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Novel Design of Cocured Composite 'T' Joints with Integrally Woven 3D Inserts

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ABSTRACT

Composites can be exploited to their full potential when cocured, wherein different parts are made and bonded together in a single cure operation to realise an integral structure. The key element in a typical cocured construction is T-joint, which forms the primary load transfer mechanism between the skin and stiffener in a structural assembly. T-joints are particularly vulnerable for pull off loads and researchers are looking at various techniques to improve the pull strength viz. stitching, tufting, 3D weaving, multilayer weaving, 3D braiding and the like. The present work uses a novel technique to improve the strength of T-joints by employing a hybrid design wherein an integral 3D 'T' insert is interleaved with a conventional T-joint. Inserts were woven using 3K and 6K carbon tows and incorporated in T-joints using CSIR-NAL proprietary process called 'Vacuum Enhanced Resin Infusion Technology (VERITy)' process. Several configurations of T-joints were tested in an UTM in the pull mode till the failure to assess the efficacy of integrally woven 3D inserts. It was observed that the initial failure load was nearly the same across the various T-joint configurations tested whereas the maximum failure loads were quite different. The normalised strength of T-joints with integrally woven 3D inserts in pull off mode was enhanced by about 30% when compared T-joints without the insert and thus vindicating the usage of integrally woven 3D insert in a cocured T-joint. The insert is conceived in such a way that it can be easily incorporated in the design of cocured structures.

Keywords: T-joints, cocuring, pull off strength, VERITy, 3D 'T' inserts

1. Introduction

Composite materials with their superior specific strength & stiffness, and fatigue properties are the materials of primary choice in aerospace industry. Currently, the emphasis is on increased performance coupled with reduced manufacturing costs. Composites offer significant cost reduction in the form of cocuring wherein various elements of a structure are cured and bonded together in a single autoclave cure. The primary advantage of cocuring is that the substructure elements are more compliant in the green stage resulting in a better integration. The other advantages of cocuring being reduced part count, simplified assembly process, reduced production cost, smooth load transfer, sealed joints, smooth aerodynamic contour to name a few.

T-joints are particularly vulnerable for out of plane loads. This limitation has evinced keen interest amongst researchers. Analytical and experimental studies have been conducted to understand the behavior of these joints [1-5]. These studies include joint behavior in 3 & 4 point bending, noodle fillet with different materials, uses of adhesive and shear properties. Both active and passive techniques have been tried to improve the pull off strength of T-joints. Chemical and rubber toughening of resins and interleaving using tough thermoplastic film are some of the commonly practiced passive approaches. These techniques have resulted in a marginal improvement in the out of plane properties. The major drawbacks with these techniques are the high cost of toughened resins and interleaving processes and difficulties in the proper distribution of fine rubber particles in the matrix. Furthermore, toughening increases the viscosity of the resin, making it less attractive for infusion driven processes. On the other hand, researchers are looking at active techniques like viz., stitching, tufting, 3D weaving, multilayer weaving, 3D braiding and the like. Stitching and tufting have the disadvantage of damaging the preforms leading to reduction of the in-plane properties. Technologies such as 3D braiding, multilayer weaving etc., have complexities associated with their development and implementation at the component level. For certain applications, it may be necessary to combine a number of textile processes in order to obtain a product that satisfies the requirements of cost, performance, production rate, manufacturing risk etc., [6]. Moreover, the practical usage in large cocured composite structures is still a distant dream. The present work adopts a novel approach to improve the strength of T-joints by employing an integral 3D 'T' insert that is interleaved with a laminated T-joint preform.

2. Concept of Integral 3D T Insert[1]

The key element in cocured construction is the T-joint, which forms the primary load transfer mechanism between skin and stiffener in a structural assembly. A typical T-Joint consists of flange, web, fillet zone and base skin as shown in Fig. 2.1 The fillet zone is popularly known as the noodle region/ Bermuda region which is generally made using roving from the same material used for T-joint.

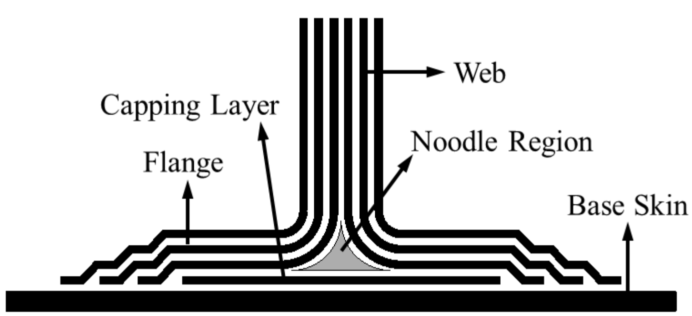

Figure 2.1: A typical composite T-joint

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It is important to understand the structural response of T-joints in order to incorporate any design changes. These are traditionally bonded joints capable of transferring loads in shear [7]. Occasionally, these joints are subjected to pull loads which will result in out of plane stresses like interlaminar tension and shear stresses in the skin stiffener interface and radius fillet zone. These stresses are concentrated at the fillet area thus rendering it to be the weakest link. Moreover, the laminated composites are weak in sustaining the above stresses. As the load increases, these stresses increase only to cross the material capability and the crack appears in fillet area, stiffness of the joint drops instantly and the joint fails without much warning. One way of increasing the load capability is to increase the stiffness of T-joint by either locally thickening the web or increasing the skin thickness or a combination of both. A novel idea is proposed in this paper wherein an integral 'T' insert [8] is conceived instead of using multiple laminae for the local thickening of T-joint. The concept of 'T' insert is to link the web and the flanges of the T-joint with a continuous integrally woven insert. This was done with the thinking that a single layer connecting the fillet zones on either side and integrated to both web and flanges would increase the local stiffness and in turn the load carrying capability of T-joint.

'T' inserts were woven on a commercial jacquard loom in the shape of a folded 'T' incorporating the noodle region in the weave architecture based on the concept of double cloth construction. Three such types of inserts using 3K and 6K of TC-33 medium modulus grade carbon tows were evaluated with and without noodle fillet. The schematics of 'T' inserts are shown in Fig. 2.2. Design specification of 'T' inserts is given in Table 1. Fig. 2.3 shows the photograph of a woven 'T' insert with noodle fillet.

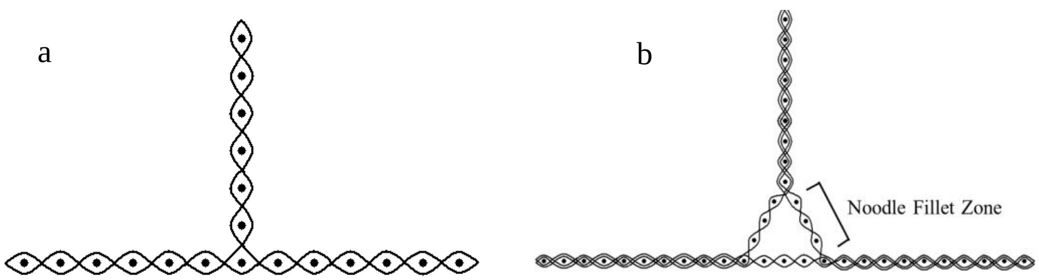

Figure 2.2: a) 'T' insert without noodle fillet & b) 'T' insert with noodle fillet

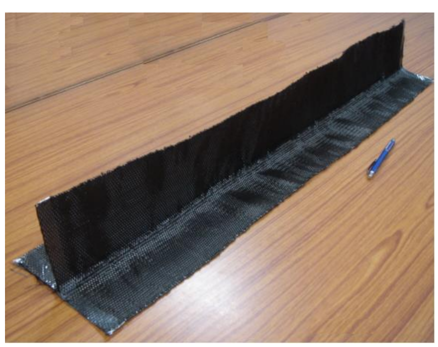

Figure 2.3: Photograph of Jacquard woven 'T' Insert with noodle fillet

Table 1: Specification of 'T' inserts

Particulars	'T' Insert with noodle fillet				'T' Insert without noodle fillet
	3K Carbon		6K Carbon		
	Web and Flange	Fillet zone	Web and Flange	Fillet zone	6K Carbon
Warp density (per cm)	5.5	5.5	3.5	3.5	5
Weft density (per cm)	11.5	6	13	6.5	5
Thickness (mm)	0.4		0.8		0.8

3. Design of T-joint Design Incorporating Integral 3D 'T' Insert

T-joints were designed and developed using CSIR-NAL proprietary process called '**V**acuum **E**nhanced **R**esin **I**nfusion **T**echnolog**y** (VERITy)' [9] process. In this process, the reinforcement is held in tool cavity and infused with resin under vacuum. The process aims at increasing the fibre volume fraction and quality of parts similar to the ones produced by autoclave/prepreg technique. Following materials were used for manufacturing of T-joints.

1. Carbon unidirectional fabric **G0827 BB 1040 HP03 1F** manufactured by M/s Hexcel Corporation.
2. **EPOLAM 2063** manufactured by M/s Axson Technologies.

The geometry of basic T-joint and the lamination scheme is given in Fig 3.1 and 3.2 respectively. The skin and web thickness of T-joints selected were 3.74 mm and 3.4 mm respectively with one side flange width of 30mm. Addition of 'T' insert in the noodle area increases the thickness locally. As pull of strength of T-joint is sensitive to local stiffness, it is important to have a proper criterion for design of various configurations.

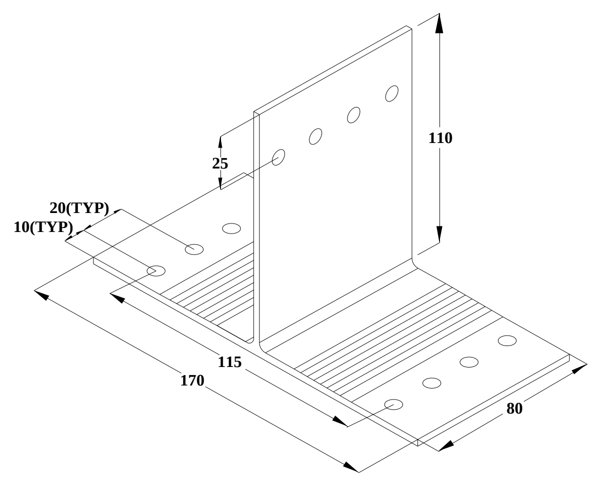

Figure 3.1: Geometry of T-joint

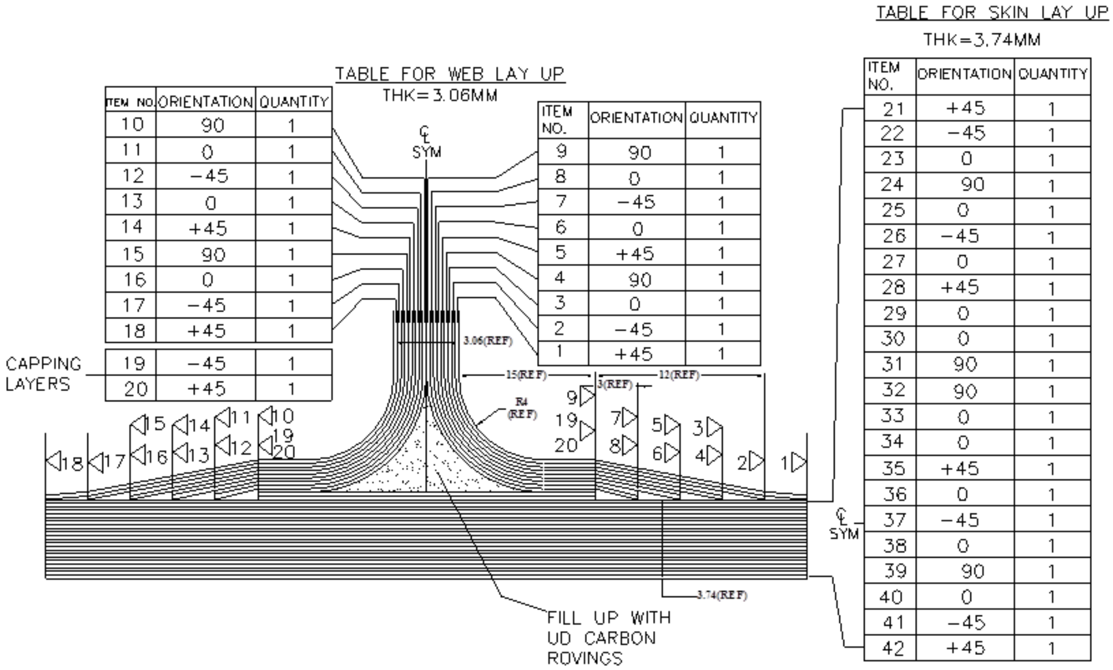

Figure 3.2: Lamination scheme of basic T-joint

T-joints were categorized into five series to evaluate the pull off strength. Series-I was configured without any insert. In order to maintain the thickness of web and skin flange interface, 2 layers of 0 degree plies were added in the stiffener layup in the mid plane of basic T-joint as shown in Fig. 3.3, which served as the reference configuration. Series-II to IV were configured with different types of ‘T’ inserts as shown in Figs. 3.4 to 3.6. The capping layers were not used in case of specimens with insert. Series-V was configured similar to Series-IV with ‘T’ insert discontinuity at noodle fillet (Fig. 3.7). This was done to assess the effect of ‘T’ insert at the fillet region. The details of configuration are given in table 2 below.

Table 2: Configuration and Description of T-joints

Configuration	Description
Series-I	Normal specimens
Series-II	Specimens with ‘T’ insert without noodle fillet woven with 6K carbon tows
Series-III	Specimens with ‘T’ insert with noodle fillet woven with 6K carbon tows
Series-IV	Specimens with ‘T’ insert with noodle fillet woven with 3K carbon tows
Series-V	Specimens with ‘T’ insert discontinued at noodle fillet woven with 3K carbon tows

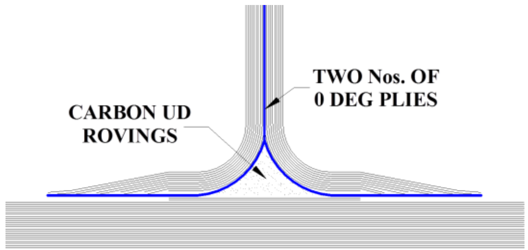

Figure 3.3: T-joint with two 0 °plies (Series-I)

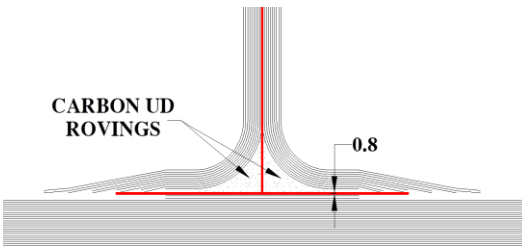

Figure 3.4: T insert without noodle fillet (Series-II)

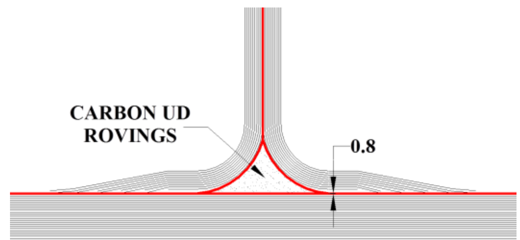

Figure 3.5: T insert with noodle fillet woven using 6K carbon tows (Series-III)

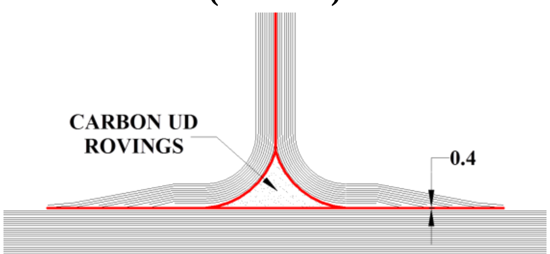

Figure 3.6: T insert with noodle fillet woven using 3K carbon tows (Series-IV)

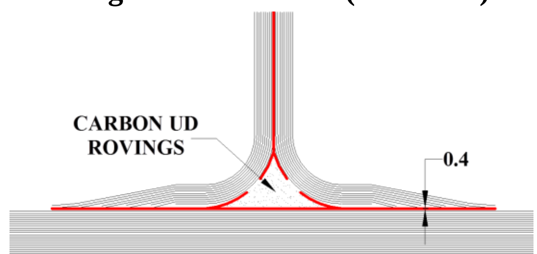

Figure 3.7: T insert with discontinued noodle fillet woven using 3K carbon tows (Series-V)

3.1. Fabrication Details

The tooling consisted of two ‘L’ shaped Aluminium angles, used to lay-up half the web and flange. One half of stiffener plies were laid up on each tool and subsequently these two halves were assembled. Noodle filler made of rovings of 0 ° UD fabric was placed in the fillet zone for Series-I specimens. In case of specimens with inserts, the insert along with 0 ° filler rovings was sandwiched between stiffener layers. The assembled part of stiffener was then placed over the skin laminate on a flat tool. T-joints incorporating these inserts were fabricated using VERITy process. Subsequently, T-joints were cured and post cured in an autoclave. Ultrasonic NDE inspection was carried out for assessing the quality. Subsequently, the specimens were cut, finished, holes were drilled and assembled on a specially designed T-pull test fixture.

3.2. Test Set-up and Procedure

Aligning the specimen in the test fixture and the entire set-up on the test machine is important as slight misalignment would cause the twisting/ bending of web leading to scatter in test results. Fig. 3.8 shows the specimens with fixture mounted in an UTM. The specimens were fixed to the fixture using M5 nut and bolt and tightened to a constant torque of 5 Nm using a torque wrench. Strain gauges were bonded at pre-defined locations as shown in Fig. 3.9. The tests were executed with a crosshead speed of 1mm/min. During the tests the applied load, deflection, strains were measured. The pull off strength of T-joint was determined by loading the specimen to failure.

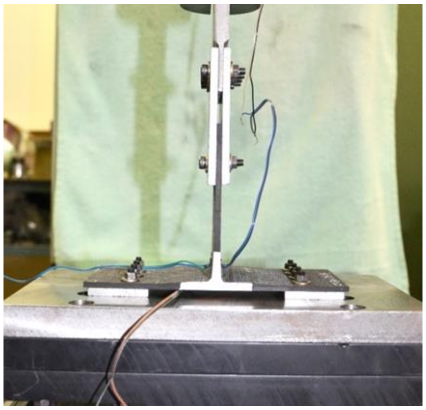

Figure 3.8: T-joint mounted in testing machine

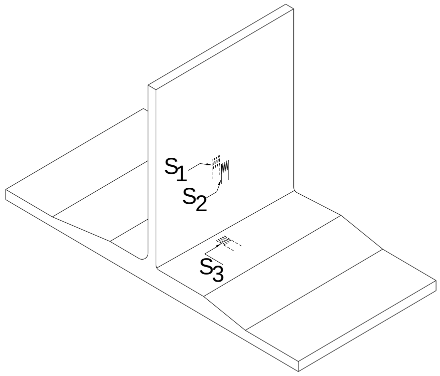

Figure 3.9: Locations of strain gauges mounted on the specimens

4. Results and Discussion

4.1. Deflection and Strain Analysis

The UTM crosshead movement was recorded by the machine during testing. Fig. 4.1 shows the load v/s average extension curve for all series. It can be seen from the graph that the initial failure was originated at nearly 3250N irrespective of series in the form of crack in the noodle fillet region, whereas the final failure was observed at different loads. After the initial failure, a slight loss in stiffness was observed across all the series. However, specimens continued to resist the load and the crack grew beyond the noodle area. The role of insert was clearly evident after the initial crack as specimens with T inserts failed at much higher loads than the ones without.

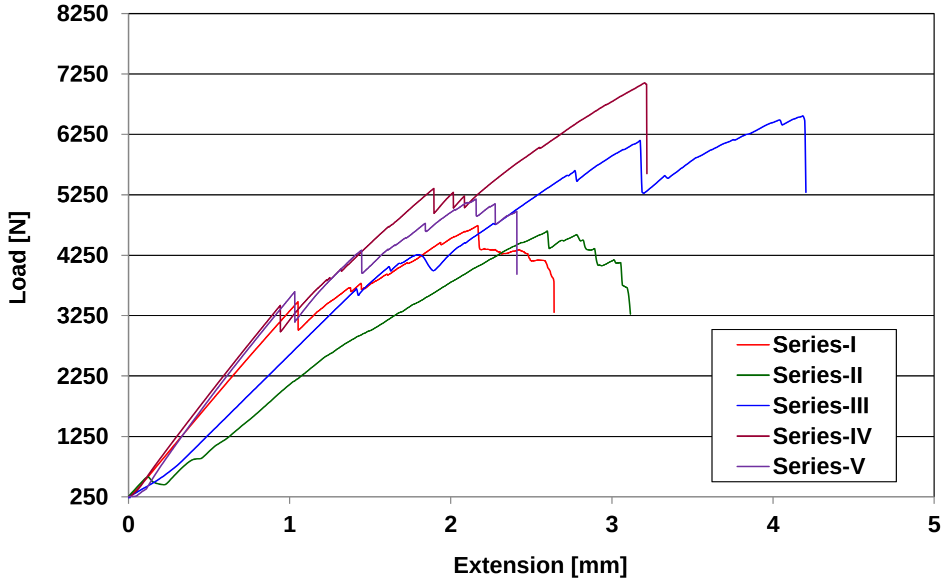

Figure 4.1: Load v/s extension plot

Strain gauge at S_3 location was used to assess the bending stiffness of skin and strain gauges at S_1 & S_2 locations were used primarily for checking the alignment of specimens and as a measure of the applied axial load. It was observed that strains at S_1 & S_2 locations were nearly the same indicating good alignment of specimen and fixture. The load v/s strain graphs at S_2 & S_3 locations for each series is presented in Fig. 4.2.

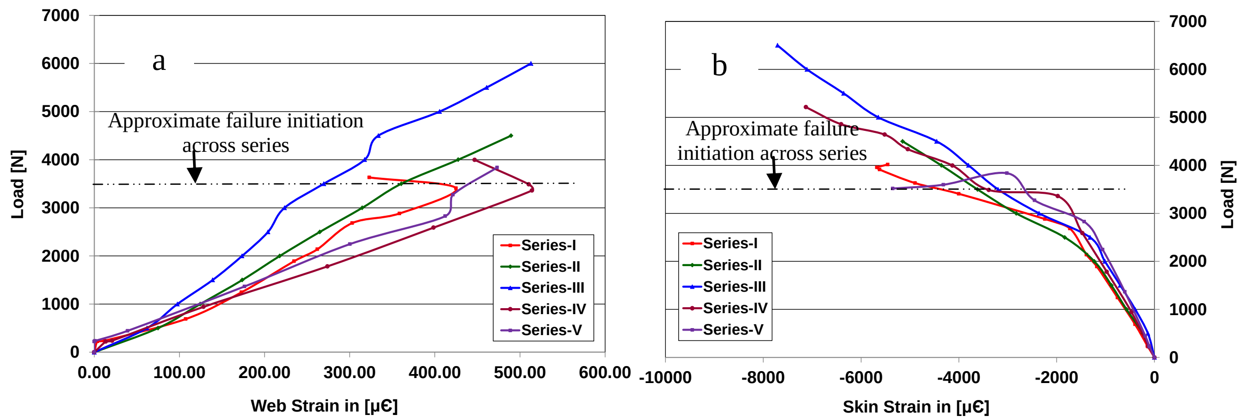

Figure 4.2: Load v/s strain plot a) web strain b) skin strain)

The approximate failure initiation load is marked on the graphs for better understanding. It can be seen that the response is nearly linear across the series till the initiation of failure. Thereafter, the strain gage response was anomalous.

4.2. Pull Off Strength

Fig. 4.3 shows the maximum failure load for all configurations. Since the local thickness at the fillet area is not the same across the series, normalised failure load was calculated. The weight of Series-I specimen has taken as reference and relative weights of specimen for remaining series were determined. The maximum failure load was divided by this ratio to get normalised pull off strength. Series-II with insert without noodle fillet did not show much improvement in pull off load. Moreover, the introduction of this insert was difficult compared to the insert with noodle fillet for Series III, IV & V. In case of Series-III with 6K insert with noodle fillet, the insert flange was kept till end of the specimens as well as the thickness of insert was 0.8mm. Hence, this configuration showed higher failure load. However, the impregnation of this insert was difficult due to its thickness. In order to reduce the thickness, the Series-IV insert was woven with 3K carbon fibre. The flange of the insert was also made short and trimmed at the end of flange layers. The specimens with 3K insert with noodle fillet (Series-IV) showed improvement in normalised pull off strength of nearly 30%. Specimens with discontinued noodle fillet (Series-V) did not show any improvement thus indicating that the continuity of noodle fillet enhances the pull off strength and proves the concept of 3D integral insert.

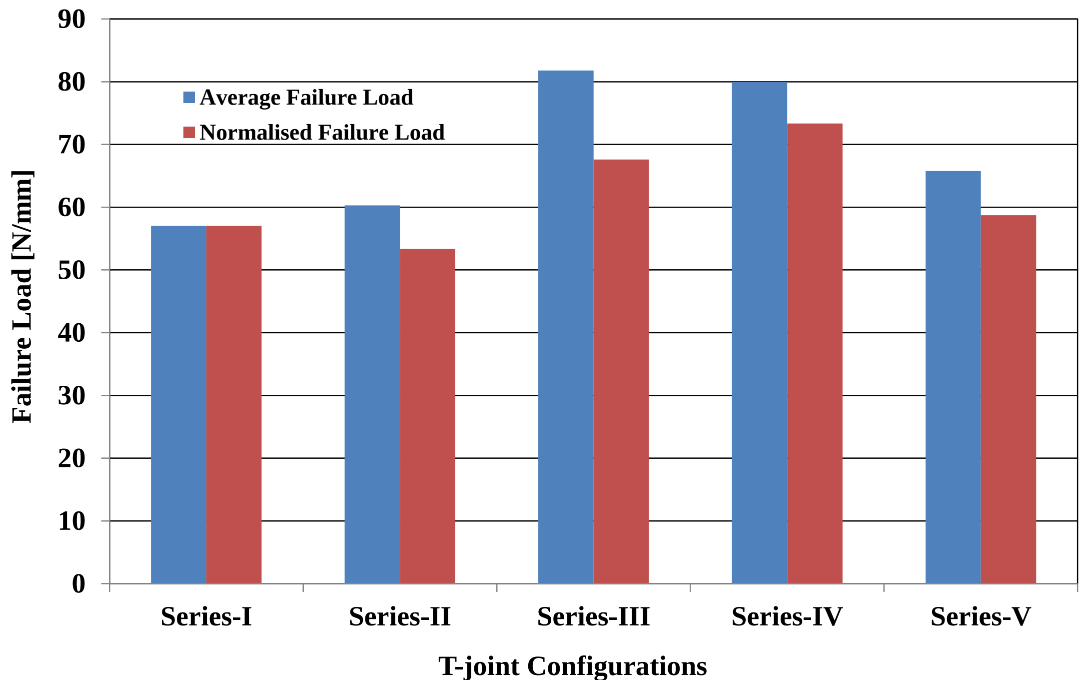

Figure 4.3: Maximum pull off load (Average and Normalised)

5. Failure Mode Analysis

Assessment of failure mode and crack propagation in different configurations will give an insight on the effect of inserts in the joint. The specimen edges in the noodle region were painted with white colour for better visibility of crack as shown in Fig. 5.1. It was observed that the failure in the form of a crack started in the noodle fillet zone in all the series. This was attributed to the stress concentration that occurs in the fillet zone coupled with roving filling which is predominantly 0^0 layers. Since there is no fibre directly transferring the load, the matrix cracks in the fillet area of noodle rovings filler. The propagation of the crack and final failure are different in each of the cases. Series-I, IV & V are taken for illustrating the growth of crack and shown in Figs. 5.2 to 5.4.

In the case of Series-I, the crack propagated vigorously in the web, but final failure occurred at the flange skin interface leaving roving filler with skin (Fig. 5.2). In specimens with noodle fillet for Series III & IV, the crack started in the fillet region and the final separation of flange and skin happened below the insert layer as shown in Fig. 5.3. A close observation of the propagation of the crack depicts the role of the insert layer, wherein it tends to bridge the three junctions and resists the crack propagation. The reinforcement continuity prevented further propagation of crack and pull-off load was resisted by matrix bond line below the insert layer and failure occurred in this zone.

The specimens without noodle fillet and discontinued noodle fillet inserts for Series II & V respectively showed similar behaviour in their failure mode (Fig. 5.4). The initial propagation progressed in the web and soon debond progressed at skin flange interface. The final failure occurred between skin and flange interface similar to Series-I. The only difference being, the roving filler remained with skin in Series-I in contrast to Series II & V.

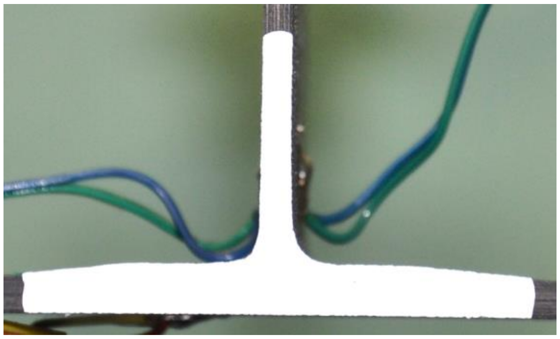

Figure 5.1: Specimen before failure

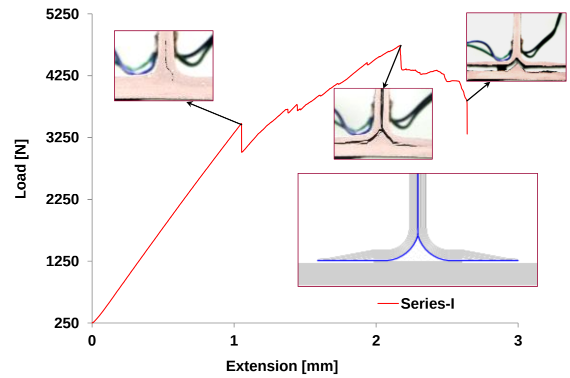

Figure 5.2: Failure mode of normal specimen (Series-I)

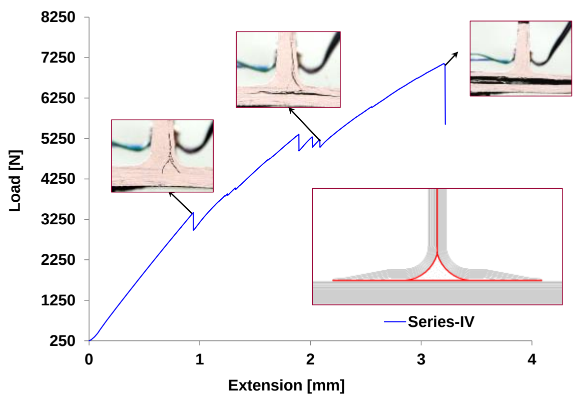

Figure 5.3: Failure mode of specimens with noodle fillet (Series-III & IV)

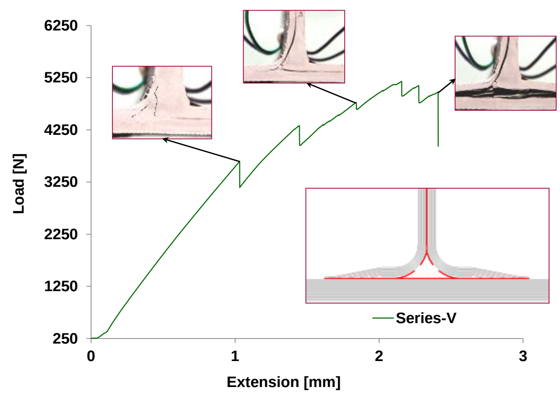

Figure 5.4: Failure mode of specimens without noodle & discontinued noodle fillet (Series II & V)

6. Conclusions

A novel design of T-joint was conceived for pull off loads using a 3D insert woven on a conventional jacquard loom. T-joints strength was evaluated for different configurations using the integral insert. Tests showed that the crack initiated in the fillet region and propagated in the web and skin layers for all configurations. The failure mode varied slightly depending on the nature of insert used. The initial failure was initiated at nearly 3250N irrespective of series, whereas the final failure was observed at different loads. The role of integrally woven 3D insert was clearly evident after the initial failure in the form of a crack at the noodle region. The specimens with insert having noodle fillet showed improvement in maximum pull off strength of about 30% which was normalised based on weight. This technique looks promising for use in large cocured structures as it is practically & economically feasible for implementation.

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