $[0^\circ/90^\circ]$ ply (Figure 3-14b), CS introduces fewer diagonal yarn connections due to reduced spacing between slit edges, rendering corner yarns prone to stretching and deformation. Furthermore, slit edge expansion amplifies compressive forces between warp and weft

yarns at corners, exacerbating localized deformation. Consequently, modifying shear angle concentration zones represents the most effective wrinkle reduction strategy, with targeted shear zone control further enhancing outcomes.

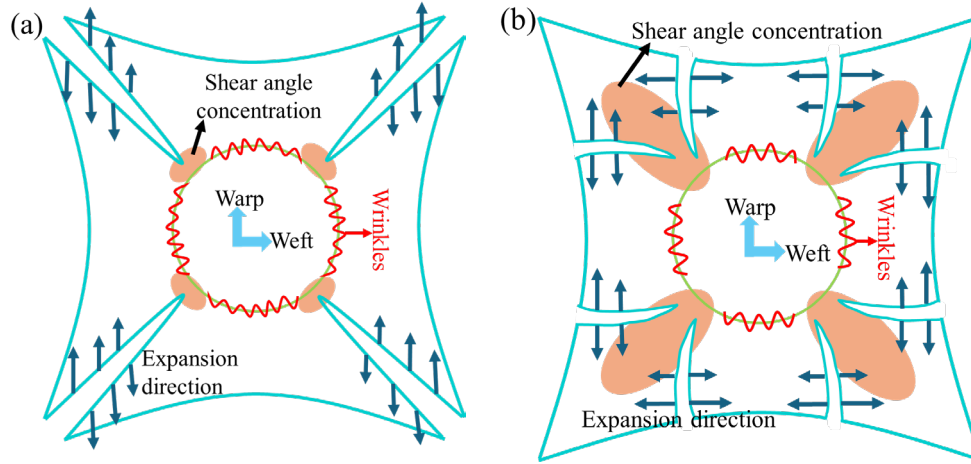


Figure 3-14 Illustration of yarn sliding along the slitting line and the zone of in-plane shear angle concentration for $[0^\circ/90^\circ]$ ply: (a) in DS case; (b) in CS case.

For the $[0^\circ/90^\circ]$ ply, this phenomenon arises from slit edge expansion toward the corners in the unformed region, as shown in Figure 3-15a, which restricts yarn slippage. Concurrently, enhanced slippage of warp/weft yarns at slitting locations within the useful zone is evident in Figure 3-8a and Figure 3-8b. The interplay of these mechanisms elevates shear angles in the concentration zone, thereby inducing edge wrinkling in the useful zone. MS demonstrates limited wrinkle reduction efficacy. For the $[-45^\circ/45^\circ]$ ply (Figure 3-15b), MS redistributes shear forces from the concentration zone to the preform diagonal, increasing tensile forces along warp/weft directions and inhibiting wrinkle formation. Additionally, MS shortens warp/weft yarns in the unformed region, reducing longitudinal compression [10]. Consequently, the $[-45^\circ/45^\circ]$ ply exhibits minimal wrinkling due to reduced yarn length.

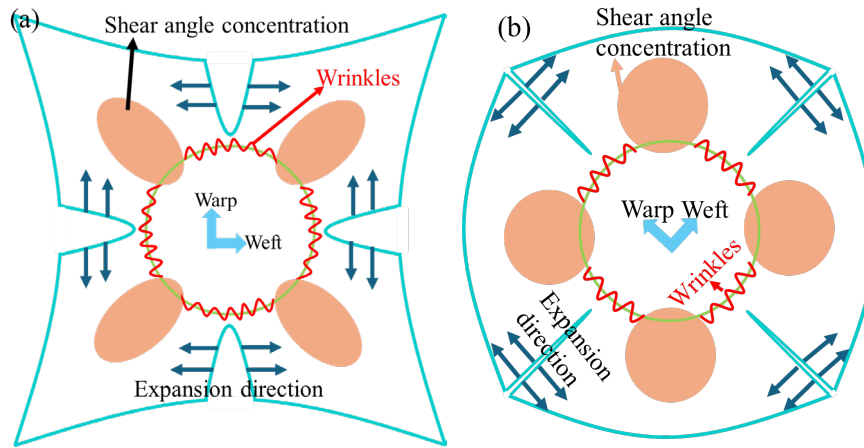


Figure 3-15 Illustration of yarn sliding along the slitting line and the zone of in-plane shear angle concentration for MS fabrics (a) $[0^\circ/90^\circ]$ ply and (b) $[-45^\circ/45^\circ]$ ply.

Precision slitting effectively reduces forming defects in continuous fiber-reinforced textile preforms by controlling shear angle concentrations during forming. While this approach demonstrates significant advantages, it introduces limitations necessitating parameter optimization. Further research is required to evaluate slitting parameters across diverse geometries and fabric architectures. Although precision slitting shows efficacy in quasi-symmetric forming, its impact on asymmetric or complex geometries remains unclear. Future studies will prioritize slitting position and depth to establish their influence on defect mitigation in varied forming applications.

3.5 Conclusion

This chapter introduces a precision slitting to mitigate forming defects in continuous fiber-reinforced textile preforms during hemispherical forming. Experimental investigations evaluated preform formability by analyzing punch force, material draw-in, shear angles, and wrinkle severity. Results demonstrated that precision slitting significantly decreased shear angles and eliminated wrinkling. Slitting position exerts a greater influence on punch force in the $[-45^\circ/45^\circ]$ ply than in the $[0^\circ/90^\circ]$ ply, while material draw-in remains largely unaffected by slitting and is governed by punch geometry. Eliminating shear angle concentration zones effectively reduces overall shear angles across all ply orientations. Controlled mitigation of these zones further minimizes maximum shear angles in critical regions, measuring 30.1° for the $[0^\circ/90^\circ]$

ply and 32.4° for the $[-45^\circ/45^\circ]$ ply. Precision slitting achieves up to 80% reduction in wrinkle severity (waviness values), with shear angle zone elimination proving most effective. These findings advance manufacturing strategies for continuous fiber-reinforced textiles, enhancing product performance while minimizing defects.

In the next chapter, a further optimization of precision slitting was explored. It primarily examines forming defects and the combined effects of slitting locations and tufting patterns on wrinkle formation. The influence of slitting locations and two tufting patterns on the shear angle and wrinkle behavior of the preform was investigated experimentally. Main discussed the effects of continuous deformation field changes on the deformability of continuous fiber reinforced textile preform.

4. Deformation field reconfiguration through slitting and tufting process

4.1 Introduction

Forming refers to a class of advanced manufacturing processes that fabric preform into a desired three-dimensional structures or product [155,156]. In the continuous fiber forming process, the fabric and the geometries of the final piece (the dimensions and the shape, for example in Figure 4-1a) have been predetermined. It might be impossible to avoid wrinkles by simply changing the forming conditions, such as the pressure, shape/position of the blank-holder, or the speed of the punch [127,147,150,153,157]. Figure 4-1b illustrates the common hemispherical forming, and the useful zone is the deformed zone after forming. In this scenario, an innovative slitting step before forming has been proposed to minimize the wrinkles [76,158]. To minimize wrinkles as much as possible, the slit edge will be positioned close to the boundary of the useful zone, as presented in Figure 4-1c. However, the absence of proper restraints on the slit edge causes the edges of the slit preform to be prone to extension along the warp or weft direction, destroy the structural integrity in the useful zone, leads to degradation of mechanical properties [76]. To address this issue, it is essential to introduce restraints

to the slitting process. Tufting usually used to provide through-thickness reinforcement of a traditional two-dimensional multilayered preform, thus improving its resistance to delamination in the final part [18], as shown in Figure 4-1d. In this chapter, the proposed pre-assembly process employs a tufting technique to control the expansion of slit edge [12,18,36]. Tufting not only stabilizes slit edges but also improves the precision and quality of the deformed preforms while maintaining the continuity of the fabric's in-plane shear deformation field [12,36,48]. Tufting modifies and reduces relative slippages between textile layers, thereby enhancing the overall forming process by balancing constraint and deformability [19].

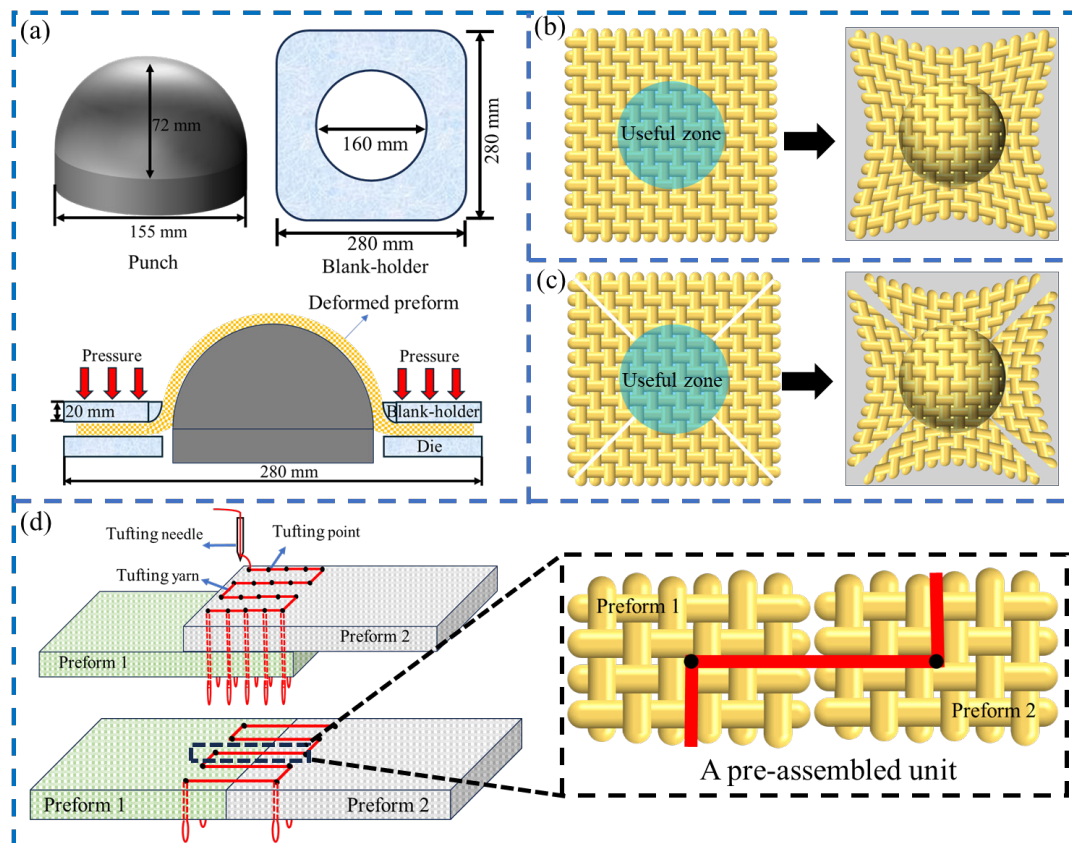


Figure 4-1 (a) Schematic representation of the hemispherical forming process, including the dimensions of the punch and blank holder; (b) Non-slit fabric before and after hemispherical forming; (c) Slit fabric before and after hemispherical forming, along with discontinuous fabrics; (d) Pre-assembly stage using tufting, showing the assembly of superposed preforms and the alignment of two preforms on a flat surface, with a close-up view of a pre-assembled unit.

As shown in Figure 4-2a, the left illustrates the continuous in-plane shear field and corresponding to the in-plane shear field in the non-slit fabric, while the right presents the simulation of the in-plane shear angle (with the orange region indicating areas of strong in-plane shear concentration) [93]. Notably, this non-slit configuration exhibits inherent in-plane shear zone, indicating the need for targeted structural intervention. Slitting and tufting modify the in-plane shear field in the forming process two times. Slitting cuts the continuous in-plane shear deformation field (see in Figure 4-2b), and then tufting intricately links the continuous in-plane shear fields with the tensile deformation fields of tufting yarns. This connection is significant as it influences the overall deformation properties of the preform part, which in turn directly alters the final mechanical properties of the preform. This reconnection is less rigid compared to the interlocking observed in woven fabric structures, permitting greater slippage during the forming stage [18]. Figure 4-2c illustrates the initial states of the tufting yarn before deformed. Figure 4-2d shows that as the two sides of the slit edge move apart, the in-plane yarn stretches, the tufting yarn slips, and the tufting seam becomes larger while the tufting loops shorten. This slippage is crucial as it accommodates the complex deformations required for deep drawing or forming operations [19]. The capacity of tufting yarns to slip within the tufting holes during the forming process is a defining feature that differentiates tufted preforms from non-tufted ones.

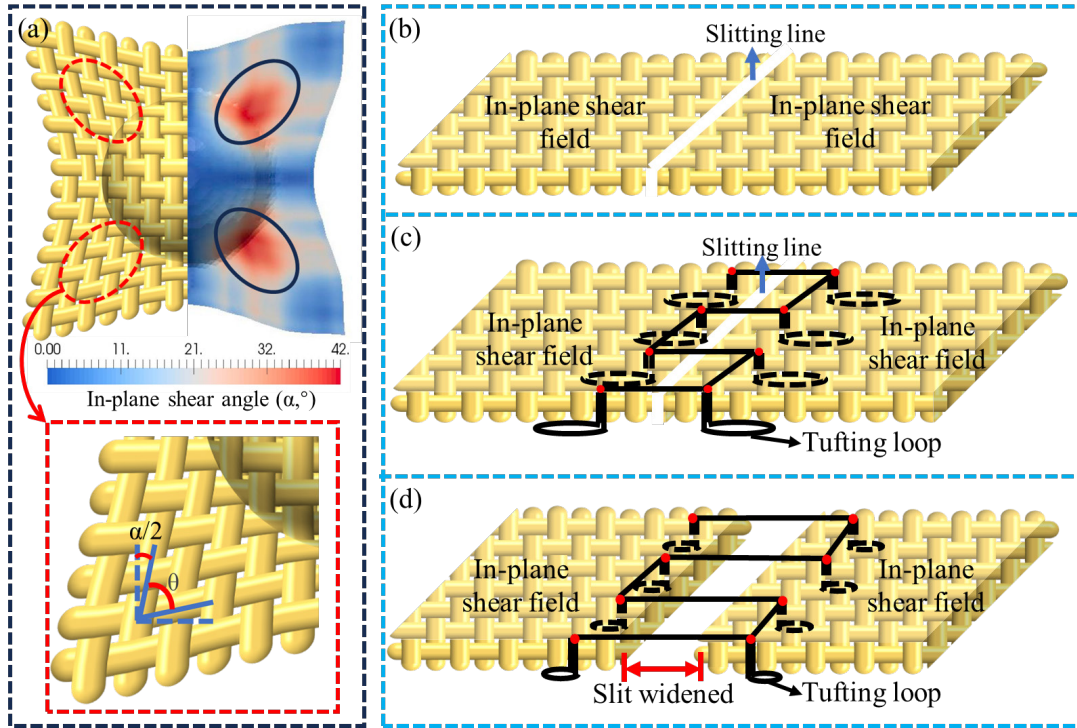


Figure 4-2 (a) Continuous in-plane shear field in non-slitted fabric and corresponding in-plane shear angles (for the $[0^\circ/90^\circ]$ ply case) [93]; (b) Discontinuous in-plane shear field caused by slitting; (c) Fabric assembly by tufting; (d) Extension of the tufting seam in the deformed fabric.

The continuous in-plane shear deformation field changes caused by slitting and tufting certainly impact the deformability of preform, thereby influencing the final mechanical performance of composite part. Slitting is carried out to disrupt the in-plane shear field, while tufting is used to replace in-plane shear with yarn tension, thereby preventing further damage caused by slitting. However, the combined effect of slitting and tufting introduces unpredictable behaviors. Consequently, this chapter aims to investigate the impact of changes in the continuous in-plane shear field and tensile deformation fields of tufting yarns on the forming behavior.

4.2 Materials and methods

4.2.1 Tested woven fabric

As presented in Table 3-1, the material used in this chapter is a continuous E-glass fiber with a plain weave pattern, featuring a balanced warp-to-weft ratio of 1:1, ensuring

uniform tensile properties in both the warp and weft directions. The fabric's key properties include an area density of $153.06 \pm 5 \text{ g/m}^2$ and a warp and weft yarn density of 11.5 yarns per centimeter. The dimensions of each preform are $280 \times 280 \times 0.15 \text{ mm}^3$.

4.2.2 Forming testing

During the forming process, the textile preform undergoes a complex deformation mode composed of tensile, in-plane shear, bending and transverse compression [159]. The shear angle refers to the angle change between warp and weft yarns during deformation. The initial state of the woven fabric, characterized by an orthogonal orientation of warp and weft yarns (in-plane shear angle = 0°), is shown in Figure 4-3a. As the shear angle increases, the yarns rotate relative to each other through coordinated slippage (shear deformation). However, when this process exceeds the critical threshold (shear locking state), restricted yarn slippage and lateral compaction triggers shear locking, leading to out-of-plane buckling and subsequent macroscopic wrinkle formation. Figure 4-3b shows the example of wrinkles observed in hemispherical forming in experiment [76].

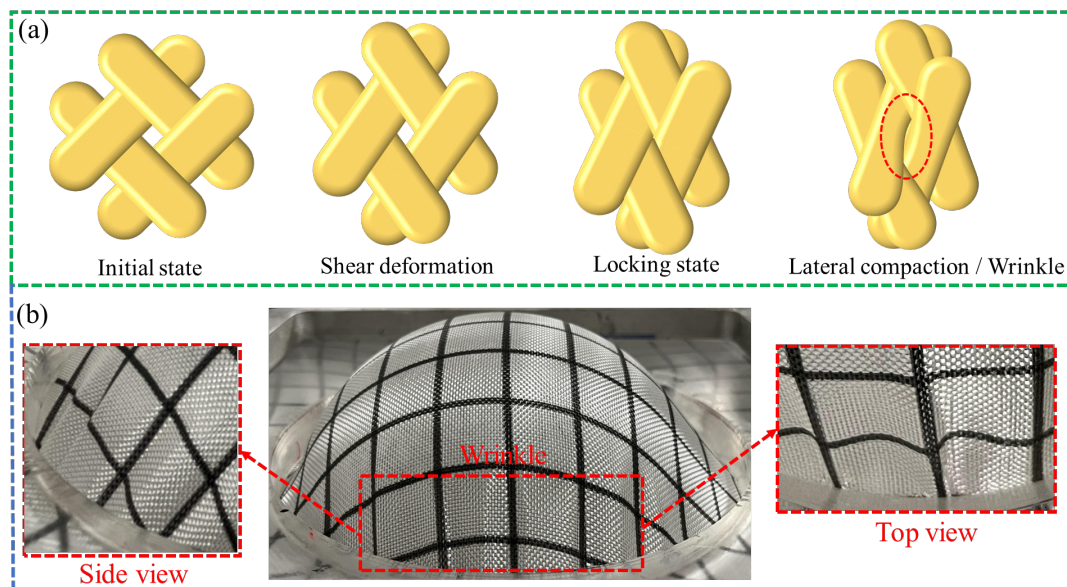


Figure 4-3 (a) Representation of the wrinkling phenomenon during forming, caused by lateral compaction under shear locking state resulting from in-plane shear deformation; (b) Example of wrinkles observed in hemispherical forming.

The forming device is the assembly of a mechanical part and an optical part consisting of video cameras and a linear infrared array associated with a mark-tracking technique. The mechanical part consists of a punch/open die system coupled with a classical blank-holder system. The hemispherical punch was mounted on the load sensor and the load sensor records variations of punch force. The main dimensions of the hemispherical punch and blank-holder is noted in Figure 3-1a. The advantage of a hemispherical punch is that a uniform load is applied in all directions within the fabric plane. Initially, black line markings are added to the surface of the preform for tracking yarn change. The preform or fabric was placed between the blank-holder and the die. After that, the blank-holder applied 0.20 MPa of pressure to the outer part of the die during the forming process. The punch achieved vertical displacement at a constant rate of 7.72 mm/s, applying a load force of 0.15 MPa. A digital camera positioned above the preform recorded the forming process, while an infrared sensor array is used to increase the visibility of the wrinkles.

4.2.3 Discontinuous in-plane shearing field

Prior experimental investigations indicate that the implementation of slitting at strong in-plane shear zones can significantly mitigate wrinkle formation during hemispherical forming [76]. Yarn tows undergo pronounced in-plane shear deformation at the corners, with regions of in-plane shear angle concentration being most pronounced for the $[0^\circ/90^\circ]$ ply, as presented in Figure 4-4a [73,82]. Thus, the strong in-plane shearing zone transforms into a discontinuous in-plane shear field, and the slitting positions are placed along the fabric's diagonal, as shown in Figure 4-4b. Conversely, in the $[-45^\circ/45^\circ]$ ply, the shear distribution exhibits a contrasting pattern. Figure 4-4c shows that the fabric edges are slightly draw-in, as shear deformation is concentrated along the central regions of each side, with small deformation observed at the corners [88,108]. Figure 4-4d illustrates that the slitting position is located at the center of the fabric to modify the strong in-plane shear distribution.

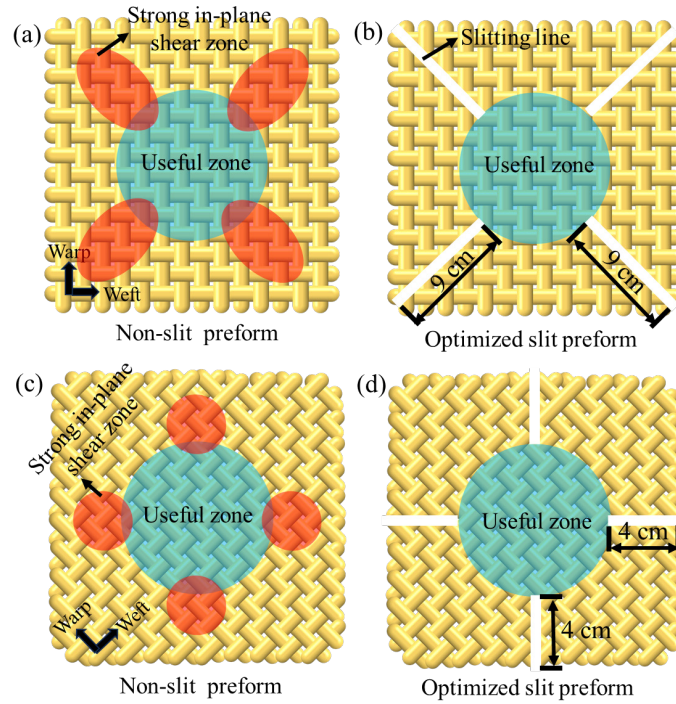


Figure 4-4 The localization of strong in-plane shear zones compared to the forming useful zones for the $[0^\circ/90^\circ]$ ply (a) and the $[-45^\circ/45^\circ]$ ply (c); Optimized slitting positions selected based on the strong in-plane shear zones and the lengths of slitting lines, for the $[0^\circ/90^\circ]$ ply (b) and the $[-45^\circ/45^\circ]$ ply (d).

4.2.4 Tensile deformation field of tufting yarns

The tufting process is the one-sided stitching technique for inserting thread through the thickness of different plies in a composite laminate. As shown in Figure 4-5a, the tufting process involves inserting a hollow needle into the reinforcement along the thickness direction and retracting it along the same path. The hollow needle used has a diameter of 1.2 mm. After the retraction of the tufting needle, the tufting yarn was retained in the preform by friction between yarn and supporting materials and held by underlying supporting material (e.g. high-density supporting foam), forming a free tufting loop on the bottom of the preform. To meet fiber strength requirements, a 67 TEX carbon fiber yarn (TENAX®) was used as tufting yarn and these tufting yarns were twisted to prevent degradation [48]. The carbon fiber yarn and its twist structure are shown in Figure 4-5b.

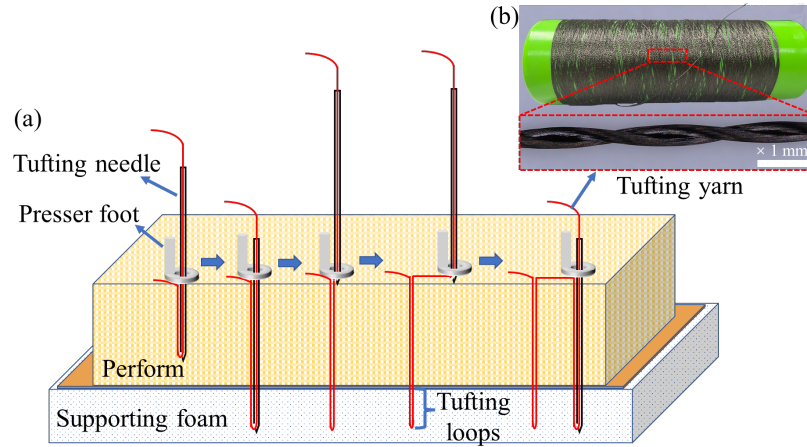


Figure 4-5 Schematic of the tufting process and the carbon tufting yarn (a) with a close-up view of twist structure (b).

Previous systematic investigations reveal that tufting significantly impacts wrinkling in multilayer composite preforms, depending on various tufting parameters (e.g., tufting density, pattern, position) [17,18,102]. This study investigated the relationship between slitting and tufting by testing two different tufting patterns to assess changes in wrinkling between slit and tufted samples. The first tufting pattern design, shown in Figure 4-6a, uses a simple rectangular tufting pattern (code RT) to link slit edge. To change the distribution of slit edge tension across the warp and weft directions, a zigzag tufting pattern (code ZT) is used, which is inclined for the yarn direction, as presented in Figure 4-6b. Thus, sample references like 90-RT denote the ply of $[0^\circ/90^\circ]$ and rectangular tufting pattern, respectively. One of the preforms after tufted is shown in Figure 4-6c and d.

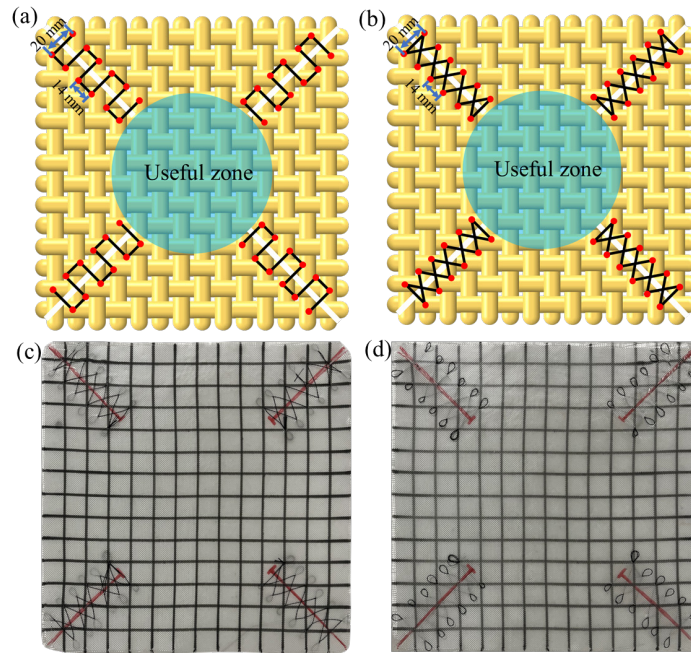


Figure 4-6 Tufting patterns (example: $[0^\circ/90^\circ]$ case): (a) Rectangular Tufting pattern (code: RT); (b) Zigzag Tufting pattern (code: ZT); (c) Front view of 90-ZT; (d) Back view of 90-ZT.

4.2.5 Wrinkling assessment

Using 2D image to characterize 3D shape of wrinkle is challenging. The depth and contours, essential to wrinkles, often fade in the transition to a flat image, highlighting the limitations of a 2D image in representing 3D shapes. Shen et al. [88] a novel image-based analysis method (Structure from Motion (SFM) and CloudCompare) has been applied to investigate the wrinkle morphologies of the quasi-isotropic fabrics during the deep forming process. The results indicated that the wrinkle characteristics are well quantified by a set of waviness parameters, whose values are matched well to the forming results. Therefore, by taking a series of high-resolution images from different perspectives and processing them with advanced image analysis techniques (SFM and Python), using the waviness to better characterize the wrinkles.

In the experiment, the effective observation area of wrinkles is above the blank-holder, as depicted in Figure 4-7a. Two linear infrared arrays provided uniform lighting, enhancing wrinkle visibility and generating clearer image data for analysis. Top view images from the high-resolution camera provided precise 2D data for analyzing wrinkle

morphology. More than 70 images from multiple perspectives and sufficient overlapping range were used to establish the point cloud data. Using the 3D reconstruction in the SFM to build an object's 3D structure from multiple 2D images, as presented in Figure 4-7b. Then, the point cloud data only retains data with a linear infrared array. Due to the quasi-symmetry of the hemispherical forming process, wrinkle patterns appear repetitively. The wrinkle morphology observed within the 0-90° exhibits sufficient representativeness to predict spatial distributions in the remaining circumferential regions. As illustrated in Figure 4-7c, the measurement angle of wrinkle and external surface of punch (base line) were systematically quantified. Subsequently, the raw wrinkle data, along with the base line coordinates, were imported into Python. A customized algorithm processed the input data by aligning the baseline with the x-axis, enabling the generation of normalized wrinkle height profiles. In the resulting output, elevated numerical values correspond to regions of increased wrinkle amplitude, whereas diminished values reflect proximity to the punch surface, thereby establishing a direct correlation between the metric and the localized deformation.

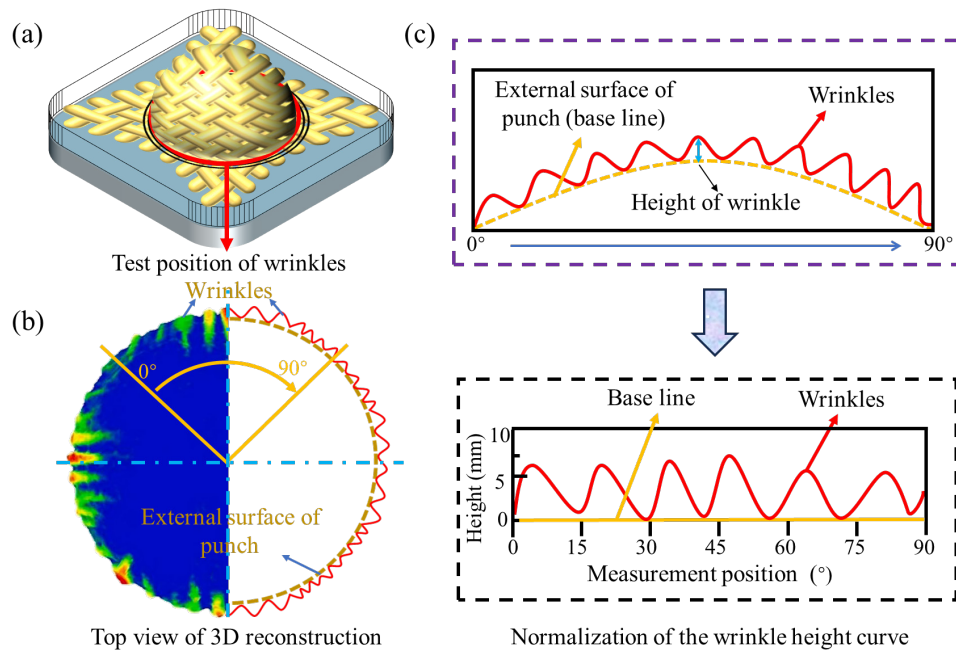


Figure 4-7 Characterization of wrinkles: (a) Testing position of wrinkles, (b) Using SFM to data materialize wrinkles, (c) Extraction of wrinkle data and determination of base line and then normalization of wrinkle height profiles.

4.3 Forming behaviors following the deformation filed changes

Figure 4-8 depicts the deformed preforms resulting from hemispherical forming using single ply of $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$. Although symmetrical deformation is generally expected during hemispherical forming, slight asymmetry was observed. During the forming process, it is challenging to maintain perfectly uniform blank-holder pressure across the entire boundary, especially considering the influence of fabric friction and thickness variations caused by tufting. These subtle differences can lead to asymmetric material flow and deformation during forming. For the $[0^\circ/90^\circ]$ ply, tufting reduces both the length and the opening size of the slit edge compared to non-tufted samples. This reduction suggests that tufting improve the connection between slit edges at the corners. Conversely, for the $[-45^\circ/45^\circ]$ ply, the differences in slit edges and distances between slits are less pronounced compared to non-tufted samples. These findings indicate that tufting process has a more nuanced effect on same fabric orientations. Therefore, it is necessary to investigate variations in slit edges and the influence of tufting yarn to enhance our understanding of the tufting process. Such an investigation could lead to improvements in the tufting technique, optimizing the performance and quality of the final product.

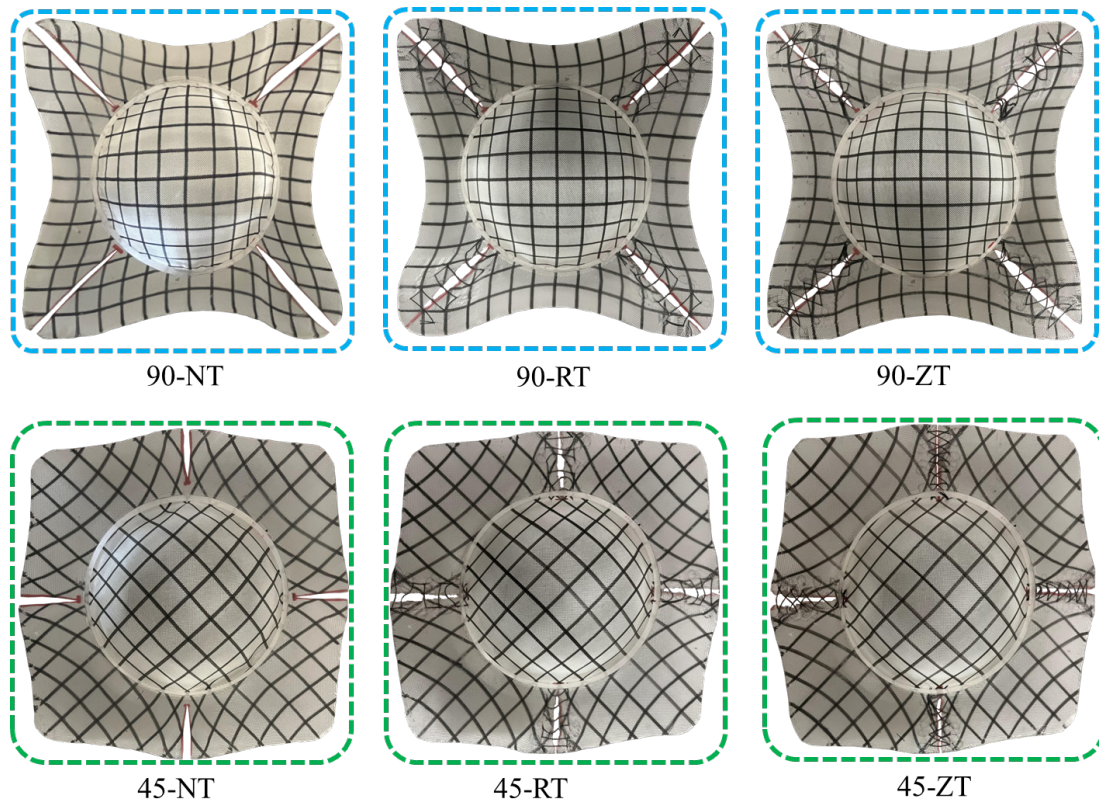


Figure 4-8 Forming results of non-tufted and tufted $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ slit-preforms (NT: non tufting, RT: rectangular tufting pattern, ZT: zigzag tufting pattern).

Figure 4-8 further reveals the quasi-symmetry of deformed geometries, demonstrating consistent morphological evolution across multiple forming results, which is a characteristic indicative of stable process and material anisotropy. To quantitatively assess formability, two key indicators were employed: punch force, which directly correlates with the material's tensile response, and in-plane shear angle, governing the reconfiguration of textile architectures through in-plane fiber reorientation. Concurrently, wrinkles were systematically measured to evaluate their spatial distribution and height, as wrinkles critically compromise structural homogeneity. Together, these factors offer a comprehensive evaluation of material formability and process effectiveness.

4.3.1 Punch force in deformed preforms

Tension in the preform is essential for minimizing wrinkles [115]. Applied tension keeps fibers aligned and tension, reducing the likelihood of deformation and wrinkle

formation. Punch force is a direct expression of the tension experienced by preform. A larger punch force applies to a greater load and increases tension in the useful zone. This elevated tension can enhance the fabric's resistance to wrinkling by promoting a more uniform material distribution. The hemispherical forming process demonstrated maximum punch force between tufted and non-tufted samples, as illustrated in Figure 4-9a. The tufting seam located at the slit edge exerts interfacial tribological interactions through dynamic frictional resistance at the blank-holder/preform interface during the forming process, as presented in Figure 4-9b. Concurrently, the tufting loops generating sliding friction regimes at both the preform/die, which collectively control the expansion of slit edge. Thus, the tufting technique enhanced the maximum punch force, attributed to its ability to restrict slit edge movement and dynamic frictional resistance between the tufted yarns and tools.

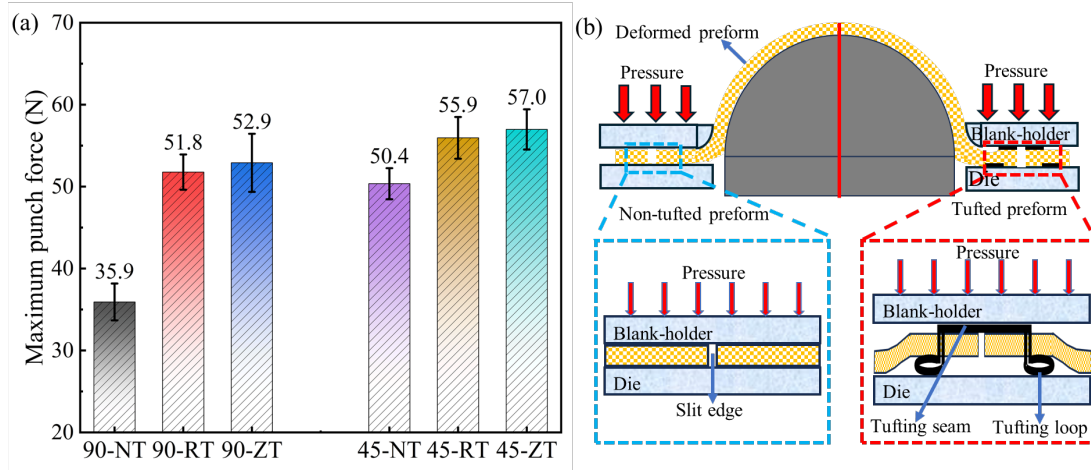


Figure 4-9 (a) Maximum punch force of deformed preform; (b) The influence of the presence of tufted yarns on preform compared with non-tufted sample.

For the $[0^\circ/90^\circ]$ ply, the increase in punch force from NT to RT and ZT is substantial for both tufting patterns (44.14 and 47.28%), as presented in Figure 4-9a, indicating that the tufting process has a positive effect on maximum punch force. The strong in-plane shear concentration primarily occurs near the diagonal of the preform for the $[0^\circ/90^\circ]$ ply. Due to the fiber alignment along the principal axes (0° and 90°), the fabric exhibits higher in-plane shear stiffness, which restricts shear deformation and leads to pronounced shear strain concentration near the unformed regions. The change in punch

force between tufted preforms (RT and ZT) is less pronounced for the $[-45^\circ/45^\circ]$ ply compared to the $[0^\circ/90^\circ]$ ply. This difference may arise because the $[-45^\circ/45^\circ]$ ply inherently exhibits a higher punch force. When fiber orientations deviate from the principal strain axes (typically 0° and 90° in hemispherical forming), shear stress concentrations develop at $\pm 45^\circ$ fiber crossover points, thereby requiring higher punch force [102].

4.3.2 In-plane shear angle characterization

In-plane shear angle is a critical process parameter that influences textile formability by defining the limits of fiber reorientation. The shear angle magnitude determines the onset of wrinkling and governs the development of strain localization, thus affecting structural integrity and the anisotropic mechanical response of the formed composites [17]. Figure 4-10 illustrates the in-plane shear angle distribution of deformed preforms with different slitting positions and tufting patterns under the $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ ply. For the $[0^\circ/90^\circ]$ ply, the region of in-plane shear angle concentration exhibits no significant shift or expansion in the RT or ZT configurations compared to the NT. The maximum in-plane shear angles recorded for NT, RT, and ZT are 34.6° , 33.2° , and 33.6° , respectively. This minimal variation ($\Delta \leq 1.4^\circ$) across tufting patterns suggests that the in-plane shear behavior is predominantly governed by the intrinsic fiber architecture and inter-yarn interactions. Furthermore, the absence of localized shear locking or severe distortion in the RT and ZT cases indicates that the tufting process does not significantly disrupt the yarn rotation or relative sliding mechanisms critical to accommodating shear.

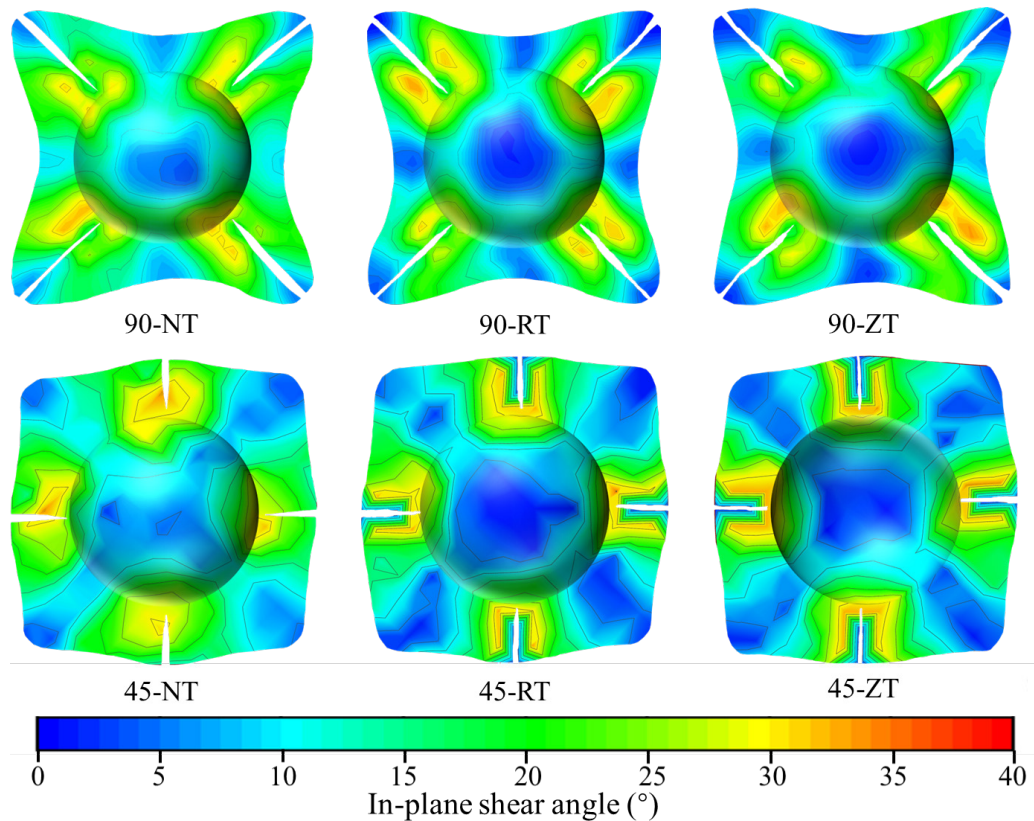


Figure 4-10 In-plane shear angle of slit and tufted preforms of $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ ply.

For the $[-45^\circ/45^\circ]$ ply, tufting has been shown to play a significant role in regulating the in-plane shear angle concentration zone, particularly in the vicinity of the slit edge. As illustrated in Figure 4-10, both the RT and ZT configurations exhibit markedly higher in-plane shear angles around the slit edge compared to the NT case, with the high-shear (yellow) zones distinctly concentrated near the slit edge. This phenomenon can be attributed to the presence of tufting yarns, which establish mechanical linkages across the slit edge. These connections generate localized shear stress concentrations that constrain excessive yarn rotation and limit shear propagation across the ply. As a result, in-plane shear deformation is more confined spatially, leading to a more controlled and stable forming behavior. The localization of the in-plane shear concentration zone near the slit edge helps to mitigate common defects such as wrinkling, fiber misalignment, or over-shearing, thereby contributing to improved preform integrity and formability in complex geometries.

4.3.3 Sliding of tufted yarn and extension of slit

Since the tufted yarns are not perfectly straight, their actual path length is slightly bigger than the direct distance between two tufting points, a geometric feature arising from the natural curvature introduced during the tufting operation. In all examined cases, this increase remains below 4%, indicating a well-controlled and consistent tufting process with minimal geometric deviations [18,48,90,102]. This small variation suggests that the tufting yarns retain their intended positioning and structural integrity prior to the forming stage, thereby ensuring their effectiveness in reinforcing the preform without introducing unintended pre-deformation or slack.

The proposed pre-assembly process utilizes tufting yarns to control the extension of the slit edge. Effective control of slit length extension serves as a key performance indicator. Figure 4-11a presents the deformed slit length and its extension relative to the initial configuration (marked in red: 90 mm for the $[0^\circ/90^\circ]$ ply and 40 mm for the $[-45^\circ/45^\circ]$ ply). Measurements indicate a notable extension of the slit length in NT configurations, with increases of 6.1 mm (6.8%) for 90-NT samples and 5.2 mm (13%) for 45-NT samples. Tufting helps mitigate slit length extension, resulting in reductions of 2% and 3% for 90-NT and 45-NT samples compared to the ZT configuration (see Figure 4-11b), respectively. This suppression of slit length extension is attributed to the mechanical interlocking effect of tufting yarns, which restricts the in-plane shear deformation field. The controlled slit length demonstrates the effectiveness of tufting yarns in providing mechanical interlocking.

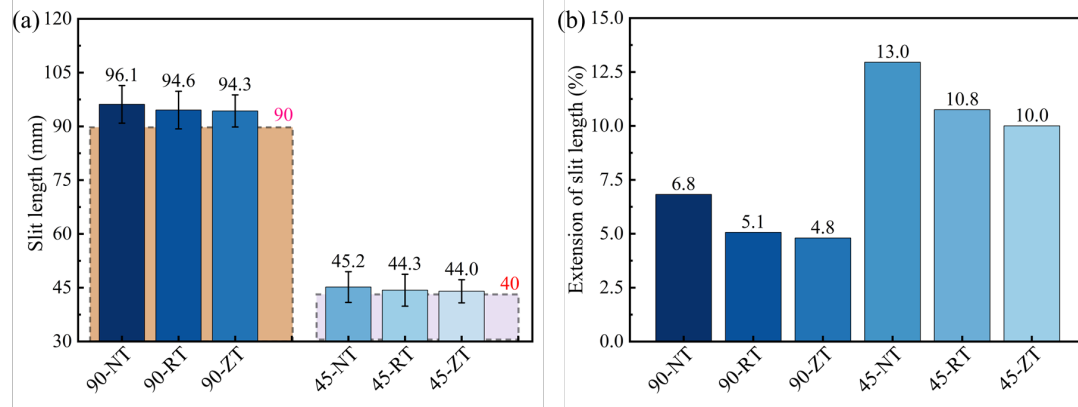


Figure 4-11 (a) The slit length after forming and initial lengths noted in red color and (b) the increases relative to the initial lengths.

During the forming stage, the length of the tufting seam increases as a result of the in-plane shear deformation within the preform. Table 4-1 quantifies the geometric evolution of the tufting seams by comparing their original and post-deformation lengths, with the increase ratio clearly reflecting process-induced changes. The increase between the initial and final lengths ranges from 12.9% to 15.0%. This length increase in the tufting seam is primarily attributed to the expansion of the slit edge and extension of the slit length during forming. As the tufting points are embedded within the preform, they move in coordination with the slit edge. The in-plane shear deformation field induces slit edge expansion, resulting in increased spacing between adjacent tufting points. This geometric change requires minor sliding of the tufting yarns to adjust for the increased slit edge spacing, contributing to the observed elongation of the tufting seam. This yarn sliding plays a critical role in absorbing local deformation without causing excessive stress concentrations. By allowing limited relative movement between the tufting yarns and the surrounding fabric, the preform is better able to conform to complex geometries during the forming process. In regions near the slit edge, where in-plane shear angle is highest, such adaptability is particularly beneficial for more evenly distributing localized shear forces and maintaining preform stability.

Table 4-1 Comparison between initial and final lengths of tufting seam.

Ref. of samples	Initial length (mm)	Length after forming (mm)	Increase ratio before / after forming (%)
90-RT	207	238	15.0
90-ZT	312	356	14.1
45-RT	165	189	14.5
45-ZT	264	298	12.9

From Table 4-1, it is also evident that ZT samples consistently exhibit short tufting seam sliding than RT samples. As shown in Figure 4-12, the reduced tufting seam sliding observed in ZT is attributed to differences in the direction of friction force (F_f) arising from variations in tufting pattern. In the RT, the tufting seams are aligned to generate a F_f predominantly perpendicular to the slit edge, as presented in Figure 4-12a. This orientation enables the tufting seams to effectively resist lateral slit edge expansion during tensile deformation. However, this also results in higher resistance to in-plane displacement between tufting points, which in turn causes more pronounced sliding along the tufting seam during tensile deformation of tufted yarn. In contrast, the ZT aligns the tufting seams at an angle to the slit edge, generating a F_f aligned with the direction of the tufting seam. Figure 4-12b shows the stretch of tufted yarn with ZT configuration. This alignment allows the load to be distributed more gradually along the tufting seam and better accommodates tensile deformation with minimal yarn displacement. The ZT configuration engages twice as many tufting yarns in frictional resistance compared to the RT, thereby enhancing its ability to distribute load more effectively. As a result, the tufting yarns in the ZT configuration undergo less stretching and reduced sliding, as evidenced by the shorter length of tufting seam change. In addition to tufting seam elongation, the insertion positions of tufting points become less consistent. For both RT and ZT, interfacial friction induces a directional migration of tufting points toward the slit edge, along with localized out-of-plane distortion of adjacent warp and weft yarns, as shown in Figure 4-12 with a close-up view unit.

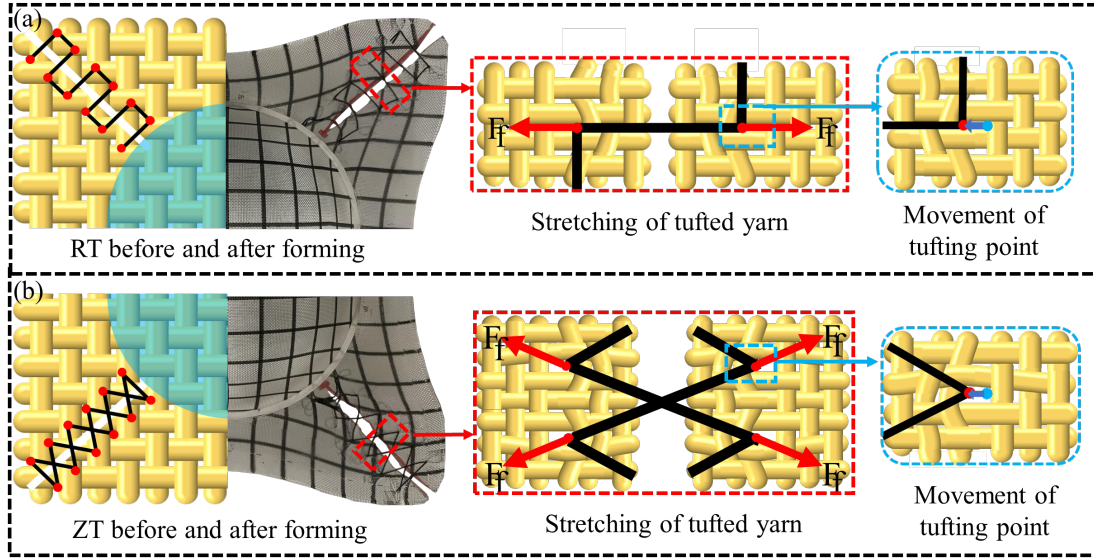


Figure 4-12 Initial (left) and final lengths (right) of tufting seam (for $[0^\circ/90^\circ]$ layer case), with a close-up view of stretching of tufted yarns and movement of tufting points (blue is the initial position and red is the final position)

4.3.4 Height of wrinkle and distribution

The forming of preforms during composite manufacturing is subject to significant variability, which affects the predictability of wrinkles [158]. Therefore, wrinkling needs to be quantified so that they can be controlled during forming process [88]. The height of wrinkles under different slit and tufted configurations is illustrated in Figure 4-13a and Figure 4-13b. The red points on the curve indicate the maximum wrinkle height within the 0° to 90° sector. The results revealed that the in-plane shear field changes affecting deformability across different preforms: Non-slit (NS) samples exhibit the most severe wrinkling, followed by RT and ZT, with NT demonstrating optimal surface quality. Specifically, tufting patterns (RT/ZT) amplify wrinkle formation compared to NT due to friction induced by tufting yarns and localized unevenness of the preform around slit edges. Despite these effects, they still outperform NS configurations through controlled in-plane shear field redistribution. The substantial increase in wrinkle dimensions observed highlights the potential balance between expansion of slit edge and tensile deformation of the tufting yarn, emphasizing the need for careful consideration of slit and tufted configuration.

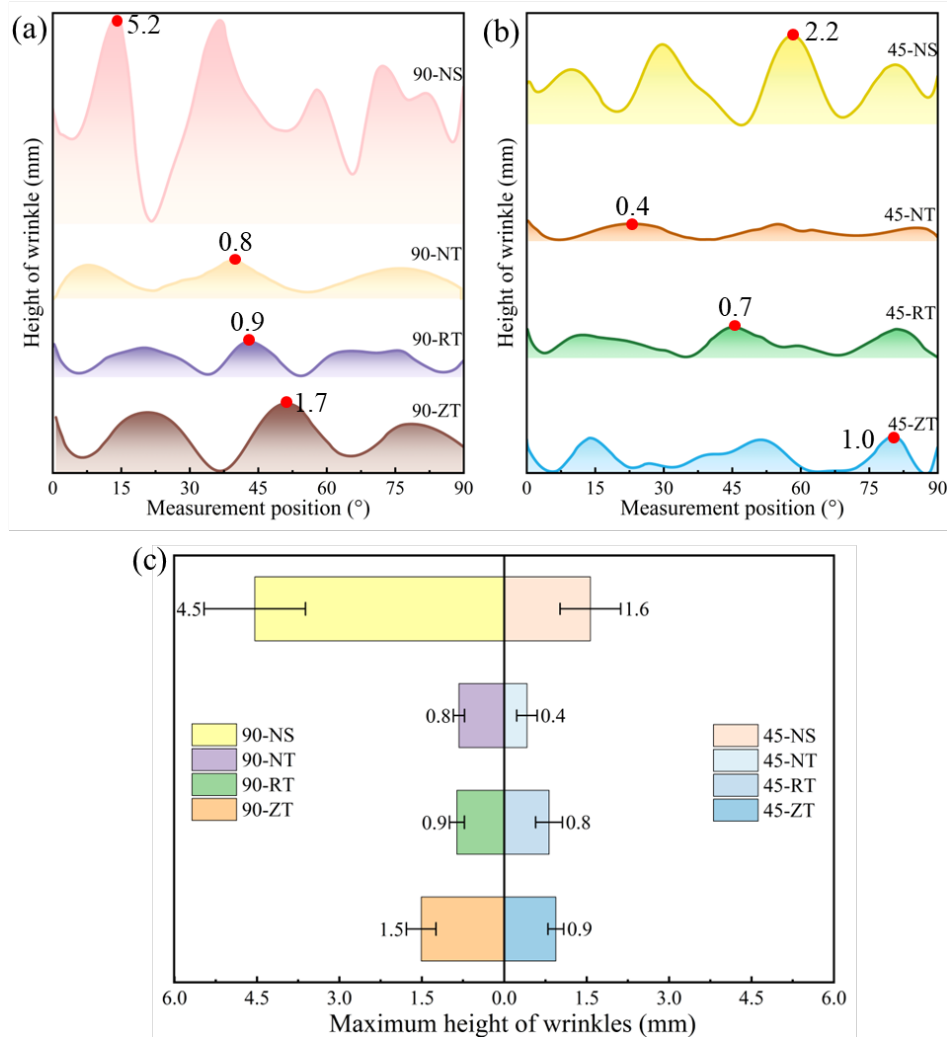


Figure 4-13 Height of wrinkle and distribution: (a) and (b) Wrinkle distribution of $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ ply (range from 0° to 90°); (c) Average of all peaks of wrinkle of $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ ply (range from 0° to 360°).

To systematically evaluate the effects of slitting and tufting processes, the average peak height of wrinkles in both $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ ply was calculated, as illustrated in Figure 4-13c. This peak height of wrinkles focused analysis prioritizes maximum height of wrinkles because they exhibit the most pronounced morphological on preform surfaces and critically determine the structural performance of final composites. The wrinkle analysis demonstrates distinct effects of slitting and tufting processes on wrinkle suppression across different ply orientations. For $[0^\circ/90^\circ]$ ply, slitting significantly reduced average wrinkle amplitudes by 82% (from 4.5 mm in NS to 0.8 mm in NT), highlighting its efficacy in in-plane shear filed through controlled yarn

reorientation. While tufting slightly increased wrinkles compared to NT (0.8 mm and 1.5 mm, respectively), these values remained substantially lower than NS, underscoring slitting's dominant role. For the $[-45^\circ/45^\circ]$ ply, slitting similarly reduced wrinkles by 73% (1.5 mm to 0.4 mm), with tufting-induced increments (increased 0.4-0.5 mm) remaining within acceptable wrinkles due to the ply's inherent shear compatibility. The data reveal a critical trade-off in preform: although tufting introduces localized yarn disturbances near the slit edges, its mechanical interlocking enhances global in-plane shear field redistribution, particularly benefiting in-plane shear sensitive $[0^\circ/90^\circ]$ ply. This configuration dependent response underscores the need for process customization: slitting remains essential for preform to mitigate in-plane shear locking, and improving the in-plane shear redistribution.

4.4 Conclusion

This chapter examined the combined effects of the slitting process and tufting patterns on hemispherical forming, focusing on in-plane shear angle field distribution and wrinkle formation. Slitting significantly reduces wrinkle amplitudes compared to non-slit configurations, while tufting introduces localized disturbances but still reduces wrinkle severity relative to non-slit cases. Tufting also reduces the slit length after forming and decreases slit edge displacement through controlled in-plane shear field. Due to tufting confined zones of concentrated in-plane shear angle near the slit edges, reducing deformation variability and enhancing forming control. The two tufting patterns had distinct effects on the in-plane shear deformation field. The rectangular tufting pattern demonstrated superior wrinkle reduction, whereas the zigzag tufting pattern was associated with increased localized stress concentrations. These findings underscore the importance of tailoring slitting methods and tufting patterns to meet the specific ply orientations and forming configurations. Optimizing these parameters can balance tensile deformation field and in-plane shear control, thereby enhancing overall preform integrity and forming accuracy. Future research should focus on developing predictive models to refine slit and tufted preform designs to minimize forming defects.

During the experimental sample preparation described in Chapters 3 and 4, significant material waste of glass fiber fabric was observed during the cutting process. To address this issue and enable material reuse, Chapter 5 will examine strategies for reusing offcuts and improving material utilization. This establishes a foundation for converting fabric scraps into functional preforms, advancing sustainable composite manufacturing through the reuse of offcuts.

5. Fabric scraps assembly and forming defect suppression by tufting

5.1 Introduction

The global composites market is projected to experience substantial growth, with a compound annual growth rate of 6.05% anticipated between 2025 and 2034, potentially reaching a market valuation of \$213.32 billion by 2034 [160,161]. The composites market is driven by the increasing demand for lightweight materials in industries such as aerospace, automotive and construction [162–164]. Among various composite technologies, continuous fiber-reinforced textile composites have emerged as a cornerstone material system, currently holding over 40% market share, due to their exceptional strength-to-weight ratio, superior mechanical performance, and design flexibility of shape [165–168].

The manufacturing process begins with the automated unwinding of fabric from large-scale rolls (see Figure 5-1a), followed by precision cutting operations that convert the fabric into preforms with basic geometries (for example, square, rectangular, or circular) tailored to the forming machinery's requirements, presented in Figure 5-1b. Optimal material utilization is achieved when cutting rectangular or square patterns along the warp and weft directions due to the sample is arranged more compactly, as present in Figure 5-1a. Optimal material utilization is achieved when cutting rectangular or square patterns along the warp and weft directions due to the sample is arranged more compactly. However, deviation from this orientation, especially cutting perpendicularly, results in considerable edge waste and a marked decrease in material utilization, as shown in Figure 5-1b. Typically, those cutter fabric scraps, varying between 25 % and 50 % of the purchased material, are disposed of, accompanied by economic losses and negative environmental impacts [160,169,170]. This waste becomes pronounced when pattern nesting optimization is limited by low production volumes and customized-manufacturing scenarios. Furthermore, subsequent machining

and finishing operations, which are performed to achieve the final desired dimensions after the composite has cured, also generate substantial waste material [171].

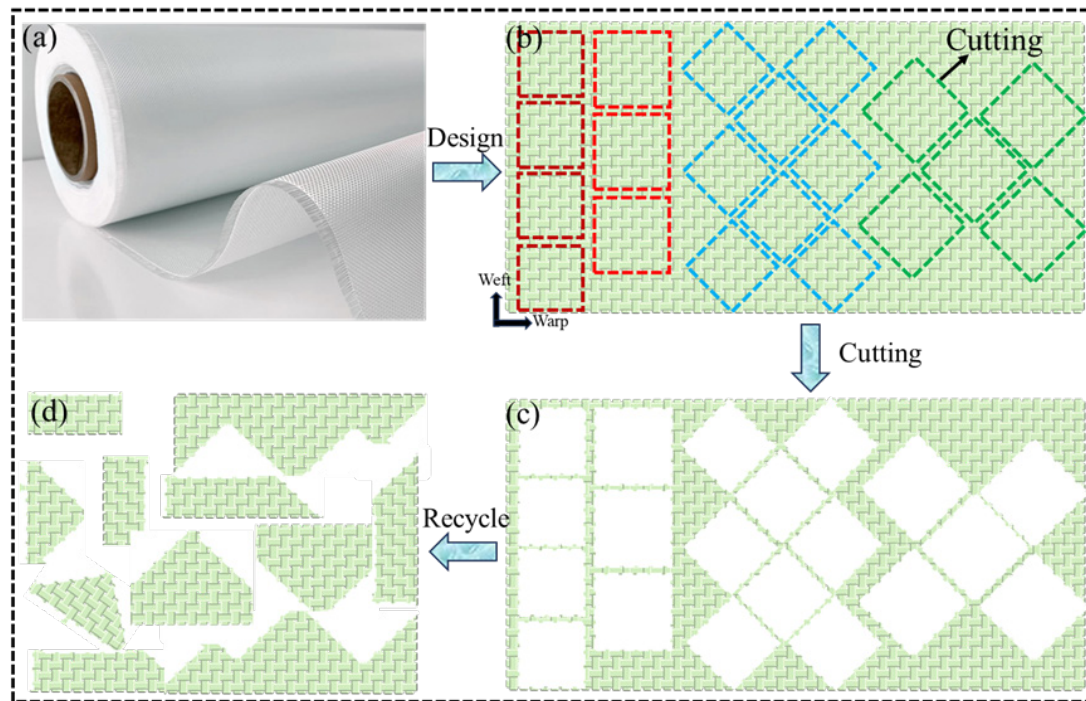


Figure 5-1 Waste of fabric scrap: (a) Glass fibre fabric from large-scale rolls; (b) Pattern pieces required for forming; (c) Fabric scrap from cutting; (d) Recycling the discarded large fabric scrap.

A considerable amount of material waste is inherent to composite manufacturing. This waste (see in Figure 5-1d), which manifests as fabric scrap and off-cuts, presents a dual challenge: it is a primary driver of high production costs and a persistent barrier to achieving efficient and sustainable production. Extensive efforts have been made to reuse and recycle of composite parts [172–174]. Current researches and industrial practices have primarily focused on both manufacturing and post-manufacturing waste, which main include prepreg scraps and end-of-life components [173–176]. Preforming-stage materials waste, particularly fabric scraps (or offcuts) generated during the cutting and forming of dry textile reinforcements, have received comparatively little attention. This is attributed to the current absence of reliable and effective approaches that enable the efficient utilization of fabrics scraps while maintaining the structural integrity of textile. This underexplored category of waste presents both a challenge and an

opportunity [160]. These uncured, structurally intact fabric scraps retain much of their original mechanical and could be effectively re-integrated into the production cycle if appropriate techniques are developed. To address this gap, this study introduces tufting technology, a through-thickness reinforcement method traditionally used to improve delamination resistance, as an approach for physically joining fabric scraps before preform forming [12,102,125]. The tufting process not only enables the joining and reuse of fabric scraps but also enhances their formability. Shen et al. [18,88] demonstrated that the tufting pattern and tufting space has an impact on the formability of tufted preform and can modify or remove the forming defects. The tufting process offers a promising pathway for fabric reuse at the preforming stage while aligning with the principles of the zero-waste cutting and patchwork manufacturing [177].

To evaluate the feasibility of fabric scrap assembly by tufting, two types of fabric scraps with distinct geometries (rectangular and triangular units) were assembled into square preforms, followed by hemispherical forming. The forming behaviours were systematically analysed through punch force, materials draw-in, in-plane shear angle and wrinkles amplitude. These establish a basic understanding for converting fabric scraps into functional preforms, advancing sustainable composite manufacturing through reusing of fabric scraps.

5.2 Methods and Materials

5.2.1 Forming parameter settings

To investigate forming defects in tufted fabric scrap assemblies, a quasi-symmetrical hemispherical punch was selected. The forming apparatus integrates mechanical and optical subsystems. The mechanical system comprises a hemispherical punch, blank-holder, and open die configuration, with principal dimensions detailed in Figure 5-2a. Four distinct fabric layers were positioned between the blank-holder and die. A uniform pressure of 0.05 MPa was applied to single-layer samples and 0.15 MPa to four-layer samples along the fabric edge via the blank-holder. The punch, driven by a pneumatic jack at 0.15 MPa, maintained a constant forming speed of 7.72 mm/s. A top-mounted

camera quantitatively analysed material draw-in and in-plane shear angles using marked black lines on samples. Concurrently, an infrared sensor array enhanced wrinkle visibility and identified wrinkle measurement positions.

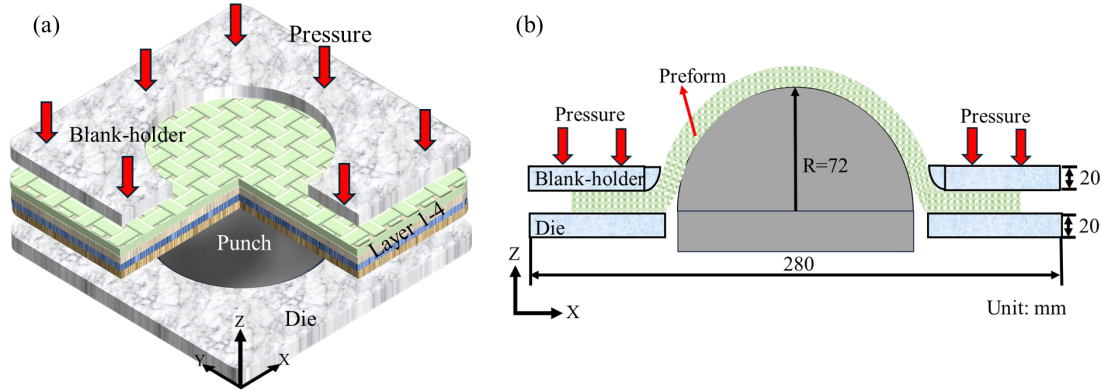


Figure 5-2 Forming device: (a) The forming device with an open-die system; (b) The punch dimensions after deformed.

5.2.2 Tufting process and design of tufting pattern

Tufting, a mature one-sided stitching process, is employed to produce through-the-thickness reinforced composites [12]. Owing to its enhanced impact resistance and delamination performance, this technique has become an established industrial method for reinforcing composites in transport and aerospace sectors [108]. Recently, it has been directly applied to dry preforms and prepregs to mitigate forming defects [18]. As illustrated in Figure 5-3, tufting involves inserting yarn into multilayered fabrics through a hollow needle, where it remains in situ following tufting needle retraction. The yarn retention mechanism relies on interfacial friction between the yarn and supporting materials (e.g., high-density foam), forming either partially embedded or fully penetrated loops depending on penetration depth. Consequently, tufting yarns experience minimal tension, thereby significantly reducing fabric damage. In this study, a hollow needle with a diameter of 1.2 mm and a penetration depth of 10 mm were employed. Tufting space denotes the inter-tuft distance within a reinforcement structure, defined as the separation between adjacent tufting points. This parameter is measurable along orthogonal (X and Y) directions, as illustrated in Figure 5-3. All test samples

featured identical tufting spaces of 10 mm in the X-direction and 8 mm in the Y-direction.

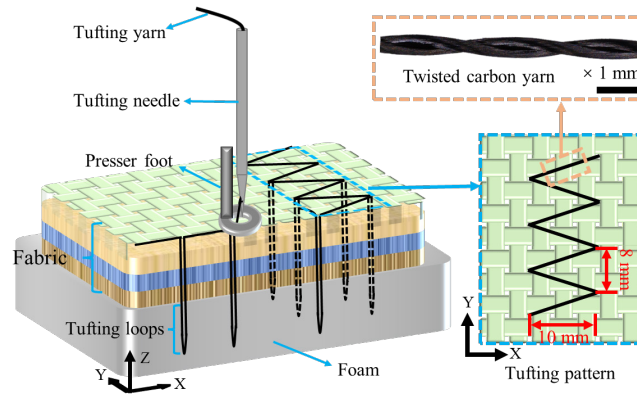


Figure 5-3 Introduction of tufting process, tufting pattern and structure of tufting yarn.

5.2.3 Materials and sample preparation

This study employs continuous E-glass plain-woven fabrics with a symmetrical 1:1 warp–weft architecture, specifically designed to minimize directional bias in in-plane mechanical behavior. The fabric has an areal density of $153.06 \pm 5 \text{ g/m}^2$, with warp and weft yarn densities of 11.5 yarns/cm. The nominal thickness is $0.15 \pm 0.02 \text{ mm}$. All test samples were cut into distinct geometries with orientations along $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$, as illustrated in Figure 5-4a. Fabric scraps were repurposed and precisely cut into two different geometric units: rectangular units (width $\times$ length: $140 \text{ mm} \times 280 \text{ mm}$) and isosceles right triangular units (base $\times$ height: $280 \text{ mm} \times 280 \text{ mm}$, as shown in Figure 5-4b.

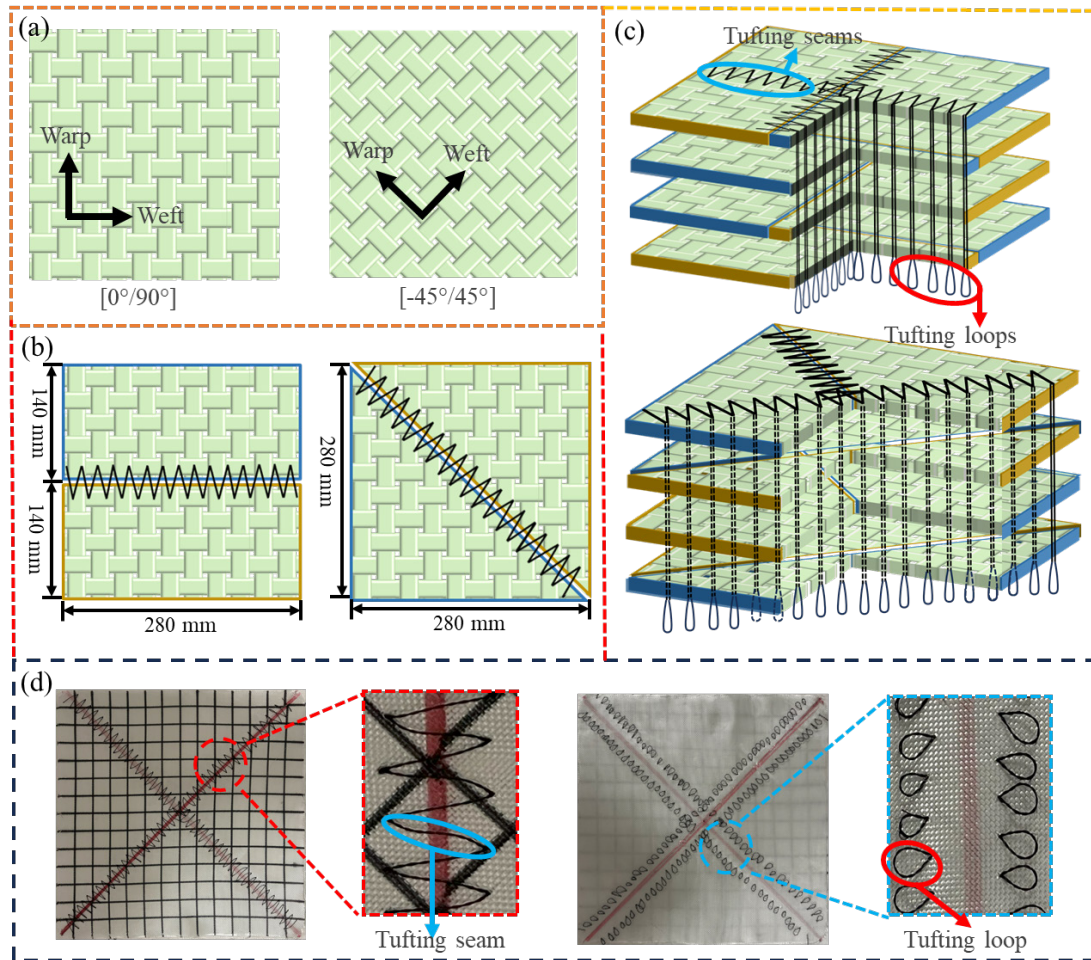


Figure 5-4 Prepare of sample: (a) The woven fabric with an orientation in $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ directions; (b) Assembled rectangular units and triangular units into $280 \times 280 \text{ mm}^2$ sample by tufting ($[0^\circ/90^\circ]$ case); (c) Schematics of the test sample with four-layer; (d) Sample of 90-4T, including the tufting seam and tufting loops.

For single-layer samples, two identical units of the same geometry were joined along their matching edges via tufting to assemble a square sample (width $\times$ length: $280 \text{ mm} \times 280 \text{ mm}$), which was then subjected to the forming process. For four-layer samples, two units were first assembled into a square preform; and then four such preforms were then stacked sequentially with 90° rotations ($0^\circ/90^\circ/180^\circ/270^\circ$) to establish orthogonal fibre orientations. The assembly and tufting process for the four-layer structures constructed from both rectangular and triangular units is illustrated in Figure 5-4c. Tufting was applied along the seams of the assembled units to enhance interfacial bonding and ensure structural stability during subsequent processing. Figure

5-4d shows the front and back views of a representative tufted sample (90-4T). The front view highlights the tufting pattern, while the back view reveals the tufting loop structures in detail. The structural parameters of all tufted samples are summarized in Table 5-1.

Table 5-1 References of test samples.

Ref. of sample	Geometry unit	No. of layers	Layer orientation	Blank-holder pressure (MPa)	Tufting points	Tufting density (points/cm ²)
90-1R	Rectangular	1	[0°/90°]	0.05	35	0.045
90-1T	Triangular	1	[0°/90°]	0.05	46	0.059
45-1R	Rectangular	1	[-45°/45°]	0.05	35	0.045
45-1T	Triangular	1	[-45°/45°]	0.05	46	0.059
90-4N	—	4	[0°/90°]	0.15	0	0
90-4R	Rectangular	4	[0°/90°]	0.15	70	0.089
90-4T	Triangular	4	[0°/90°]	0.15	92	0.117
90-RT	Rectangular/ Triangular	4	[0°/90°]	0.15	162	0.207
45-4N	—	4	[-45°/45°]	0.15	0	0
45-4R	Rectangular	4	[-45°/45°]	0.15	70	0.089
45-4T	Triangular	4	[-45°/45°]	0.15	92	0.117
45-RT	Rectangular/ Triangular	4	[-45°/45°]	0.15	162	0.207

5.3 Structural integrity of assembled tufted preforms

The formability of assembled tufted preforms is highly sensitive to forming parameters, especially in single-layer configurations. Blank-holder pressure and tufting density are identified as key factors affecting the quality and integrity of the preforms. In single-layer configurations, excessively high blank-holder pressure caused tufting loop detachment and separation of the assembled units. Conversely, insufficient tufting density reduced the effectiveness of mechanical interlocking, weakening the preform's resistance to deformation during forming. Based on preliminary trials, a blank-holder pressure of 0.05 MPa was found optimal for maintaining structural integrity in single-layer preforms. Figure 5-5a shows the forming results of single-layer assembled tufted preform. Although the surface of the formed sample was generally free of visible

wrinkles, a distinct opening between the two assembled units was observed. Figure 5-5b presents the projected area of the openings, revealing that the 45-1R sample exhibits the largest opening dimensions among all single-layer configurations when comparing opening area, opening length, and maximum opening distance, as presented in Figure 5-5c. These geometrically enlarged openings act as local stress concentrators, potentially degrading composite structural performance. Concurrently, tufting yarn length progressively decreases with increasing radial distance from the hemispherical apex (Figure 5-5d), while larger openings correlate with reduced the length of tufting loops along extended tufting seams (the distance of two tufting points), as presented in Figure 5-5e. This inverse relationship indicates that forming deformations redistribute tufting yarns: greater in-plane extension along tufting seam directions reduces available yarn length for out-of-plane tufting loops formation, directly linking planar strain to out-of-plane feature suppression.

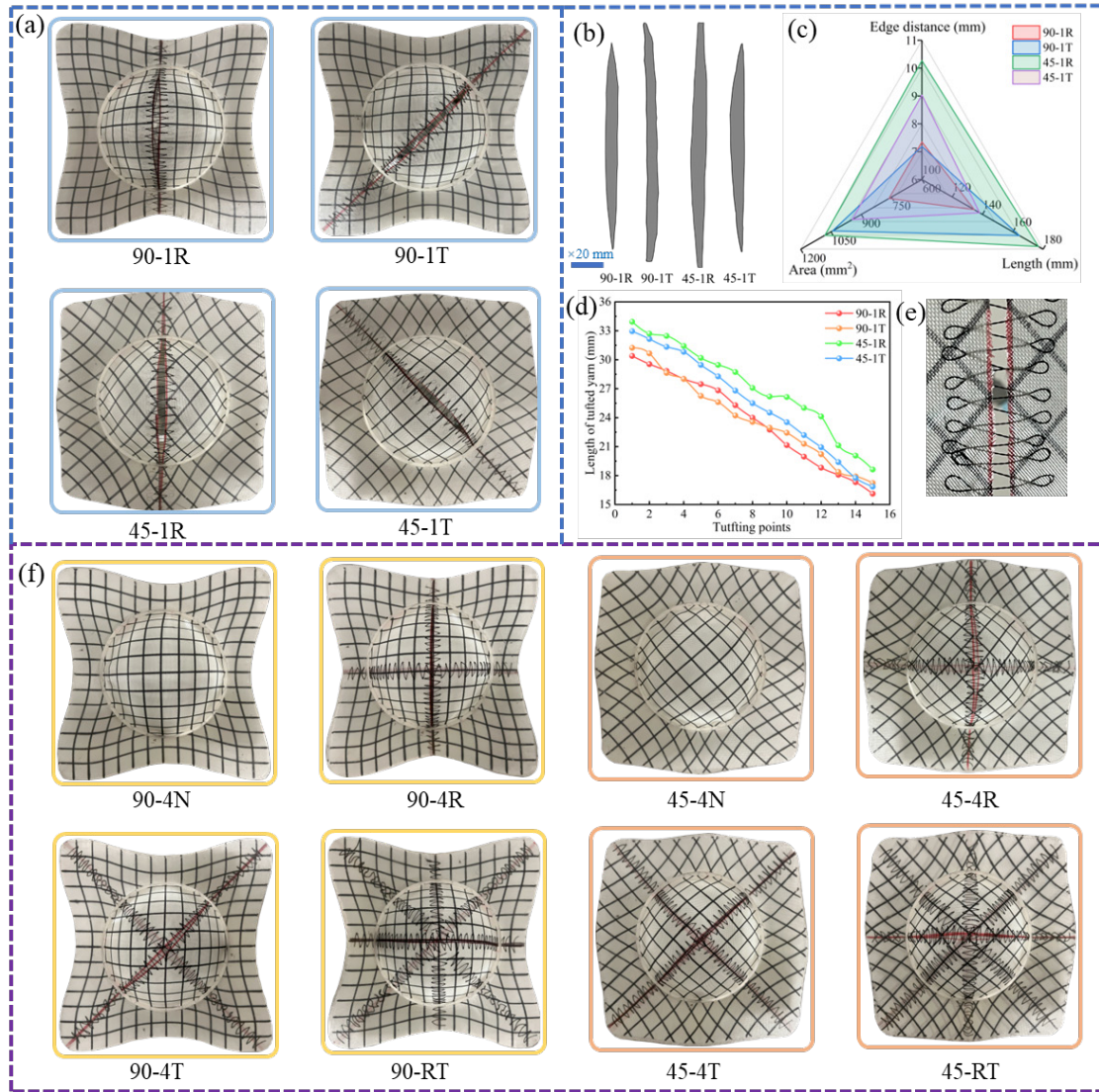


Figure 5-5 (a) Single-layer assembled tufted preform; (b) Projected area of the opening after forming; (c) Quantitative comparison of opening parameters in single-layer samples; (d) Decreasing tufting yarn length with distance from hemispherical center; (e) Reduced tufting loops length along extended tufting seams; (f) Four-layer preform demonstrating enhanced structural integrity.

In contrast, four-layer assembled tufted preforms showed significantly reduced openings between assembled units. As shown in Figure 5-5f, no significant openings were observed in the useful zone (formed regions), and the structural integrity of the useful zone was better maintained. The additional layers likely increased interlayer friction and mechanical constraint, which helped stabilize the tufted structure during deformation. Therefore, the forming analysis primarily focused on four-layer

configurations. To quantitatively evaluate formability, four key factors were employed. Punch force and material draw-in reflect the tensile response of the fabric, while the in-plane shear angle indicates the fabric's ability to accommodate structural reorientation. Additionally, systematic wrinkle characterization was carried out to assess wrinkle distribution and amplitude, since wrinkling is a critical defect that compromises both dimensional accuracy and structural uniformity. Together, these indicators provide a comprehensive framework for evaluating forming performance and the effectiveness of the assembled tufting strategy.

5.3.1 Variations of tufted yarn after forming

Tufted yarn deformation, which plays a critical role in reinforcing textile composite preforms, is essential for maintaining internal structural stability and influences the mechanical performance of the final composite. Figure 5-6 illustrates the variations in tufted yarn morphology after forming. The results demonstrate that in-plane shear is the main factor affecting tufted yarn length and bending. In the $[0^\circ/90^\circ]$ layer, the 90-4R (Figure 5-6a) shows excellent morphological stability, with tufted yarns maintaining their initial straight orientation and exhibiting minimal bending and length variation. In contrast, the 90-4T undergoes significant changes in tufted yarn morphology. The deformation behavior can be categorized into two zones: in the upper hemisphere, where in-plane shear is limited, the tufted yarns remain largely straight, similar to 90-4R; in the lower hemisphere, where in-plane shear and compressive strains are more pronounced, marked out-of-plane bending occurs due to contraction between tufting points (Figure 5-6b). Similarly, the 90-RT exhibits zone-specific deformation: yarns in the middle-tufted zone resemble those in 90-4R, while those in the diagonal tufted zone behave like 90-4T, as shown in Figure 5-6c. Conversely, the 45-RT shows the opposite pattern, its middle-tufted zone behaves like 90-4T, and the diagonal tufted zone aligns with 90-4R. These findings confirm that tufted yarn deformation is primarily governed by local strain distribution, with in-plane shear serving as the primary factor.

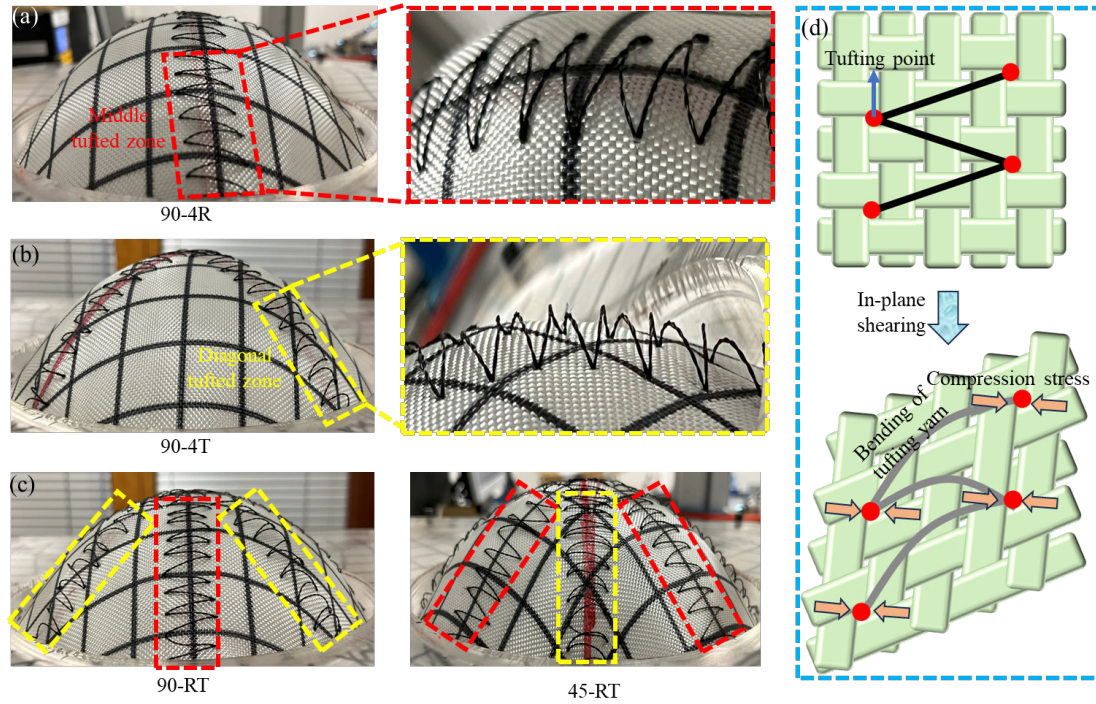


Figure 5-6 Variations of tufted yarn: (a) Sample of 90-4R and its side view; (b) Sample of 90-4T and its side view; (c) Sample of 90-RT and 45-RT; (d) The schematic of bending of tufting yarn.

Shen et al. [90] reported that no significant deformation or sliding of the tufting yarns occurs during diagonal tufting because the yarn segments rotate uniformly with the fabric, avoiding major distortion. In contrast, horizontal and vertical tufting demonstrate distinct deformation behaviors. Horizontal tufting primarily induces tufting yarn bending due to transverse compression generated during in-plane shear. This compression results in out-of-plane bending as the tufting yarns adapt to in-plane shear-induced deformation. For vertical tufting, in-plane elongation between tufting points introduces tensile forces that facilitate tufting yarn slippage through the fabric, effectively increasing the apparent tufted yarn length. As shown in Figure 5-6d, the horizontal spacing between tufting points becomes greater than the vertical spacing during deformation, resulting in greater bending of tufted yarns in horizontally tufted regions. Importantly, the degree of tufting yarn bending is positively correlated with the in-plane shear magnitude: the greater the in-plane shear, the more significant the tufting yarn bending. The bending of the tufted yarn can have an important effect on the resin

infusion in the LCM process. Therefore, strong in-plane shear areas should be avoided tufting in assembled tufted samples.

5.3.2 Punch force response and stress redistribution

During hemispherical forming, the punch serves as the principal external load driving fabric deformation. This force is applied normal to the fabric surface by the punch head, initiating primarily in-plane tensile deformation. Meanwhile, the fabric generates a reactive force against the punch due to its in-plane tensile stiffness and inter-yarn friction. Figure 5-7a and Figure 5-7b displays the punch force during the forming process. Single-layer tufted samples exhibited a 32-51% reduction in punch force relative to normal samples, while four-layer samples showed a consistent 39-51% reduction. This marked decrease highlights the effectiveness of stress redistribution caused by tufting in reducing deformation resistance in both single- and multi-layer configurations. The difference in punch force originates from intrinsic structural differences between the two configurations. In normal samples, yarns are continuously interlaced in both warp and weft directions. During deformation, these yarns undergo significant tensile stretching and must overcome substantial inter-yarn friction. To adapt to the double-curvature geometry of the hemisphere, the yarns also rotate relative to one another, resulting in pronounced in-plane shear deformation, as shown in Figure 5-7c. This combination of tensile stretching, in-plane shearing, and contact friction leads to increased fabric resistance and, consequently, a higher peak punch force, as illustrated in Figure 5-7d.

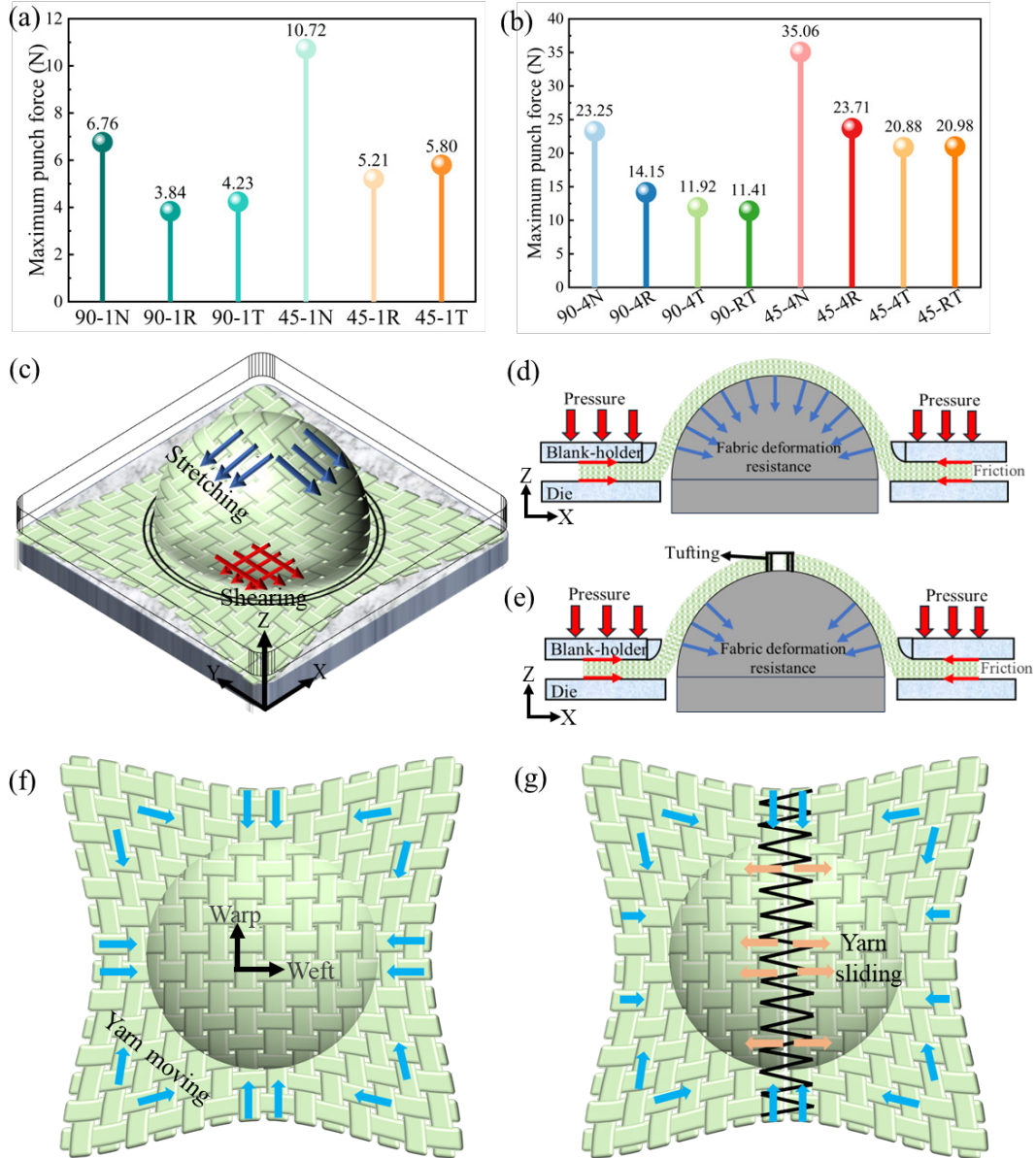


Figure 5-7 Punch force response of (a) single-layer and (b) four-layer assembled tufted samples; (c) Deformation mechanisms during forming: yarn stretching and in-plane shearing; Comparative analysis of deformation resistance and inter-yarn friction in (d) normal and (e) assembly-tufted samples; (f) Global deformation of yarn moving; (g) Localized yarn sliding behavior in tufting regions of normal samples.

In contrast, the assembled tufted samples introduce controlled structural discontinuities within the tufted regions, which modify the local deformation mechanisms. These regions permit relative yarn sliding between adjacent assembled units, allowing localized accommodation of curvature without necessitating elongation of warp or weft yarns, as shown in Figure 5-7e and Figure 5-7g. As a result, the overall

fabric response becomes more compliant, with deformation governed more by yarn slippage than by yarn stretching. The presence of tufted regions thus shifts the dominant deformation mechanism from yarn elongation to localized sliding. This structural transformation reduces the global mechanical resistance and lowers the punch force during forming by promoting warp/weft yarn slippage and enhancing in-plane shear deformation fields.

5.3.3 In-plane displacement analysis

Material draw-in refers to the inward displacement of fabric edges toward the punch during forming, primarily influenced by punch force and blank-holder constraints. It serves as a key indicator of in-plane yarn movement and plays a critical role in determining formability, fiber alignment, and the occurrence of defects. Figure 5-8a and Figure 5-8b illustrates the material draw-in measured along both warp and weft directions for various assembled tufted samples. All the orthographic projections exhibit similar deformation patterns in the X-Y plane. The results indicate that, despite variations in the geometric configuration of the assembly units (rectangular vs. triangular), the overall material draw-in remains relatively consistent across all four-layer samples. This consistency suggests that the fabric deformation mode is predominantly governed by the warp and weft directions rather than the configuration of the assembled tufted units.

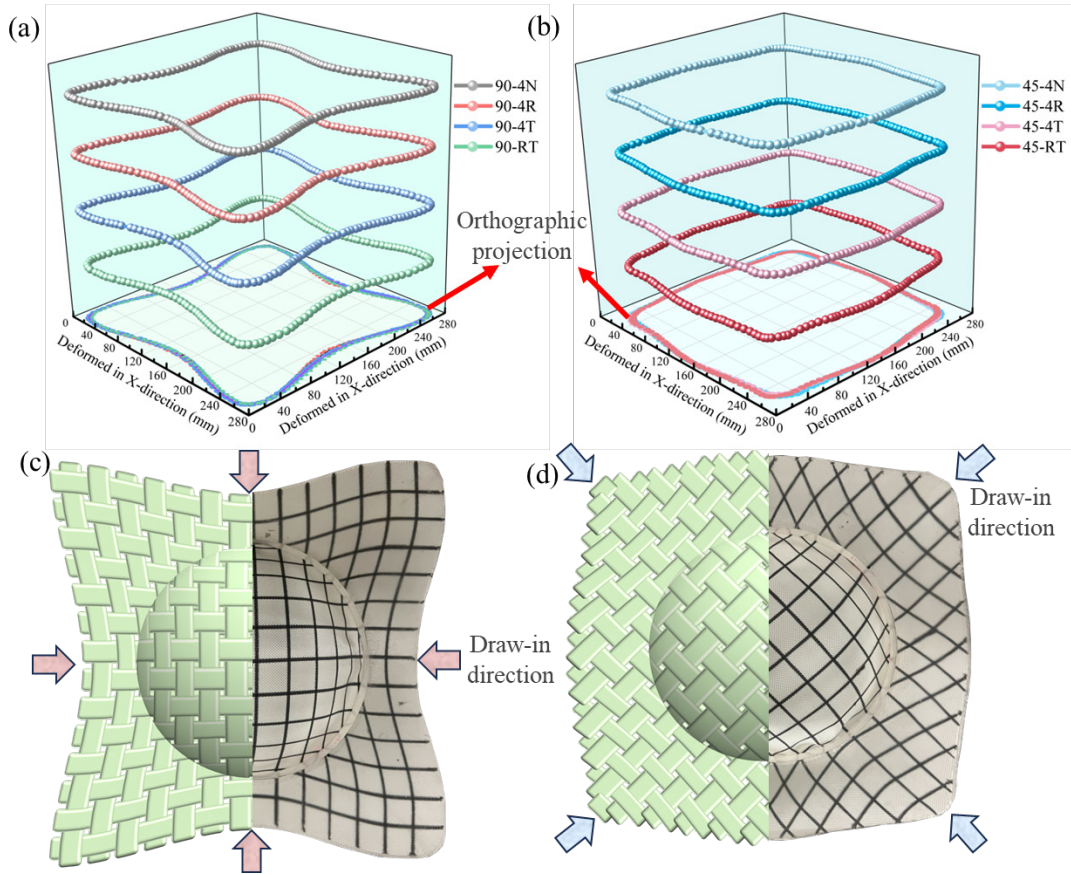


Figure 5-8 Material draw-in behavior of four-layer assembly-tufted samples: (a) and (b) Draw-in distribution of the $[0^\circ/90^\circ]$ layer and $[-45^\circ/45^\circ]$ layer; (c) and (d) Schematic illustration of draw-in directions for the $[0^\circ/90^\circ]$ layer and $[-45^\circ/45^\circ]$ layer.

The tufting process, while introducing localized connections between assembled units, does not significantly alter the fundamental in-plane deformation behavior governed by the woven structure. When the fabric deforms under the punch, the primary deformation mechanism is in-plane shearing, as the yarns are quasi-inextensible and inter-yarn sliding can occur [115]. For the $[0^\circ/90^\circ]$ layer (Figure 5-8c), pronounced in-plane shear occurs at the corners, and all four sides of the fabric are drawn toward the center due to the inextensible nature of glass fibers. In contrast, for the $[-45^\circ/45^\circ]$ layer, a different deformation pattern is observed: the fabric edges are slightly drawn in at the center of each side, with in-plane shear deformation primarily concentrated in those regions, as shown in Figure 5-8d. These findings suggest that while tufting may influence local yarn mobility or resistance (as discussed in Section 5.3.1), it does not

disrupt the overall deformation pattern dictated by the woven structure. Consequently, material draw-in remains a structure-driven response, largely reflecting the intrinsic anisotropy of the textile architecture.

5.3.4 In-plane shear deformation

The in-plane shear angle serves as a sensitive indicator of the fabric's accommodation to double-curvature forming [115]. It reflects the internal rotation between orthogonal yarns and correlates directly with the onset of or wrinkling during. Distinct differences in-plane shear behavior was observed between assembled tufted samples and normal sample, as presented in Figure 5-9. In the $[0^\circ/90^\circ]$ layer, the maximum shear angle in the normal sample (90-4N) reached 38.30° , while its assembled tufted sample (90-RT) exhibited a reduced value of 32.62° , representing a 14.8% in-plane shear angle attenuation. A comparable reduction was also noted in the $[-45^\circ/45^\circ]$ layer, the maximum in-plane shear angle is change from 38.6° to 33.2° compared to the 45-RT. The result of $[0^\circ/90^\circ]$ illustrates the stabilizing influence of assembled tufted units to reduce the in-plane shear angle, both rectangular and triangular assembly units help to reduce the maximum in-plane shear angle. Moreover, changing the shape of the assembly unit does not alter the location of the regions where strong in-plane shear occurs. In the $[0^\circ/90^\circ]$ layer, regions of strong in-plane shear angles are predominantly localized along the diagonal directions of the preform, extending from the central useful zone toward the four corners of the preform. In contrast, in the $[-45^\circ/45^\circ]$ layer, strong in-plane shear regions are mainly distributed at the middle of preform, extending from the useful zone toward the midpoints of the edges.

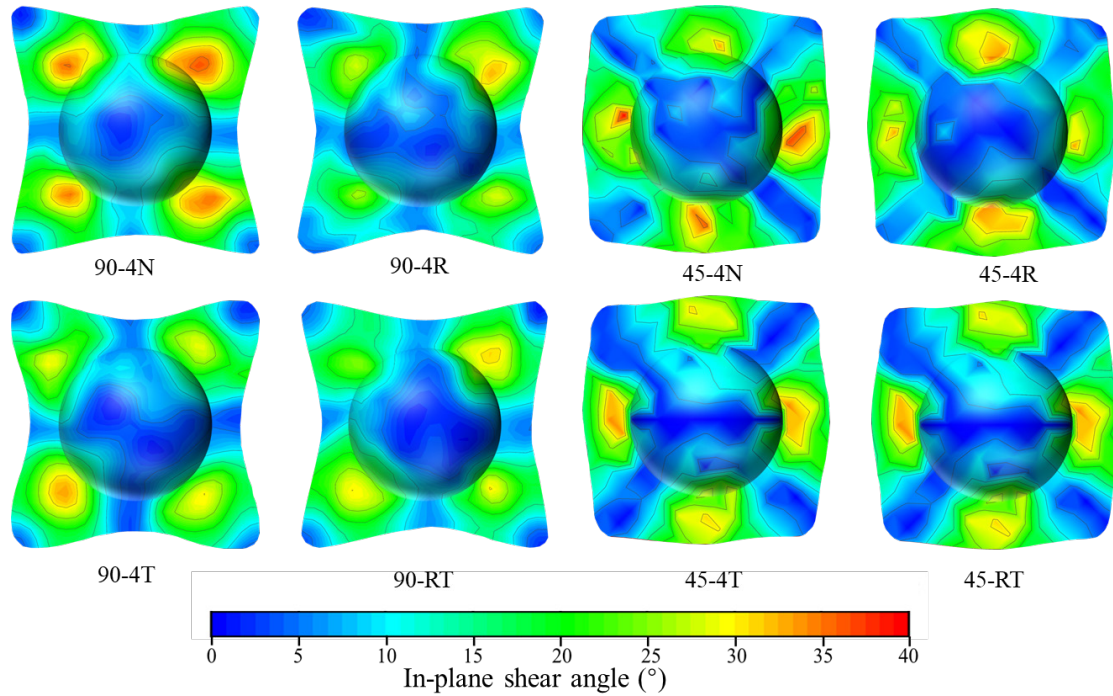


Figure 5-9 In-plane shear angle behavior of assembled tufted samples with different assembly units

Unlike the continuous fabric structure in normal samples, the assembled tufted sample is the diversification of preform into more units to improve the structural discontinuities, which make the weft/warp yarn easily to slip. The tightly interlaced, continuous network of warp and weft yarns imposes strong kinematic constraints on yarn rotation during hemispherical forming. These structural discontinuities introduced by tufting fundamentally relax these kinematic constraints imposed on warp/weft yarn rotation during forming. This enables the warp/weft yarns to redistribute in-plane shear more readily in the vicinity of the tufting zone through minor slippage at the crossover points or within the yarn bundles, rather than accumulating excessive in-plane shear deformation uniformly across the fabric. In other words, the reduction in maximum in-plane shear angle implies a delayed onset of shear locking behavior, and hence, reducing the risk of wrinkles that typically initiate at high in-plane shear angles near locking. It suggests that tufting zone do not merely serve as mechanical connections, but also actively influence and guide the in-plane shear deformation field during forming by creating localized zones of reduced constraint that facilitate deformation

redistribution.

5.3.5 Distribution of wrinkles after deformation

Wrinkling remains a critical quality indicator in textile forming, and its effective suppression represents a persistent technical challenge in this field. During forming, punch forces readily induce localized stress concentrations (such as, in-plane shearing), leading to the formation of wrinkles. Fortunately, slitting in the strong in-plane shear region can effectively reduce the formation of wrinkles [76]. Figure 5-10a and Figure 5-10b illustrates the wrinkle distribution and height after forming for normal samples and assembled tufted samples. The results demonstrate that the assembled tufted samples exhibit a reduction in the height of wrinkles compared to normal samples. Relative to assembled tufted specimens, the $[0^\circ/90^\circ]$ layer displays markedly intensified wrinkling, with the 45-4N sample demonstrating reduced wrinkle severity compared to 90-4N. This behavior originates from in-plane shear behavior and yarn rotation governed by warp/weft yarn. The length of orthogonal yarn in $[0^\circ/90^\circ]$ layers severely restrict in-plane shear deformation, elevating susceptibility to out-of-plane deformation. Conversely, the $[-45^\circ/45^\circ]$ layer exhibits enhanced in-plane shear capacities due to its $\pm 45^\circ$ fiber orientation: the shorter the fabric yarn on the periphery is, the less they are compressed along the length direction [115]. The presence of assembly unit makes it easier to change the yarn through the yarn slipping. This mechanism effectively redistributes forming stresses via in-plane shearing and slipping, mitigating strain localization and reduce wrinkle formation risk.

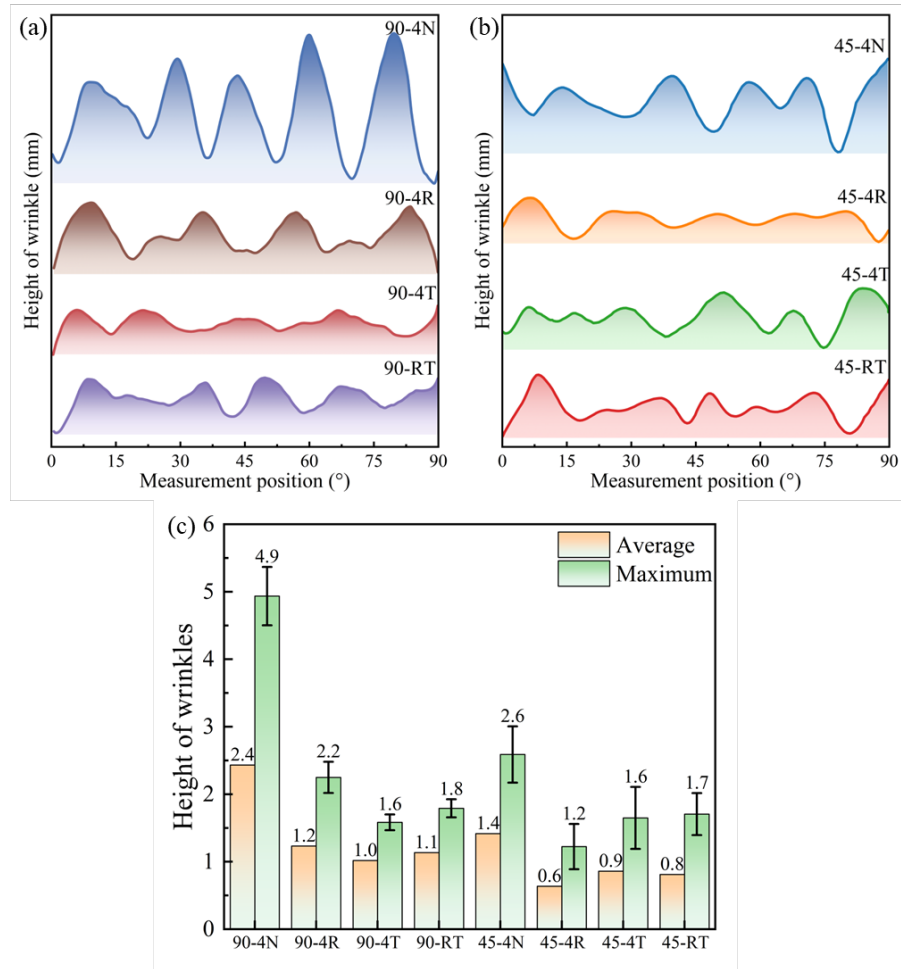


Figure 5-10 Height of wrinkle and distribution: (a) and (b) Wrinkle distribution of $[0^\circ/90^\circ]$ and $[-45^\circ/45^\circ]$ ply (measurement angle range from 0° to 90°); (c) Average value of wrinkle and maximum height of wrinkle (range from 0° to 360°).

To characterize the wrinkles more explicitly, the average and maximum heights of wrinkles were calculated [88]. Specifically, sample 90-4R displays the highest wrinkle heights (with an average height of 1.2 mm and a maximum height of 2.2 mm), while all other assembled tufted samples exhibit lower values (Figure 5-10c). Notably, even the 90-4R sample, which shows relatively higher wrinkle heights, shows no visibly apparent wrinkles upon macroscopic examination, as depicted in Figure 5-5f and Figure 5-6a. Values for assembled tufted samples range from 0.6 mm to 1.1 mm. This height of wrinkles is acceptable range for the wrinkles, which is lower than 90-4R. These results highlight the effectiveness of the assembled tufted architecture in mitigating wrinkling behaviour and offer a promising design strategy for reusing fabric scraps

while reducing wrinkles.

Although assembling two units for each layer effectively reduces strong in-plane shear angle and wrinkle formation during the forming process, but the yarns between the assembled units are not continuous. This discontinuity may compromise the structural integrity and mechanical performance of the final composite material. Compared to samples composed of single continuous unit, the mechanical behavior of the resin-infused composite materials remains uncertain. Meanwhile, the in-plane deformation leads to in-plane defects (such as fibers sliding and misalignment [79,86]), the discontinuity of yarn increase this forming defects. A systematic investigation into the mechanical properties of the deformed composites is required in future studies.

5.4 Conclusion

This chapter proposes an assembly tufting approach to reduce forming defects in composites assembled from fabric scraps during hemispherical forming. The results show that assembled tufted configurations reduce punch force by 39-51% compared to normal samples; meanwhile, overall material draw-in remains relatively consistent. Tufting does not significantly alter the fundamental in-plane deformation behaviour governed by the woven structure. Instead, the assembled tufted architectures effectively suppress excessive in-plane shear deformation and wrinkling by enabling localized yarn slippage, thereby redistributing strain and addressing a longstanding challenge in textile composite forming. Notably, the assembled tufted sample (90-RT) reduces the maximum in-plane shear angle by 14.8% (from 38.30° in the conventional 90-4N to 32.62°), while sample 90-4R reduces maximum wrinkle height by 2.7 mm and maintains a macroscopically smooth surface. Beyond defect mitigation, this approach enhances material utilization and reduces raw material waste through systematic integration of fabric scraps. However, yarn discontinuities at assembly units require further investigation regarding their impact on composite mechanical properties. Future work will assess interlaminar strength and damage tolerance to evaluate industrial scalability.

General conclusion

This thesis focuses on investigating the formability characteristics of continuous fiber-reinforced textile composites, which are essential for manufacturing composite parts with complex geometry. Understanding the nature of forming defects, clarifying the underlying deformation mechanisms, and identifying the influence of key manufacturing parameters represent the principal research objectives. The current study provides a basis for determining optimal forming conditions to minimize forming defects. Slitting and tufting technologies have emerged as promising methods for pre-assembly processes and through-thickness reinforcement in composite manufacturing. This thesis investigates a novel approach to influencing the forming behaviour of fabric by incorporating slits and tufts.

At first, as the in-plane shear property is one of the most critical factors of forming process, a picture frame test is used to characterize it. Experimental results show that slitting increases shear resistance and induces localized shear angle reduction near the slit without altering the global shear locking angle. Tufting further enhances shear force by restricting yarn mobility at higher shear angles. The combined use of slitting and tufting offers a practical strategy to tailor in-plane shear performance.

After that, evaluating the formability of slit preforms during hemispherical forming, focusing on forming defects and the variation of slitting locations. The experimental results indicate that precision slitting enhances preform formability by reducing shear angles and minimizing wrinkles. Moreover, slitting in the shear angle zone reduces the forming defects by decreasing the stress and forces, further diminishing shear angles and the severity of wrinkles. On this basis, selecting two slitting positions with less wrinkles and subsequently introduced tufting yarn to connect the slit edge and prevent the slit edge extension along the warp or weft direction. The experimental results revealed that the relationship between in-plane shear deformation field and tensile deformation of tufted yarn in slit and tufted preforms underscores the intricate interaction between deformation mechanics and tufting-induced constraints.

Furthermore, these findings emphasize the critical need to select compatible slitting position and tufting patterns to balance tensile deformation field and in-plane shear field, thereby improving formability.

In addition, to reduce the waste of fabric due to cutting from large-scale rolls, the feasibility of fabric scrap reuse in textile forming was verified. Two types of fabric scraps with distinct geometries (rectangular and triangular units), were assembled into square preforms using tufting technology. Through hemispherical forming validation, the tufted architecture redistributes strain via controlled yarn slippage, reducing punch forces by 39-51% while maintaining material draw-in integrity. Additionally, the proposed method reduced the maximum in-plane shear angle by 14.8% and decreased wrinkle amplitude by 2.7 mm, while preserving surface quality. By enabling the reuse of fabric scraps, this approach enhances material utilization efficiency and offers a practical pathway toward circular composite manufacturing.

Perspective

In this thesis, picture frame tests explored slitting parameters' influence on in-plane shear deformation, focusing on shear deformation, locking angle, and shear locking state. However, yarn state evolution during shearing, including warp/weft rotation within shear/slit zones and transformation around slit boundaries, remains insufficiently understood. During forming, slit edge behavior deviates from planar assumptions via 2D-to-3D transformation, requiring simulation to capture its influence. In picture frame tests, tufted yarn and slit edge interaction mainly depends on sliding friction with warp/weft yarns. Yet during forming, sliding friction occurs between the blank-holder and tufted yarn, which complicates the yarn change process. Therefore, further research must characterize tufted yarn behavior considering tufted loop length, yarn diameter, tufting pattern and so on. While effective for quasi-symmetric forming, slitting impacts on asymmetric or complex geometries remain unclear. Future work will focus on determining optimal slitting positions and lengths to understand their influence on formability. Finally, although assembling units per layer reduces in-plane shear and wrinkles, the resulting yarn discontinuity compromises structural integrity and mechanical performance. Compared to continuous-unit samples, the mechanical behavior of composites remains uncertain. Additionally, yarn discontinuity exacerbates in-plane defects like fiber sliding and misalignment. Future studies require systematic investigation of the deformed composites' mechanical properties.

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Abstract

The forming of continuous fiber-reinforced textile preforms is widely employed to achieve complex shapes in lightweight composite structures. However, forming defects can reduce the quality and service life of the final product. Currently, slitting and tufting technologies are employed to produce textile composite reinforcements. This study systematically evaluates the in-plane shear properties and formability of slit and tufted preforms during hemispherical forming, with a focus on slit variation, tufting yarn behavior, and forming defects. Accordingly, this work can be divided into three principal aspects: First, picture frame tests were conducted for in-plane shear characterization using optical measurement techniques to evaluate the effects of slit and tufted configurations on the shear response of glass woven fabrics. Second, the formability of slit and tufted preforms during hemispherical forming was evaluated, with particular attention to punch force, in-plane shear angle, slit and tufted yarn variation, and forming defects. Third, two types of fabric scraps with distinct geometries (rectangular and triangular) were assembled using the tufting process into square preforms, followed by hemispherical forming. The formability behaviors were systematically analyzed through material draw-in, in-plane shear angle, and wrinkling to investigate the consistency of patch geometry and forming behavior. These findings offer critical insights for enhancing the manufacturing efficiency, reducing the fabric waste and quality of continuous fiber-reinforced textile composites.

Résumé

La mise en forme des préformes textiles renforcées par des fibres continues est largement utilisée pour réaliser des géométries complexes dans les structures composites légères. Cependant, la présence de défauts de préformage peut compromettre la qualité et la durée de vie en service de la plaque composite finale.

Les technologies de pré-découpe et de piquage suivant l'épaisseur de la préforme sont employées pour la fabrication des textiles composites. La présente étude évalue de manière systématique les propriétés de cisaillement dans le plan ainsi que la déformabilité des préformes pré-découpées et piquées lors d'un préformage hémisphérique, en portant une attention particulière à la variation des découpes, au comportement des fils de piquage et aux défauts de préformage.

Ce travail se décline ainsi en trois volets principaux : Premièrement, des essais de cadre articulé (Picture-Frame tests) ont été réalisés afin de caractériser le cisaillement dans le plan à l'aide de techniques de mesure optique, permettant d'évaluer l'influence des configurations de découpe et de piquage sur la réponse au cisaillement des tissus en fibres de verre. Deuxièmement, la déformabilité des préformes pré-découpées et piquées lors du préformage hémisphérique a été étudiée, en analysant particulièrement la force de poinçonnage, l'angle de cisaillement dans le plan, la variation des découpes et des fils de piquage, ainsi que les défauts. Troisièmement, deux types de chutes textiles présentant des géométries distinctes (rectangle et triangle) ont été assemblées par piquage pour réaliser des préformes carrées, suivies des essais du préformage hémisphérique. La déformabilité a été analysé à travers l'avalement du renfort, l'angle de cisaillement dans le plan et la formation de plis, afin d'étudier la cohérence entre la géométrie des patches et le comportement pendant la mise en forme.

Ces résultats apportent des connaissances essentielles pour améliorer l'efficacité de la fabrication, réduire les pertes de matière et optimiser la qualité des composites textiles renforcés en Z par des fibres continues.