

Pull-off Behavior of Stitched Composite T-Joints

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Abstract

T-joints are key structural elements that connect opposing surfaces, thereby providing the load path between flat or curved panels (i.e., upper and lower wing skins) and transverse components (i.e., stiffeners). Due to the low interlaminar strength of polymer matrix composites and their geometrical discontinuities, these joints are vulnerable to pull-off loads. To address these issues, through-thickness reinforcements can be employed to enhance the interlaminar capability of these type of joints. In this study, T-joints were manufactured using through-thickness stitching in dry carbon preforms and cured using the vacuum-assisted resin transfer molding (VARTM) process. Stitched and unstitched T-joints were tested under pull-off loading conditions, and surface strain fields were obtained using a 3D digital image correlation system. The ultimate load, displacement, and absorbed energy of the stitched T-joints were greater than their unstitched counterparts by approximately 16%, 34%, and 58%, respectively. Failure mechanisms were identified by examining fracture surfaces using optical microscopy. Results demonstrate that through-thickness stitching significantly improves the damage tolerance of T-joints, which highlights the effectiveness of stitching to enhance the structural integrity of large aerospace components.

Keywords: Stitching, T-joints, Delamination, VARTM, Polymer Composite, Pull-off Test

Introduction

The T-joint is a common type of joint architecture that provides a load path between opposing structural components in structural assemblies [1–4]. A typical location of such joints is in the stiffened skin panels of a composite wing (Figure 1). Composite T-joints are formed by co-curing, adhesively bonding, or mechanically fastening skins or flat plates to a stiffener. The primary components of a T-joint consists of a web (stiffener), flanges, and a delta fillet region also known as the “noodle” to fill the radius region (Figure 2). The flanges of the T-joint are secured to the skin panel.

T-joints are subjected to out-of-plane loads, resulting in high interlaminar stresses that cause progressive failures due to delamination between the skin and the T-joint flanges [2,4–9]. These interlaminar stresses cause failure between plies as the fibers do not provide reinforcement in the through-thickness direction [10–16]. Geometrical discontinuities (e.g., ply drops, corners, curved free edges), and material discontinuities (e.g., facesheet-to-core interfaces in sandwich composites, delta fillet-skin/flange interaction, and multi-material joints) can be initiators for delamination damage in T-joints [17–21]. In composite T-joints, failure mechanisms can be broadly categorized as disbonding between the delta fillet and stiffener or skin, delamination in the stringer in the radius bend region, and disbond of the skin/flange or in the web [4,10,22–28]. Additional observed failure modes include translaminar and intralaminar failure of the composite plies, but these failure modes

often occur after delamination has occurred. Factors, such as voids, resin-rich areas, manufacturing defects, matrix cracking, high out-of-plane loads, and impact damage, can lead to damage initiation and failure.

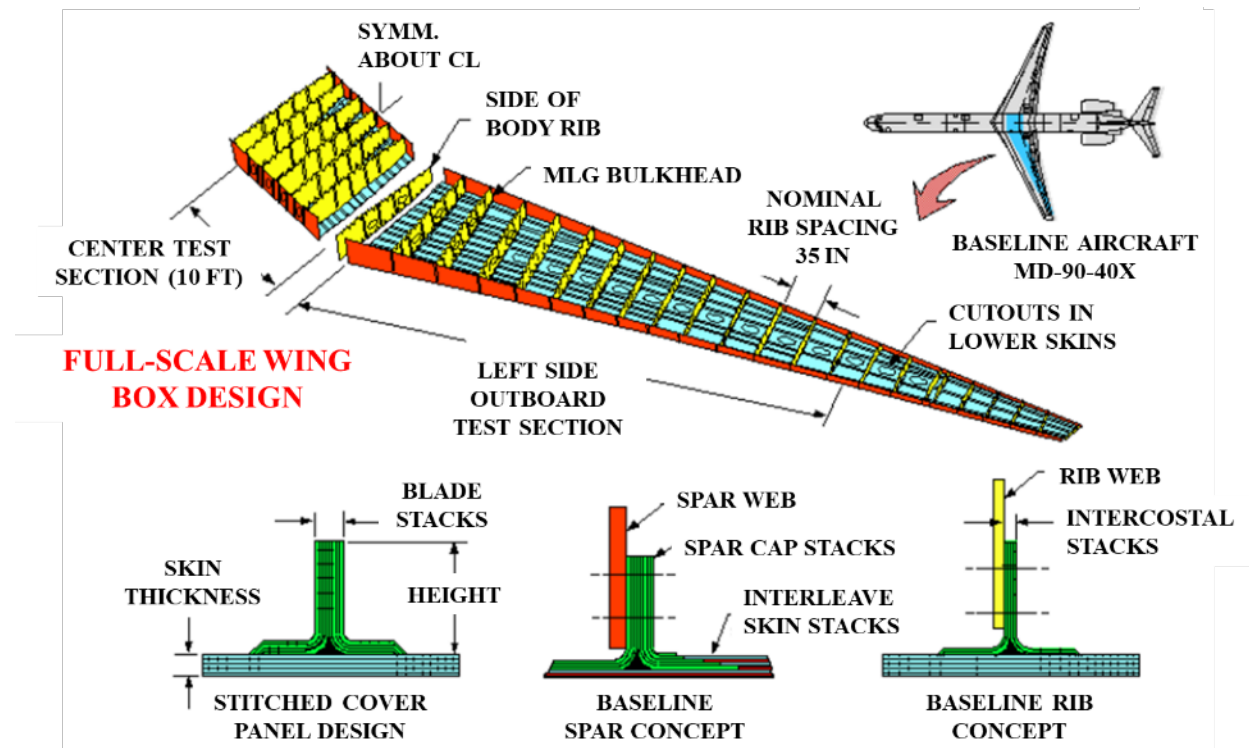


Figure 1: Composite wing cover panel wing concept (reprinted from [29]).

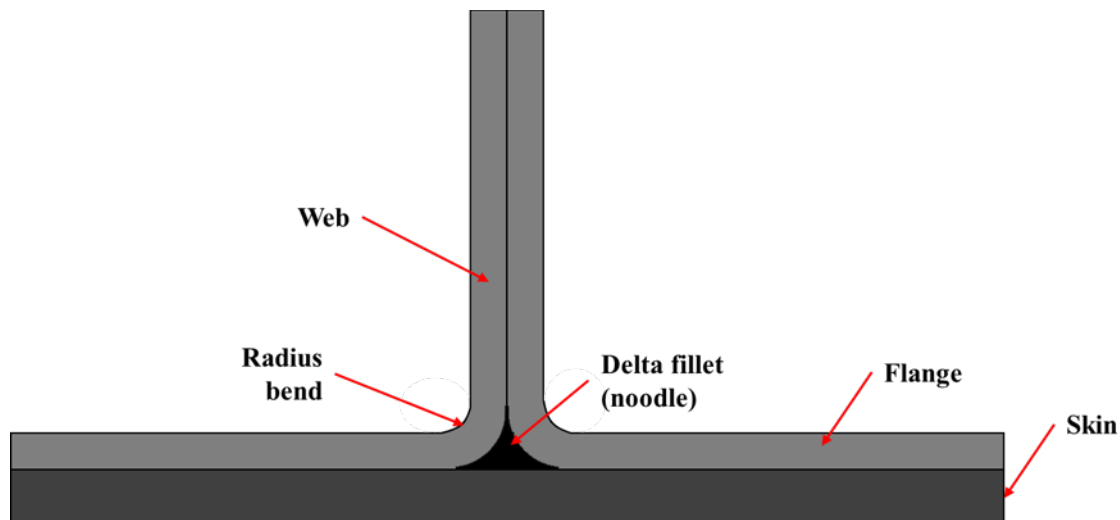


Figure 2: Schematic of a T-joint.

The plies within the radius bend and the fillet interface areas are frequently the damage initiation sites as the joint is subjected to high out-of-plane stresses [30]. To reinforce these critical areas,

various methods have been employed; these include using toughened resin systems, adding filler to decrease geometric stress concentrations in the radius, and using through-thickness reinforcement techniques, such as Z-pinning, metallic arrow pins, tufting, and stitching [20,24,28,31–36]. Khor, et al. reported an increase of 114% in peak load and up to 450% increase in the absorbed energy in tufted T-joints [37]. Similarly, Cartié, et al. reported an increase of 10% in the overall absorbed energy in T-joints reinforced with z-pinning and about a 100% increase in T-joints reinforced using tufting [36]. Kim, et al. studied the pull-off failure behavior of T-joints stitched using a novel 1-thread stitching process and reported an increase of 47.5% in the failure load when compared to their unstitched counterparts [38].

Stitching has been of great interest for through-thickness reinforcement due to the ease of manufacturing large-scale unitized components compared to other techniques, such as z-pinning or metallic arrow reinforcements [1,39]. The stitching process involves sewing dry preforms using an industrial sewing machine using carbon, aramid, glass, or polyester-based threads. Different stitching techniques have been utilized, such as lock stitch, modified lock stitch, chain stitch, and one-sided stitching using a 1-thread stitching process [21,38,40–43]. Factors, such as stitch pitch and spacing, can be varied to obtain the desired stitch density and interlaminar properties [42,43]. Previous studies of stitched composite structures have shown a reduction in overall weight by reducing the need for mechanical fasteners [1,29,44]. Stitching has also improved the interlaminar fracture toughness of laminated composites in both Mode I and Mode II loading conditions [40,43,45,46]. Although studies have been conducted on stitching effects on flat laminates, the influence of stitching on composite joints, such as the T-joint, pi-joint, and C-joint, have not been explored extensively. Very few studies have been conducted on the mechanical response of T-joints that are stitched using a combination of stitching techniques [26,30,47]. In this study, the pull-off behavior of a stitched composite T-joint using one-sided and double-sided stitching techniques is evaluated.

Experimental Methodology

Fabrication

Stitched and unstitched T-joints were fabricated from Hextow™* AS4 warp knitted non-crimp fabric (NCF) stacks. Each NCF stack is a group of seven plies knitted together using a nonstructural knit stitch with a layup of $[\pm 45^\circ/0^\circ/90^\circ/0^\circ/\pm 45^\circ]$, where the 0° plies are double thickness, resulting in $[0^\circ/\pm 45^\circ/90^\circ]$ ply percentages of approximately [44/44/12]. The T-joint web comprises eight stacks of the seven-ply NCF, and the skin consists of five stacks of the same NCF, resulting in a total of eight stacks in the web and nine stacks in the skin-flange region. The 0° plies run in the through-thickness direction (depth) perpendicular to the joint axis of the specimen in both web and skin. Toray's standard modulus woven T300 carbon fiber was used in the delta fillet region. The selected layup is based on the layup of the wing skin-stringer from a previous experimental study of a full-scale stitched graphite-epoxy composite wing [29,39]. All stitching

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was done at NASA Langley Research Center (LaRC) using the Integrated Structural Assembly of Advanced Composites (ISAAC) Facility, shown in Figure 3a. The web portion was stitched first using a double-sided chain stitch using an RS566 end-effector mounted on the six-axis industrial robotic arm. The remaining unstitched preform was opened to fashion the stringer and stitched after adding skin stacks; herein, a one-sided modified chain stitching technique was implemented via an RS535 end-effector, which utilizes an insertion needle and a catcher needle (Figure 3b). Both end effectors were manufactured by PFAFF Industrial. The insertion needle with the reinforcement thread penetrates the dry perform at a 45° angle while the catcher needle penetrates the preform at 90° and picks up the thread. This process eliminates the need for access to the underside of the preform, thus enabling stitching of parts with complex geometries [48]. The constructed T-joint preform of length 1.88 m had alternating stitched and unstitched zones of approximately 185 mm in length as shown in Figure 4.

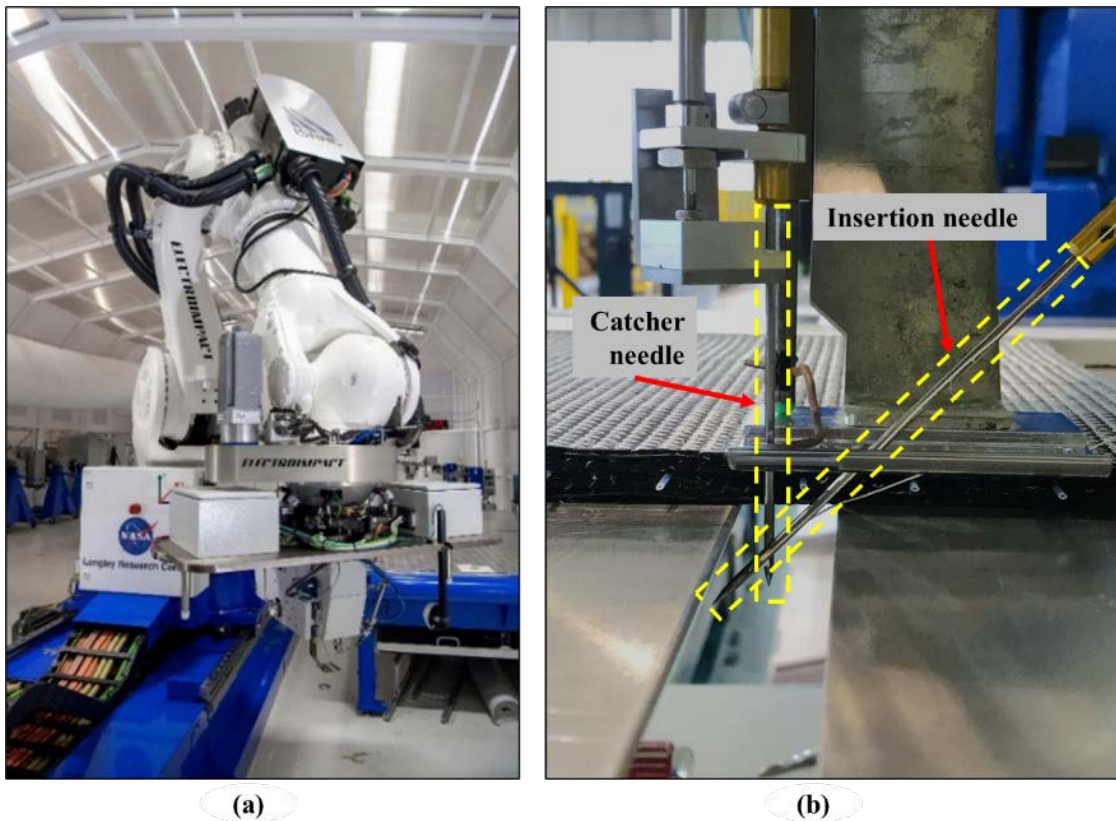


Figure 3: NASA LaRC ISAAC system (a) with an RS535 end-effector and (b) insertion and catcher needles used in the one-sided end effector (right).

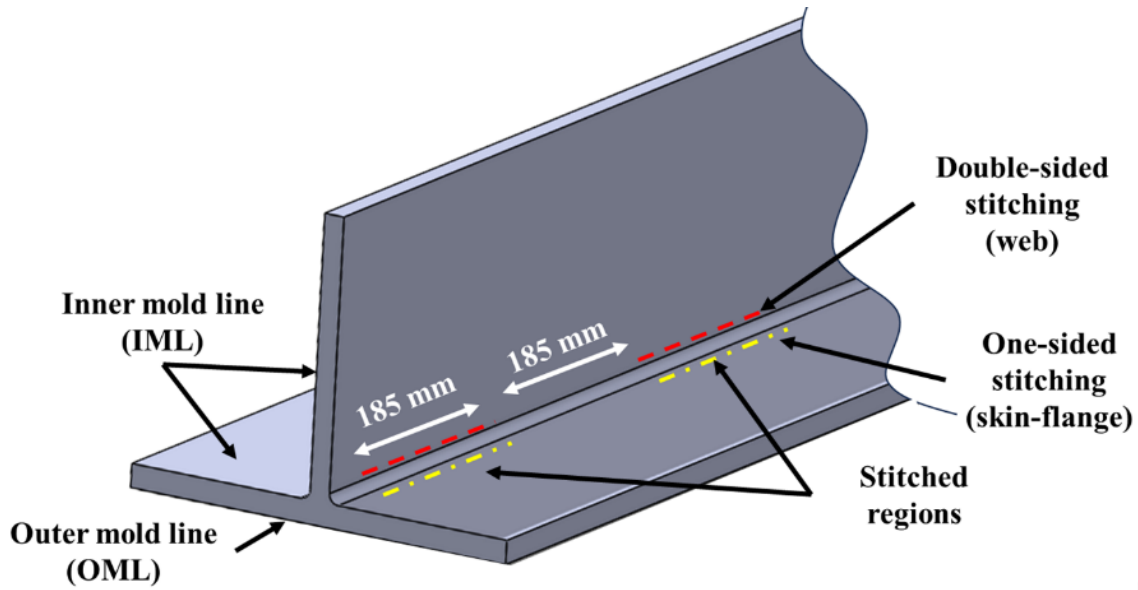


Figure 4: T-joint web and skin stitching locations prior to cutting.

Following stitching, the dry preform was VARTM infused with Hexflow™ 1078 resin, an out-of-autoclave epoxy system manufactured by Hexcel® Corporation. The resin was preheated to 88 °C to obtain correct infusion viscosity, and the part was cured according to the manufacturer's cure cycle (Figure 5). A waterjet cutter was used to trim the skin-flange regions (average thickness = 12.1 mm) and webs (average thickness = 10.7 mm). Using a band saw with a diamond-edged blade, the cured T-joint structures of length 1.88 m were sectioned into stitched and unstitched T-joint test articles with an overall dimension of 203 mm x 76 mm x 153 mm (Figure 6). Four holes with a diameter of 9.92 mm were drilled in the skin/flange region of the T-joints for mounting onto the test fixture (Figure 6). Holes were drilled using a computer numerical control (CNC) machine.

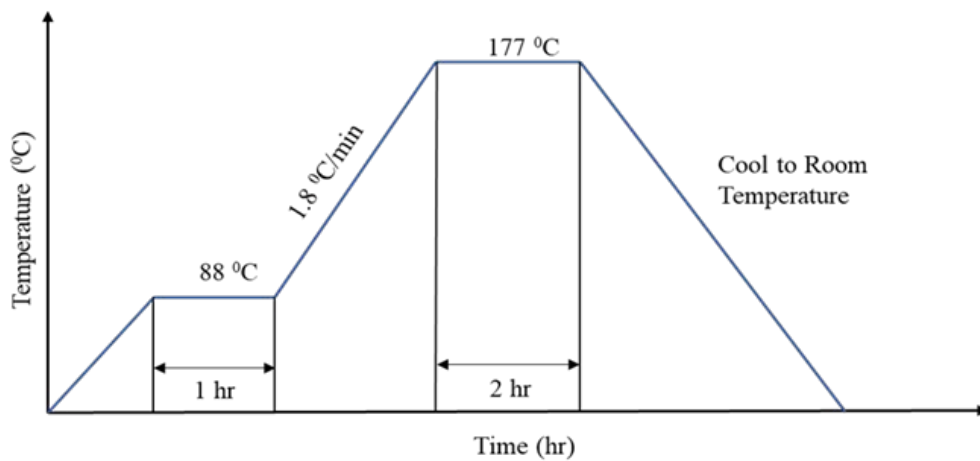


Figure 5. Cure cycle used in the infusion of the T-joint preforms [41].

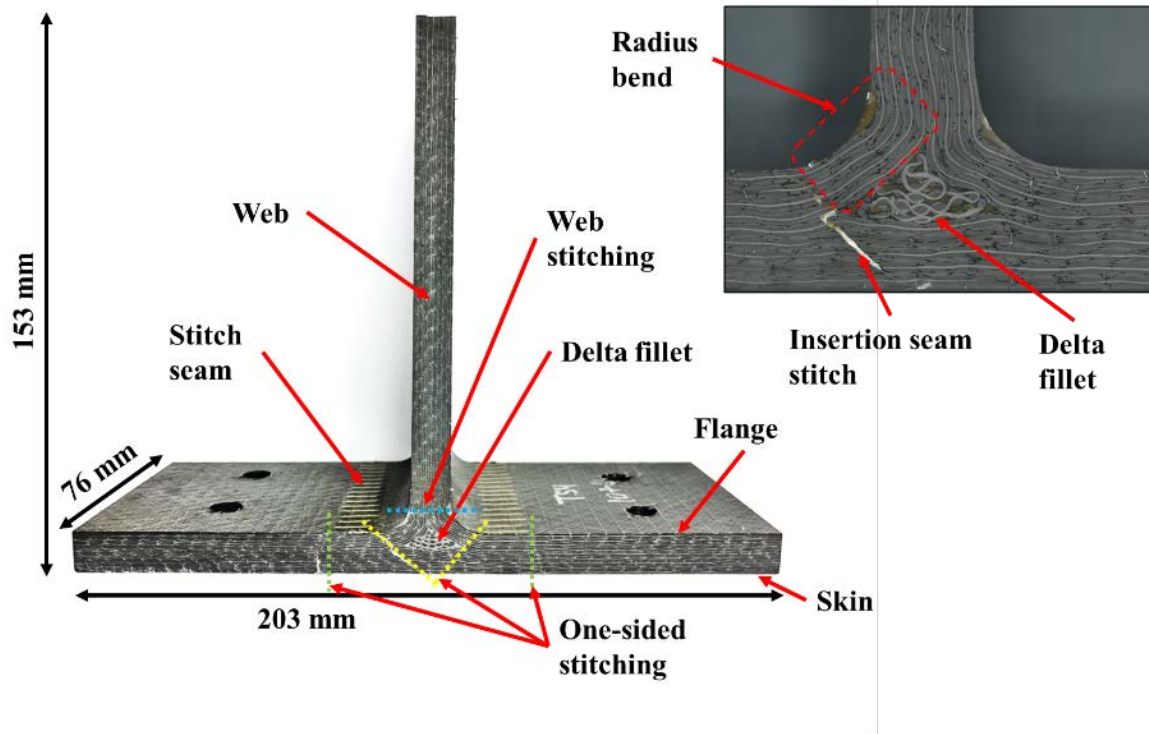


Figure 6: Stitched T-joint specimen with stitching locations and delta fillet features (inset).

Pull-off tests of T-joints

The T-joint pull-off testing was conducted using a 50-kN mechanical test frame at NASA LaRC. Both front and back faces of the T-joints were painted with a speckle pattern, and two Correlated Solutions VIC-3D digital image correlation (DIC) systems were used to monitor surface strains in and around the delta fillet region [49,50]. Images were captured with four 12-megapixel cameras (two on each face). To monitor web strains, four axial strain gages were mounted on the web in back-to-back pairs. A Micro-Measurements StrainSmart® System 7000 data acquisition system was used to collect strain data. The smooth skin surface (outer mold line) of the test article was bolted to a metallic base plate, and the web of the specimen was clamped using grips, as shown in Figure 7. Approximately 50 mm of the web was clamped in the grips using 10 MPa grip pressure. Clamp plates were used to fix the T-joint specimen to the base plate. The tests were conducted using displacement control at a rate of 0.5 mm/min.

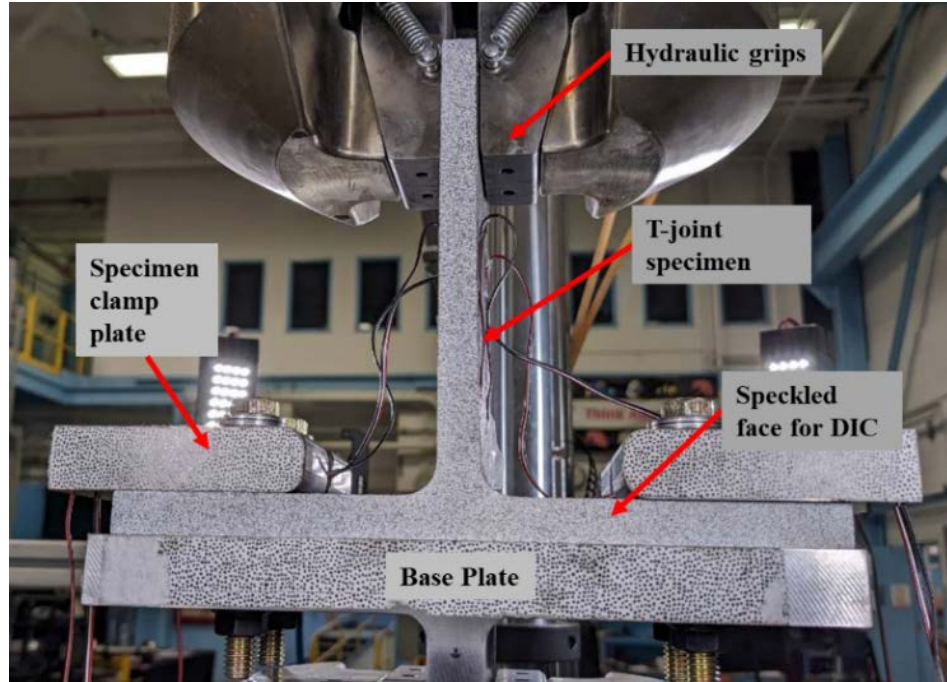


Figure 7: T-joint pull-off test setup.

Results

Load displacement response

A total of six specimens (three stitched and three unstitched) were tested. The stitched specimens are designated as S-# and unstitched specimens as US-#, where # is the specimen number. The load-displacement response of all stitched (red lines) and unstitched (black lines) specimens is shown in Figure 8.

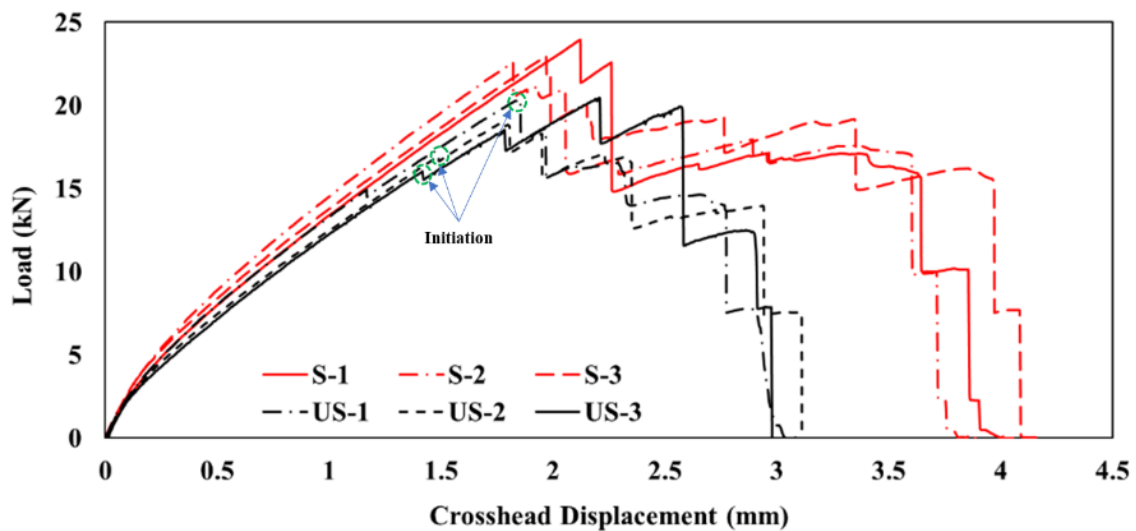


Figure 8: Load displacement curves for the stitched and unstitched specimens.

Initiation load and displacement

Prior to initiation of failure, a bilinear load-displacement response is observed for both the unstitched and stitched specimens when subjected to tensile loading. At an applied displacement of 0.1 mm, an inflection and 50% slope reduction in the load-displacement response are observed. This behavior may be attributed to compliance of the fixture and exceedance of the preload of the clamping force when loading is applied. However, it is worth mentioning that as tensile loading is applied to the web, rotations near the clamped interfaces were observed. Sufficient rotations at the clamped boundary conditions may develop in-plane tension in the skin-flange region and alter the stiffness (load-displacement slope) of the T-Joint as loading is applied. No failure during this initial inflection of the load-displacement response was observed. The majority of the response prior to initial failure consists of linearly increasing load as the web is placed under axial tension. Once the specimens reach the critical load, initial failure occurs, followed by a sudden decrease in the load. Table 1 lists the loads and displacements at various points for all specimens. The initial failure in unstitched specimens occurred at a lower loads and displacements when compared to the stitched specimens. On average, the failure initiation load and displacement for the stitched specimens were 43% and 29.5% higher, respectively, when compared to those of the unstitched specimens. The absorbed energy, which corresponds to the total area under the curve, was also calculated [37,51]. The average absorbed energy until the initiation for the stitched specimens was 113% higher than the unstitched specimens (Table 1). Initiation of failure was observed to occur before the peak load in the unstitched specimens, whereas in stitched specimens, the initiation of failure occurred at the peak load.

Peak load and ultimate displacement

The stitched specimens have a 15% higher average peak load when compared to the unstitched specimens, demonstrating improved damage resistance due to stitching. The average displacement at the peak load is similar (within 1%) for both specimen types. At the peak load, the absorbed energy for stitched specimens is about 14.9% higher compared to unstitched specimens, which is consistent with the difference in peak loads. It is also noted that the failure mechanisms are different in stitched specimens compared to the unstitched specimens. In the unstitched specimens, the load decreases due to the formation and growth of delaminations, whereas in the stitched specimens, the stitches bridge the crack surfaces, resulting in a higher displacement at ultimate failure. The total displacement at failure for stitched specimens is 33.6% higher when compared to the unstitched specimens; which can be attributed to the additional damage tolerance capacity due to stitching.

Damage in the delta fillet region

For all specimens, delaminations initiated in the radius bend area slightly above the delta fillet region (Figure 6); this is attributed to the resin-rich areas, also demonstrated in other studies [36,49,51,52]. Also, the crack propagates along the web and the flange/skin interface for all specimen types. The surface morphology of the T-joints close to the radius area is discussed in more detail in the upcoming section.

Table 1: Mechanical properties at critical load and displacement of T-joint tensile tests.

	Initiation			Peak Load			Ultimate Displacements	
Specimen	Load (kN)	Displacement (mm)	Absorbed Energy (kN·mm)	Load (kN)	Displacement (mm)	Absorbed Energy (kN·mm)	Displacement (mm)	Absorbed Energy (kN·mm)
US-1	14.93	1.66	10.05	20.36	1.854	22.13	3.05	37.82
US-2	16.96	1.48	14.42	18.83	1.797	19.94	3.038	34.45
US-3	16.03	1.41	12.91	20.45	2.21	27.21	2.98	38.69
Avg. US	15.97 ±0.82	1.52 ±0.011	12.46 ±1.81	19.88 ±0.74	1.95 ±0.18	23.09 ±3.04	3.02 ±0.03	36.99 ±1.83
S-1	23.52	2.12	29.80	23.52	2.122	29.8	4.02	56.8
S-2	22.60	1.82	23.79	22.60	1.821	23.8	3.91	56.16
S-3	22.75	1.98	26.01	22.75	1.977	26	4.18	62.4
Avg. S	22.95 ±0.4	1.97 ±0.12	26.53 ±2.48	22.95 ±0.4	1.97 ±0.12	26.53 ±2.48	4.04 ±0.11	58.45 ±2.80
Diff. (%)	43.7	29.5	113	15.5	1.01	14.9	33.6	58.04

To facilitate discussion of the DIC data, locations of interest in the load-displacement data for the specimens S-1 (stitched) and US-1 (unstitched) are shown in Figure 9. Points A and 1 indicate damage initiation for unstitched and stitched specimens, respectively. Points B and 2 correspond to the decreased load in post-damage for unstitched and stitched specimens, respectively. Similarly, points C and 1 correspond to the ultimate load for the unstitched and stitched specimens, respectively. Segment E-F corresponds to the large load drop for the unstitched specimens before ultimate failure. Points 5 and 6 in the stitched specimens correspond to the load before and after the stitch failure. The DIC images corresponding to these points for both unstitched and stitched specimens will be described in subsequent sections.

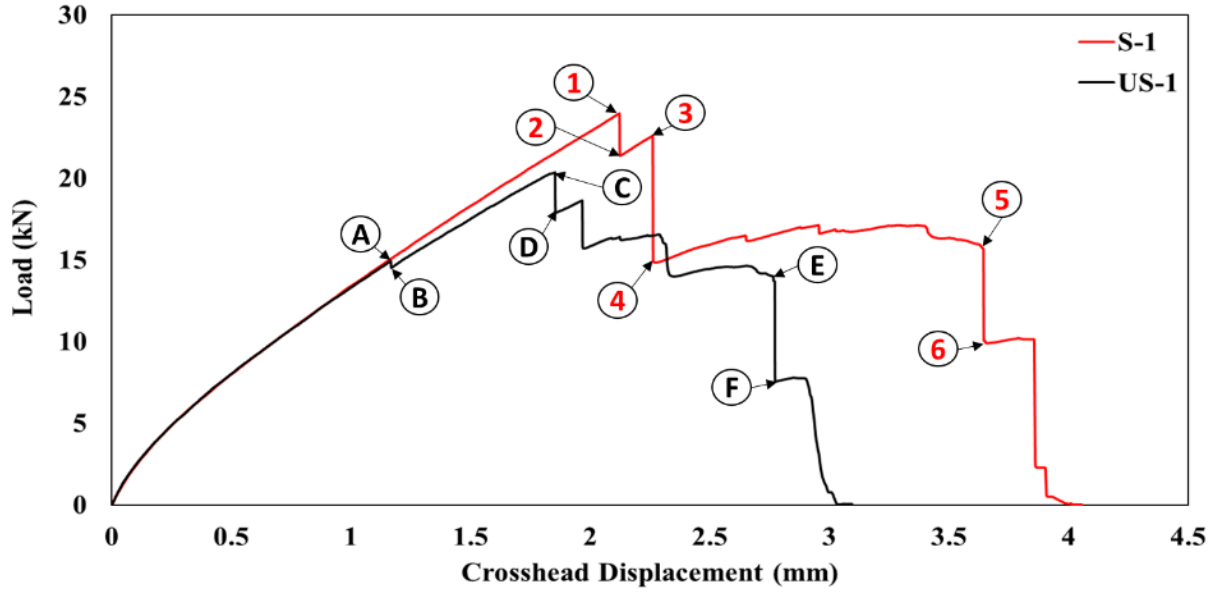


Figure 9: Typical T-joint pull-off load–displacement curve for the T-joints with and without stitching. The load-at-first failure (A, 1), ultimate load (C, 1), stitch failure for specimen S-1 (5), and ultimate failure for specimen US-1 (E) is shown.

Unstitched T-joints

The specimens were sectioned in half (~37 mm from the edge), and the surfaces were prepared for imaging. Microscopy images of the sectioned surface of the failed unstitched specimen US-1 and stitched specimen S-1 were made, and in the following sections are compared to DIC data images.

In the unstitched specimens, the initial damage occurred early, as indicated by segment AB in Figure 9. For the unstitched specimen US-1, the maximum principal DIC strain fields from the front and back of the specimen prior to initiation and after damage initiation are shown in Figures 10a and 10b, respectively. The initial damage in the radius bend area marked with a yellow line is indicated in Figure 10b. The resin-rich pockets observed in the radius bend are a potential site for delamination damage. An optical microscope image of the areas around the delta fillet and the radius bend area with the resin pockets is shown in Figure 15. The resin rich areas outside the radius bend on the inner mold line surface and around the knit stitches are also visible in Figure 15. The delamination initiated in the radius area and transitioned along the web and skin flange interface as the testing progressed.

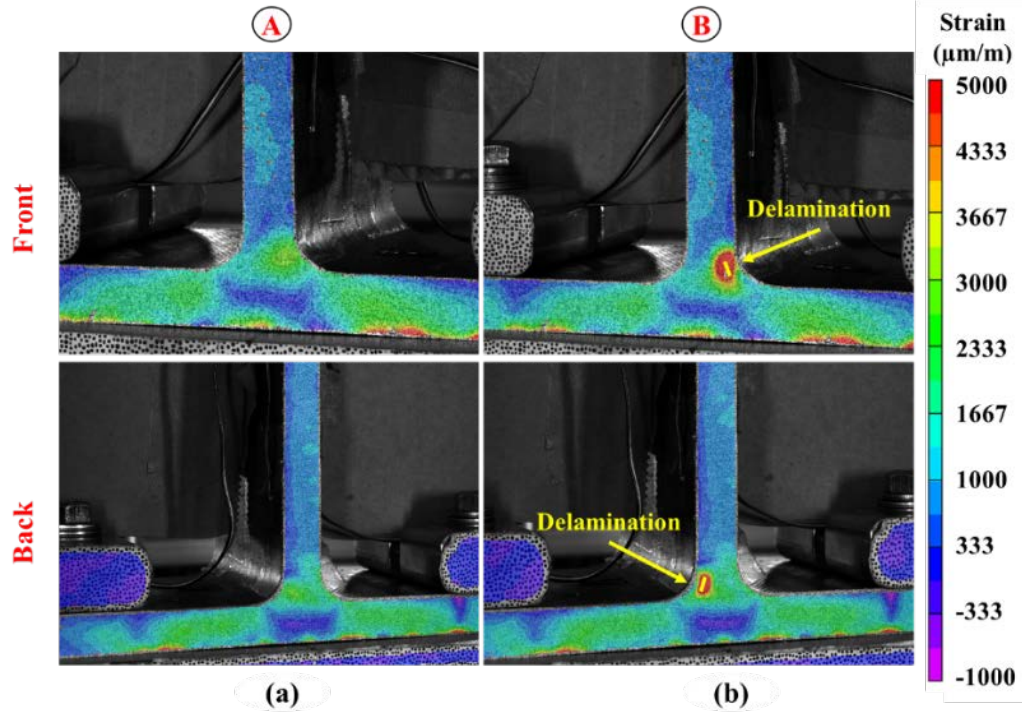


Figure 10: Specimen US-1 principal strain and damage initiation (Figure 9; segment AB) (a) before damage (14.93 kN), and (b) initial damage with delamination outline (14.51 kN).

Once the damage is initiated, the size of the damage continues to grow in the reduced stiffness region until a subsequent peak load (Figure 9, Point C) is reached, at which point the delamination grows abruptly as the load drops (Figure 9, Segment CD). The change in damage size at the peak and post-peak loads is shown in Figures 11a and 11b, respectively. The size of the damage is larger on the front side of the specimen than on the back side. This could be due to localized resin-rich areas and material variation along the specimen width.

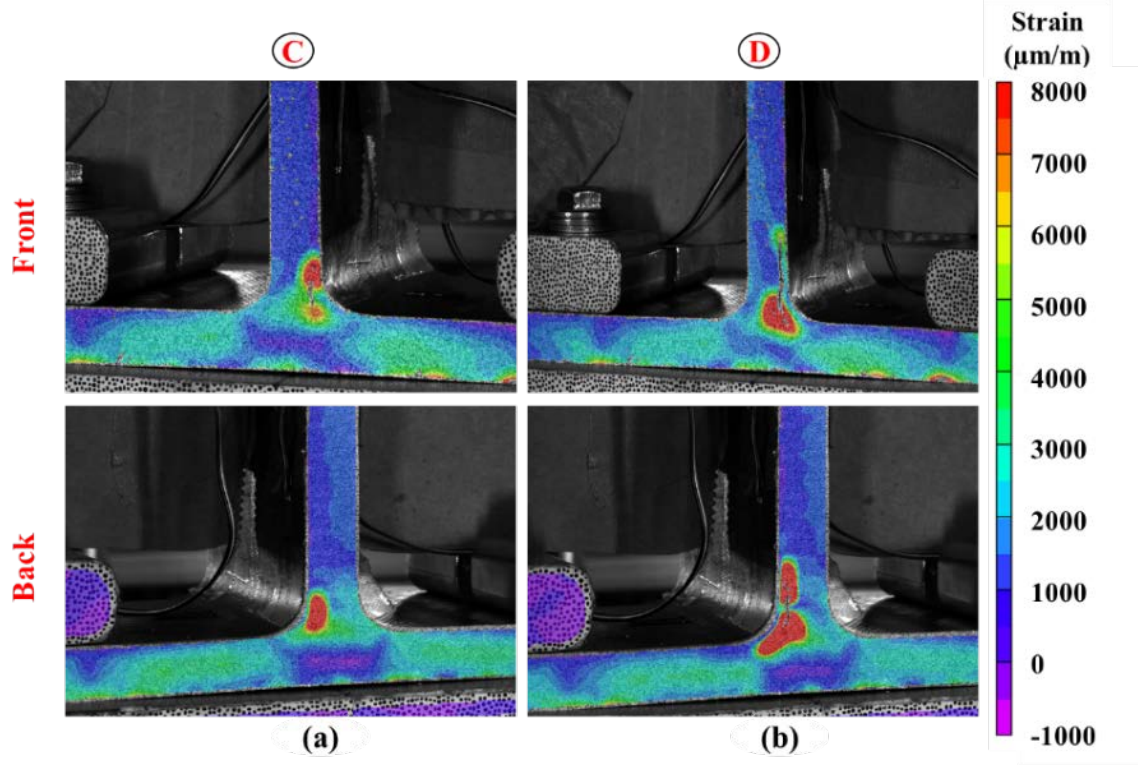


Figure 11: Specimen US-1 principal strains (Figure 9; segment CD) at (a) peak load (20.36 kN) and (b) post-peak load (18.7 kN).

The DIC images corresponding to segment EF for unstitched specimen US-1 are shown in Figure 12. This segment corresponds to the large delamination growth in the skin-flange interface. As the applied displacement increases, the delamination grows further into the skin-flange interface (Figure 12a). Eventually, it reaches the clamped region, at which point the tests were terminated. It was also observed that the delamination around the delta fillet was limited to the delta-fillet-to-stiffener plies interface in the radius bend area. No delamination was observed between skin stacks and the bottom of the delta fillet (Figure 12b). However, some slight delamination migration was observed as the crack front progressed to the bolted flange interface. A long delamination that forms in the web along the 90° fibers and along the skin-flange interface in specimen US-1 is shown in Figure 13. Multiple sites of delamination migration are observed as transverse matrix cracks form; these cracks stop once they reach adjacent plies, after which the delamination grows along an adjacent ply interface. Delamination is primarily observed to occur near a 90° ply interface. The 90° fibers are the off-white color lines in all the micrographs and run along the length of the web and along the skin-flange interface (Figure 13 inset).

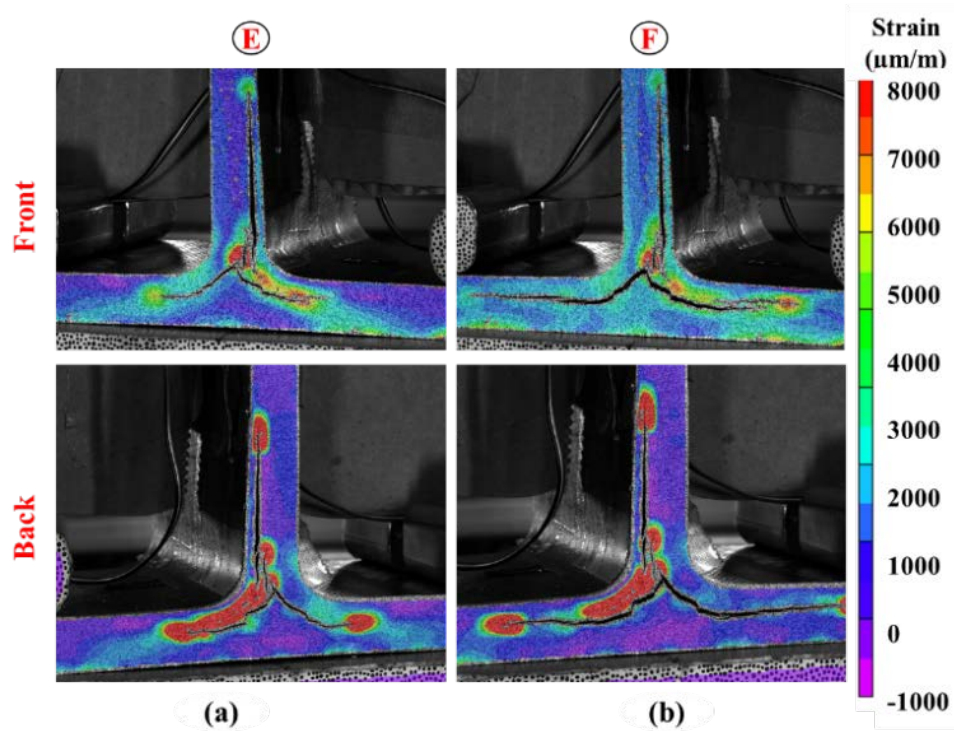


Figure 12: Specimen US-1 principal strains (a) before final failure (Figure 9, point E) and (b) after final failure (Figure 9, point F).

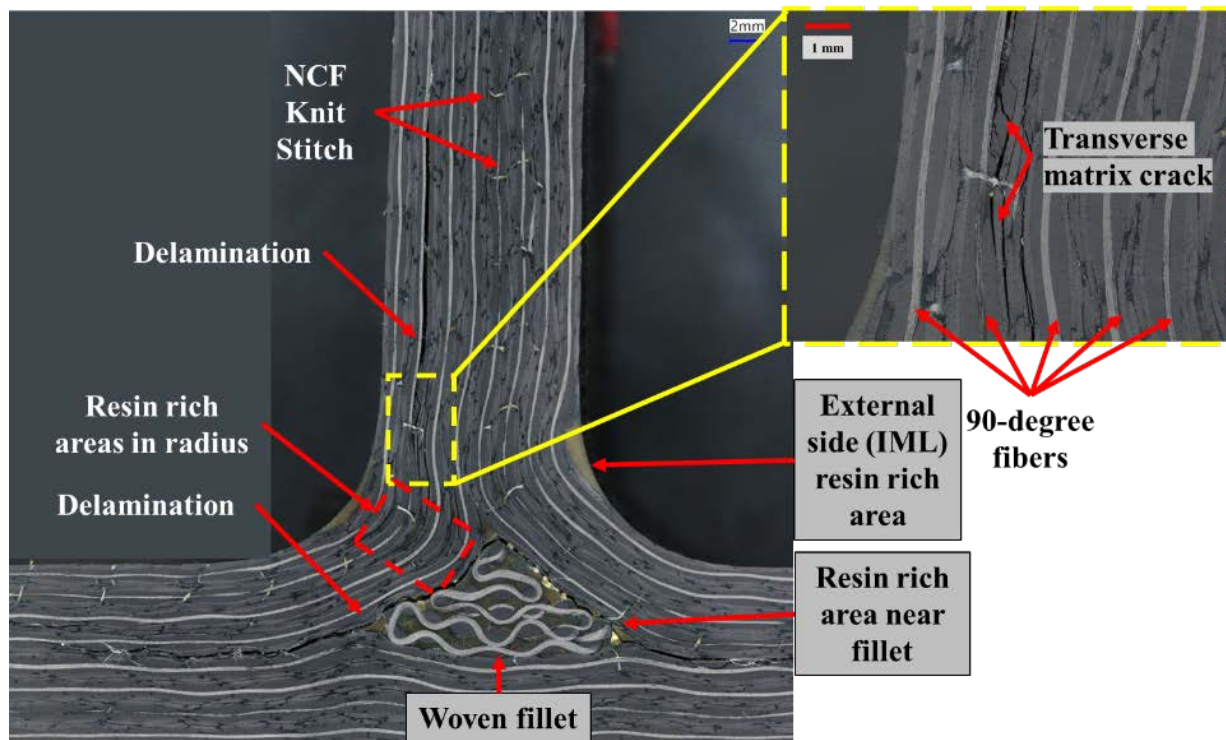


Figure 13: US-1 crack path and inset transverse matrix crack and delamination in the web.

Stitched T-joints

The DIC images from the damage initiation segment (1-2) for the stitched specimen are shown in Figures 14a and 14b. It is noted that the size of the initial damage is much larger for the stitched specimen when compared to the unstitched specimen. Similar to the unstitched specimens, resin-rich areas around the radius bend, the delta fillet, and between plies in the radius bend are observed (Figure 15). The initiation sites are generally in the radius area similar to those in the unstitched specimens; this is attributed to the multiple resin-rich regions formed between the plies in the radius bend area (Figure 15). Additional resin-rich areas formed around the stitches (web and skin), as shown in Figure 15. The resin-rich area on the external side of the radius is larger compared to the areas formed in the unstitched specimens and can be attributed to fiber compaction due to stitching.

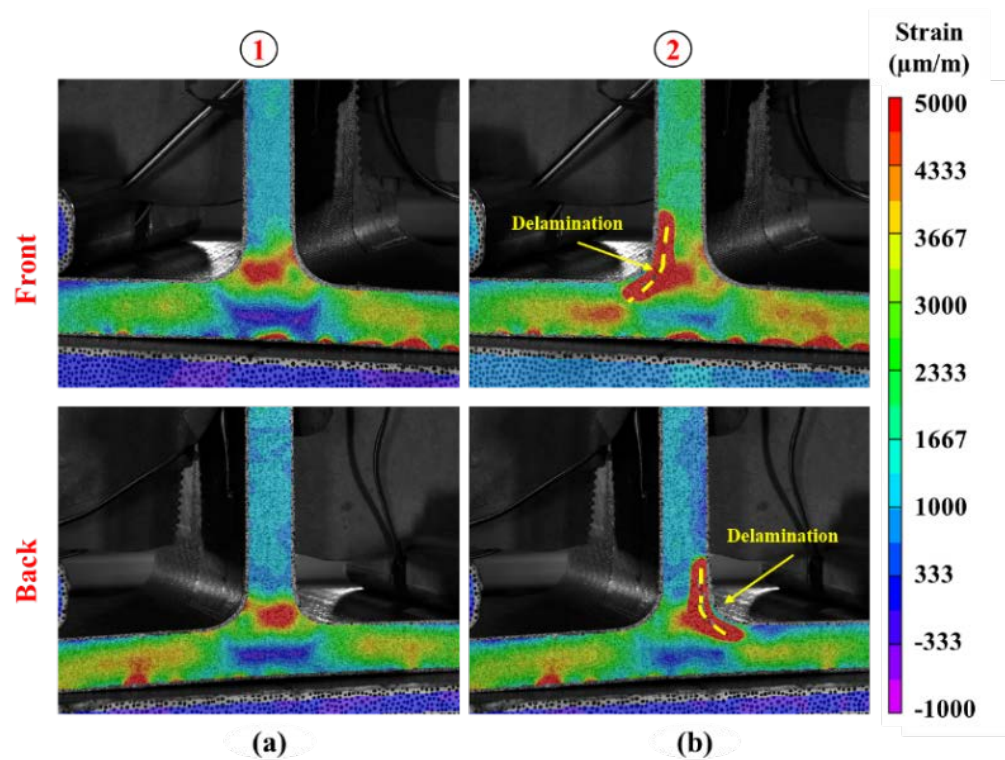


Figure 14: Specimen S-1 principal strains (Figure 9; segment 1-2) (a) before damage (23.52 kN), (b) initial damage with delamination outline (21.51 kN).

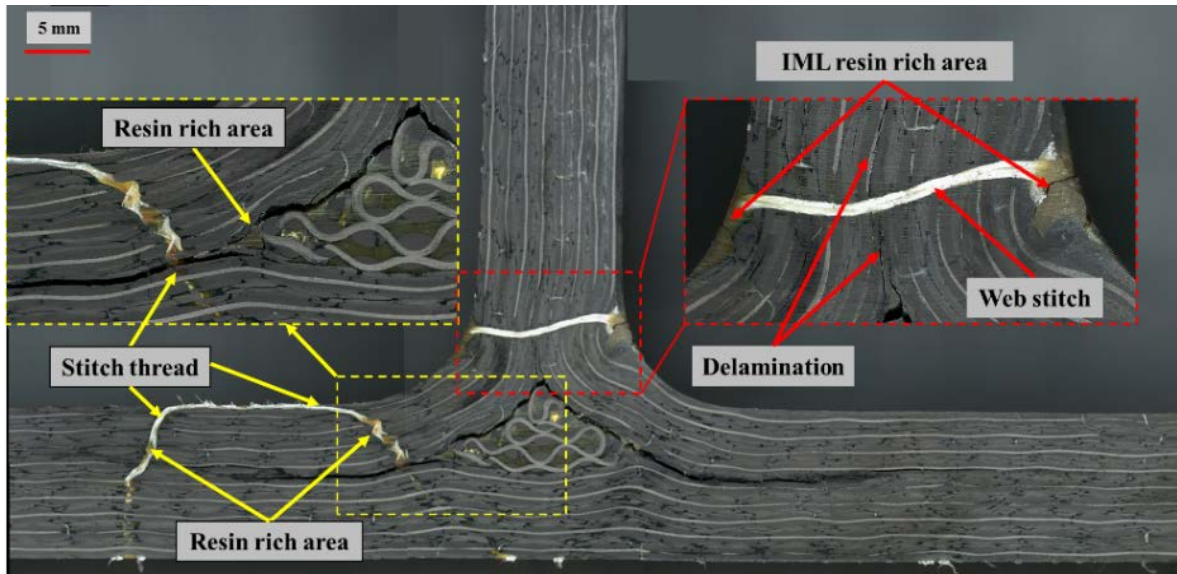


Figure 15: Crack path in stitched specimen S-1.

A major growth in delamination occurred post-peak load in segment 3-4, a point where the load abruptly decreases. This load drop corresponds to the formation of delaminations around the delta fillet; this is in addition to the growth in the delamination in the radius bend area and is shown in Figures 16a and 16b. It is observed that the crack grows in the web area passing around the web stitches as delamination can be observed on either side of the stitches without any stitch failure (Figure 15).

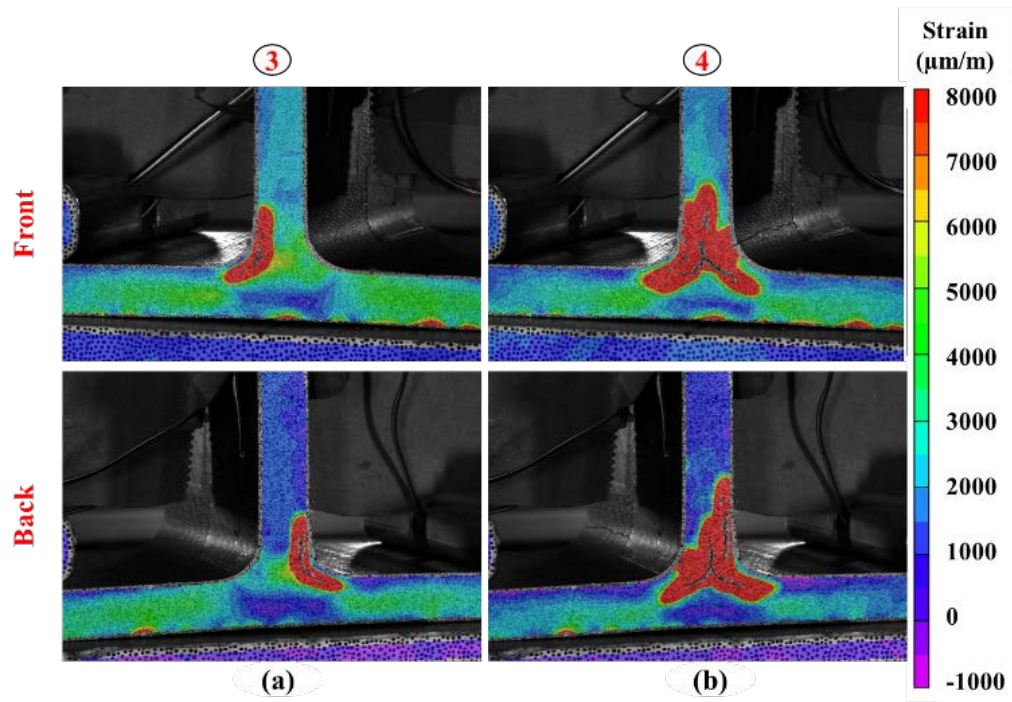


Figure 16: Specimen S-1 principal strains at (a) point 3 (22.5 kN) and (b) post load drop at point 4 (14.8 kN).

The DIC images corresponding to segment 5-6 for stitched specimens are shown in Figure 17. This segment corresponds to the breakage of the insertion seam stitch, leading to final failure. Pull-out failure in the insertion stitches were observed once the specimens were sectioned post testing. As the applied displacement increases, the delamination grows further into the skin-flange interface, and the stitch bridges the interface, as shown in Figure 17a. Upon stitch failure, the delamination suddenly grows along the skin-flange interface, as shown in Figure 17b. Similar to the unstitched specimens, no damage was observed below the delta fillet region. The stitches in the web did not fail during testing and can be seen in Figure 18. The delamination propagates around the stitch and continues to grow along the length of the web. In the skin-flange interface, the delamination front passes around the stitches initially, until the failure of the insertion row stitches. The matrix crack in the resin pockets on the specimen surfaces can also be seen in Figure 18 (inset right).

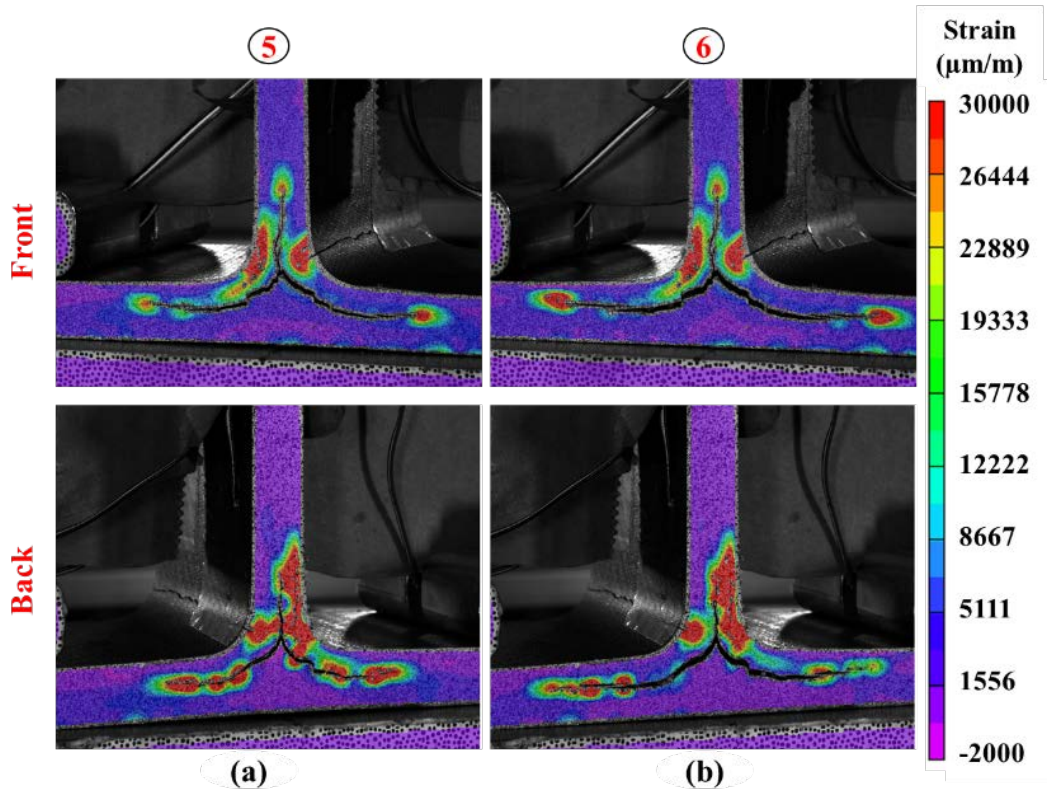


Figure 17: Specimen S-1 principal strains (a) before stitch failure (point 5) (b) after stitch failure (point 6).

Significant resin pockets are observed around the stitches (Figures 15 and 18). In addition to the disbond between the resin and the fiber (Figure 18a), localized fractures in the resin-rich regions around the stitches close to the crack were also observed. The localized fractures around the insertion seam and resin-rich region around the catcher seam for stitched specimen S-1 are shown in Figures 18a and 18b, respectively.

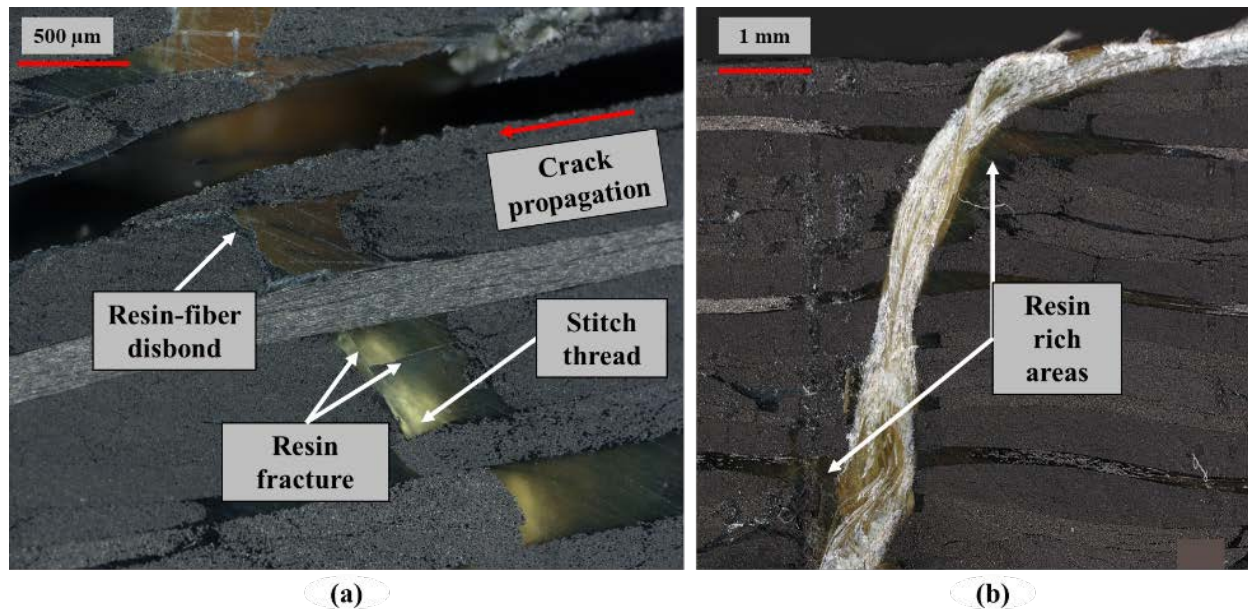


Figure 18: (a) Cracks in the resin-rich area around the insertion stitch and (b) resin-rich area around the catcher stitch.

Optical Microscopy Results Summary

The following observations were common for both stitched and unstitched specimens.

1. Fiber waviness was observed in the radius bend area.
2. A resin-rich area was formed on the external side of the radius bend during the manufacturing process (Figures 13 and 15). This can be attributed to the mismatch in radius of the support tool and the preform due to the use of available fillet material instead of a tailored fillet material. Similar resin-rich areas have also been observed in T-joints without filler material [30].
3. A crack was observed running along the length of the specimens in the external side resin-rich area in the radius (Figure 17 front side images in the right fillet).
4. Small resin-rich regions were observed in all specimen types around the NCF knit stitches.
5. Some delamination initiated in the interface between different stacks (+45/+45 interface) and propagated in the transverse direction to the 90° fibers, after which the delamination grew mostly along the 90° fibers (delamination migration). This can be attributed to the lower fracture energy requirement for a crack to propagate along the fiber direction [53,54].
6. The edges of the delta fillet areas were sites for localized resin accumulation (Figures 13 and 15 inset).

The following observations were different for stitched specimens as compared to the unstitched specimens.

1. In the stitched specimens, areas of resin-rich regions were observed around stitches in the web and in the flange (Figure 15 and 18).
2. In the stitched specimens, the size of the resin pool on the external side was larger than that of the unstitched specimens. This could be due to localized compaction of fibers due to web stitching (Figure 15).
3. Web stitches did not fail; however, delamination damage can be observed in areas beyond the stitches in the web (Figure 15 inset).

Conclusions

In this study, the mechanical behavior of stitched T-joints under pull-off loading conditions was compared to unstitched baseline specimens. Stitching significantly enhanced the mechanical performance of the T-joints in terms of failure load, ultimate displacement and absorbed energy. The stitched specimens have a 15% higher average ultimate load and 33.6% higher ultimate displacement compared to unstitched specimens, demonstrating improved damage resistance due to stitching. Additionally, the stitched specimens had average absorbed energy that was 113% higher than the unstitched specimens. The post-testing micrographs revealed resin-rich areas in the specimens, especially around the radius bend area. These resin-rich areas were identified as potential damage initiation sites. Fiber waviness in the radius bend and delamination migration along the crack path were observed for both specimen types. A large resin pool developed in the stitched specimens around the reinforcement thread. Overall, the experimental results show that stitching improves the load at initial failure and the post-failure toughness of T-joints. The results of this study will be used to enhance the development of more accurate computational models to predict the behavior of stitched composite T-joints.

Acknowledgments

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