APPLICATION OF A BIO-INSPIRED DESIGN STRATEGY TO DELAY DAMAGE INITIATION IN A FRP T-JOINT UNDER BENDING

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1 Introduction

A key design principle found in nature is that biological load carriers (such as wood or bone) self-optimise to the axiom of uniform stress [1-3]. Achieving uniform stress across a joint is advantageous because material is not wasted, and there is no specific weak site that is more prone to cracking.

Trees were selected as the biological load carrier for this investigation because they are formed from wood, an orthotropic composite with a fibre structure similar to FRP material [4]. Trees respond to complex loading conditions by tailoring both the material properties of wood and the macro-structural features across the tree-branch joint [5-7]. This hierarchical strategy is commonly found in nature, whereby elements from the nano-, micro-, meso- and macro-length scales interact in synergy in order to achieve uniform stress.

At the micro-length scale, trees alter the micro-fibril angle (equivalent to the fibre angle in FRP composites), together with the wall thickness and packing density of the wood cells to optimise mechanical properties such as modulus, tensile strength, shear strength and damage tolerance to the prevailing loading conditions, caused by wind loads and the self-weight of the branch [5, 8]. As a result of this strategy trees attain a near iso-strain response across the joint [9].

Previous research indicates that fibre reinforced polymer T-joints undergo progressive failure under bending loading through a combination of delamination crack growth within the tensile side of the radius bend and crack growth across the fillet region at the stiffener base (where the skin and stiffener are joined) [7, 10-11]. These damage mechanisms are initiated by the mixed mode I/II loading conditions that exist along the geometric stress raiser of the radius bend. It is postulated that a reduction in the interlaminar tensile stress (σ_{33}) within the radius bend and fillet zones will delay the onset of damage initiation and thus increase the bending load capability of aerospace CFRP T-joints.

Therefore, the objective of this study is to evaluate the hypothesis that the failure load of composite T-joints can be improved using the bio-inspired design strategy of optimised fibre orientation, which is based on the biomimetic principle of uniform stress. Numerical analyses and experimental testing of a representative carbon-epoxy bonded T-joint with conventional and bio-inspired stiffener ply orientations are compared to determine whether the failure initiation load can be improved by mimicking the principle of uniform stress that exists in tree branch-to-trunk joints.

2 Research Methodology

2.1 Finite Element Modeling of T-Joints

Finite element analysis was performed on carbon/epoxy T-shaped joints with conventional or bio-inspired stiffener ply lay-ups to determine the stress distributions and failure initiation point under the loading condition of an elastic bending force applied to the stiffener.

The design geometry and boundary conditions of the T-joint are shown in Fig. 1. The geometry and boundary conditions were identical for both the conventional and bio-inspired designs. The boundary conditions consisted of the skin clamped on either side of a working section of 150 mm

containing the stiffener. A 20 N bending load was applied perpendicular to the stiffener to perturb the model within the linear-elastic range of the material. It was assumed that damage initiation occurs within the linear range of the force-displacement curve, meaning the stress distribution obtained from the perturbed FE model could be linearly scaled up to the stress value causing damage initiation.

The baseline conventional T-joint consisted of a 16 ply quasi-isotropic $[45/0/-45/90]_{2s}$ carbon-epoxy laminate in the skin and stiffener sections. The key difference between the conventional and bio-inspired design was that the stiffener plies in the bio-inspired design were not quasi-isotropic as they are in the conventional design, but were orientated to induce minimum interlaminar stress in the bend radius.

The T-joints were analysed using linear-elastic finite element modeling with PATRAN 2010 as the pre-processor. The model was solved and post-processed using ABAQUS 6.9-2. The joint was constructed as a 3D model from HEX-20 solid elements. The fillet region under the stiffener was modeled as unidirectional carbon/epoxy prepreg oriented in the z-direction through the width of the joint specimen.

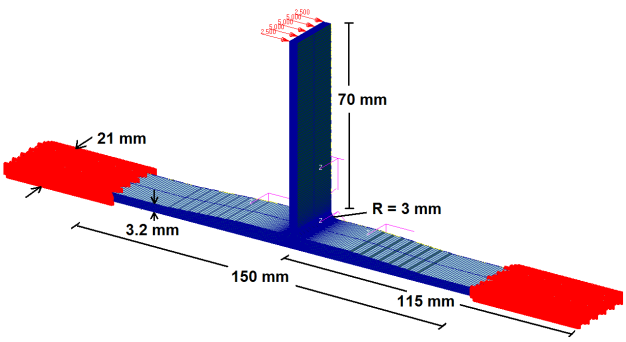

Fig. 1. Finite element model of CRFP T-Joint showing boundary conditions

A numerical optimisation program was developed using the ESTECO software modeFRONTIER that was capable of varying the ply orientation of the stiffener plies and calculating the resulting effect on the interlaminar (σ_{33}), in-plane (σ_{11}) and shear (σ_{12}) stresses within the T-joint. The optimisation program was inspired from the tailoring of the micro-fibril angle observed within trees to achieve a uniform stress field within joint connections where a geometric stress concentration is present. Due to the requirement of a symmetrical and balanced lay-up to prevent excessive warping of the stiffener, the final optimisation program contained four variables corresponding to four ply angles in the stiffener lay-up according to [1/2/-2/-1/3/4/-4/-3]s.

In order to compare composite T-joints with similar bulk structural properties, the in-plane (A_{11}) and bending (D_{11}) moduli of the bio-inspired stiffener laminates were both constrained to values within 10% of the conventional design. The bio-inspired T-joint design thus had the following constraints:

i. Four ply angle variables which had to result in the stiffener laminate being symmetric and balanced according to [1/2/-2/-1/3/4/-4/-3]s
ii. Stiffener in-plane modulus (A_{11}) constrained within +/-10% of the conventional design
iii. Stiffener bending modulus (D_{11}) constrained within +/-10% of the conventional design.

The optimisation program was run with the single objective of minimising the peak interlaminar stress (σ_{33}) in the radius bend. The program was capable of tracking any change in the location of the peak interlaminar stress as the optimisation process progressed. The optimiser was Multi-Objective Simulated Annealing (MOSA) and each program iteration loop contained 150 iterations. Once the optimised ply stacking sequence had been determined using the program, this was incorporated into the FE model of the T-joint. The skin laminate retained the quasi-isotropic ply pattern; only the stiffener plies were optimised for minimum interlaminar stress. The bio-inspired T-joint design was elastically loaded using the FE model under the same conditions as the conventional joint design to determine changes to the internal stress and the location for failure initiation under a stiffener bending load.

2.2 Experimental Testing of T-Joints

Bending tests were performed on the conventional and bio-inspired T-joint designs using a 50 kN Instron testing machine. The joint specimens were identical in shape and the test boundary conditions were the same as those applied in the FE model. The

conventional and bio-inspired joints were fabricated using unidirectional carbon/epoxy prepreg tape (Lavender VTM264) and were cured in an autoclave at 120ºC for 1 hour at 90 psi. For the bend tests, the skin was clamped on either side of a 150 mm working section containing the stiffener. The stiffener and skin both had an average thickness of about 3.2 mm equivalent to a cured ply thickness of 0.2 mm. The bending load was applied via a rigid clamp attached to a hinged joint connected to the vertical cross-head of the loading machine (refer Fig. 2). The bending load was applied at a rate of 3 mm/min. Six samples were tested for each of the conventional and bio-inspired T-joint designs.

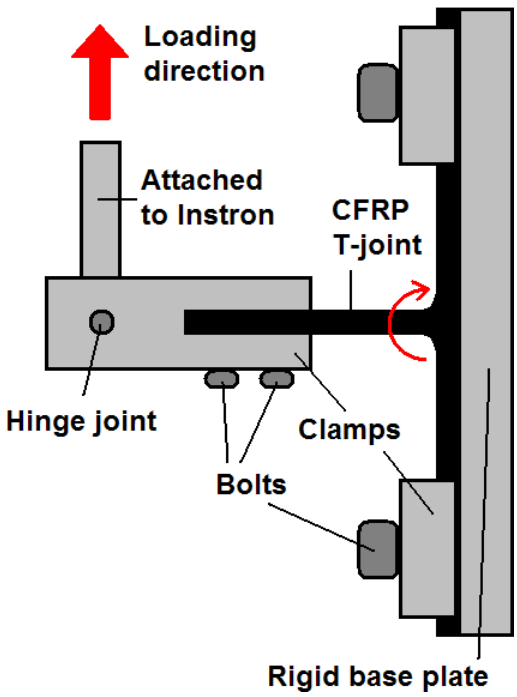

Fig. 2. Schematic of bending testing experimental set-up

3 Results and Discussion

3.1 Finite Element Analysis of T-Joints

The interlaminar (σ_{33}) stress distribution in the radius bends and fillet region of the conventional T-joint when subjected to an elastic stiffener bending load is shown in Fig. 3. The region of maximum stress occurs on the tensile side of the radius bend and is indicated by the line across the radius. The high stress concentration is caused by the geometry of the radius bend in response to the applied bending moment and showed agreement with a previous study concerning bending of a single L-joint [12]. This stress analysis indicates that initial damage, most likely in the form of delamination cracks, will occur in the centre of the tensile side radius bend where the interlaminar stress is highest.

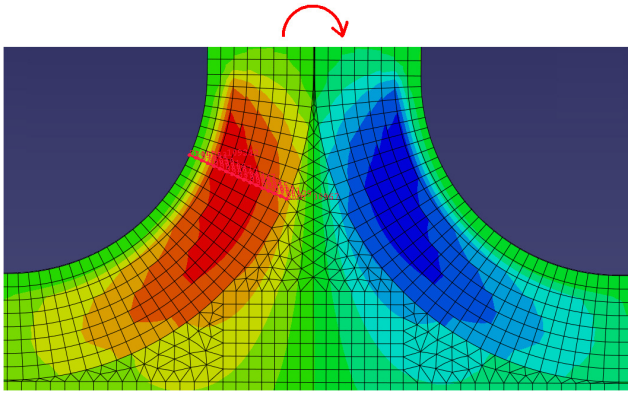

Fig. 3.Conventional T-joint: interlaminar stress in radius and fillet region – Path of maximum stress is indicated. The red and blue shading indicates tensile and compressive stress, respectively, and the magnitude of the stress is represented by the deepness of the shading.

The optimisation program converged on the values of the four ply orientation variables for the stiffener design that produced minimum interlaminar stress in the bend radius of the bio-inspired T-joint. The bulk elastic properties of the laminates used in the bend radius of the conventional and bio-inspired joints were similar. The in-plane modulus of the bio-inspired design was 5.3% lower and the bending modulus was 8.3% higher compared to the baseline quasi-isotropic design.

The interlaminar tensile stress (σ_{33}) distribution in the radius bends and fillet region of the bio-inspired T-joint design is shown in Fig. 4. This plot has the same contour limits as Fig. 3. As with the conventional design, the path of maximum stress occurs on the tensile side of the radius bend. The FE analysis reveals that the stress concentration is reduced in magnitude and there is a more even stress distribution within the radius bend region of the bio-inspired T-joint. The FE model indicates that initial damage will occur in the centre of the tensile radius bend and possibly also towards the free edge of the tensile radius bend.

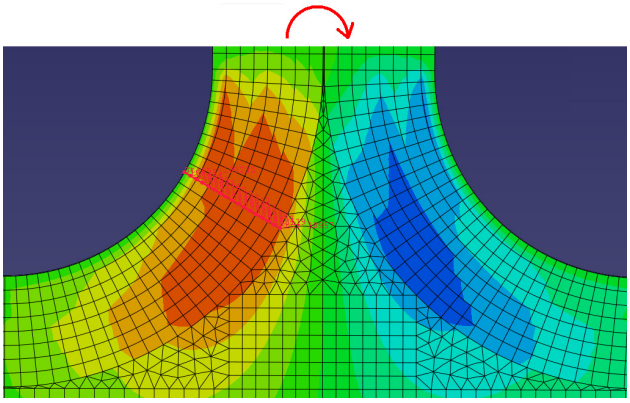

Fig. 4. Bio-inspired T-joint: interlaminar stress in radius and fillet region – Path of maximum stress is indicated

The finite element predicted differences in the peak interlaminar, shear and in-plane stresses in the bio-inspired T-joint is given in below.

Δ Change compared to conventional T-joint (%)	Bio-inspired T-joint (%)
In-plane modulus	-5.3
Bending modulus	+8.3
Peak interlaminar tensile stress (σ_{33})	-15 (Ply 4)
Peak interlaminar shear stress (τ_{13})	-19 (Ply 1)
Peak in-plane tensile stress (σ_{11})	+13 (Ply 1)

Table 1. FE predicted differences in bulk properties and stress distribution within the radius bend of the bio-inspired T-joint compared to the conventional design. Radial location of peak stresses indicated in brackets

The FE analysis predicts a 15% decrease in the peak interlaminar tensile stress (σ_{33}) for the bio-inspired T-joint, compared to the conventional design, as shown in Fig. 5. Although the objective function of the optimisation program did not specifically consider shear stress, the bio-inspired design also showed a 19% reduction to the peak interlaminar shear stress (σ_{13}) across the radius bend compared to the conventional design (Fig. 6).

The finite element modeling also predicts a 13% increase in the in-plane stress (σ_{11}) for the bio-inspired joint design. Since formation of delamination damage is only weakly dependent on the in-plane tensile stress it is assumed this increase will not influence the formation of cracks generated under mixed mode I/II interlaminar stresses and therefore not influence the onset of initial damage.

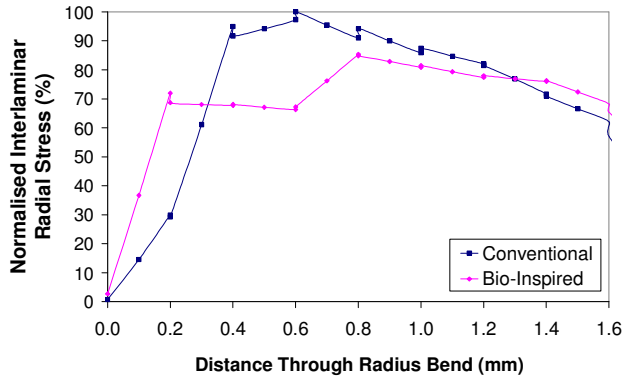

Fig. 5. Stress distribution through region of peak interlaminar tensile stress in the radius bend

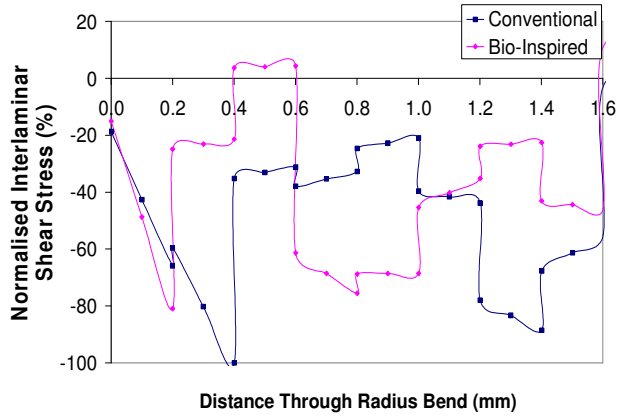

Fig. 6. Stress distribution through region of peak interlaminar shear stress in the radius bend

3.2 Experimental Analysis of T-Joints

Experimental bending load-displacement curves for the conventional and bio-inspired T-joints are shown in Fig. 7. The failure mode for both joints was similar and occurred in a two-step process. The first load drop corresponded to the initiation of delamination cracks in the tensile side radius bend, as shown in Fig. 8. The second load drop corresponded to a crack forming between the radius

bend and the fillet region adjacent to the radius bend (also shown in Fig. 8).

The only difference in failure mode was the bio-inspired T-joint had an extra delamination crack that developed towards the free edge of the radius bend (refer Fig. 8. b). This occurred in six out of the six optimised samples as predicted by changes in the interlaminar stress distribution shown in Fig. 4.

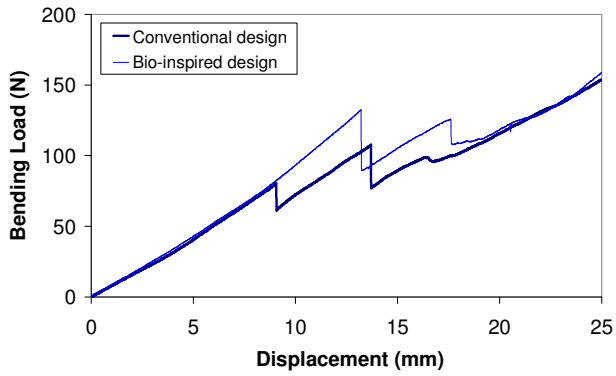

Fig. 7. Typical load-displacement curve for quasi-isotropic and optimised T-joint under bending

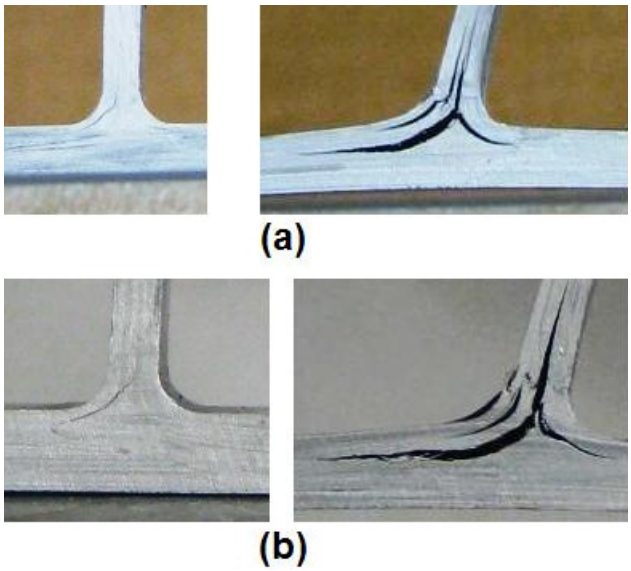

Fig. 8. Damage initiation (left-hand side) and end of bending test (right-hand side). (a) Conventional and (b) bio-inspired T-joints

The results of the experimental validation of the finite element predictions for the two T-joint designs are given in Table 2. The two joints had similar stiffness properties, which validates the constraints placed on the in-plane and bending moduli for the ply optimisation. The bio-inspired joint was slightly stiffer (7%), which may be due to the bending modulus being 8% higher. The experimental results validated the hypothesis that damage initiation can be delayed by optimising the ply orientation in the radius bend. Compared to the conventional T-joint, the displacement and load at damage initiation was respectively 28% and 42% higher for the bio-inspired joint.

	Conventional T-Joint	**Bio-inspired T-Joint**
Stiffness (N/mm)	8.38 (0.85)	8.94 (0.72)
Displacement at damage initiation (mm)	8.88 (0.93)	11.4 (1.15)
Damage initiation load (N)	84.8 (13.1)	120 (14.4)
Displacement at Peak Load (mm)	15.3 (3.3)	17.7 (1.4)
Peak Load (N)	126 (29.9)	125 (19.6)
Elastic strain energy (J)	361 (84)	634 (122)
Strain energy to 25 mm displacement (J)	2227 (167)	2220 (168)

Table 2. Comparison of structural properties between the conventional and bio-inspired T-joint designs determined by the experimental bend test. The numbers in brackets are the standard deviation based on six measurements

The experimental improvement in the damage initiation load was significantly higher than the predicted 15% reduction based on the change in the peak interlaminar stress given by the FE analysis (see Fig. 4 and Fig. 5). The results suggest that in mixed mode I/II failure, the interlaminar shear stress

has a significant influence on damage initiation, and the 19% decrease in peak shear stress contributed in synergy with the 15% decrease in the peak interlaminar stress to produce this result. The two T-joint designs showed no significant difference in average peak load.

The bio-inspired joint absorbed about 75% more elastic strain energy compared to the conventional joint, due to the delay in damage initiation resulting in an increase in both the displacement and load at which first damage occurred. Bending testing was stopped at 25 mm displacement, at which point there was no difference in the total absorbed strain energy between the conventional and bio-inspired joints. This suggests the design modification of optimising the ply orientation does not contribute to increased toughness, and is successful only in delaying the initiation of delamination damage in the radius bend.

3 Conclusion

This study has proven that the failure initiation load and absorbed elastic strain energy of composite T-joints under bending loads can be improved by mimicking the biological principle of uniform stress within connections such as tree branch-trunk joints. Conventional bonded composite T-joints are prone to delamination cracking within the bend radius when bending loads are applied to the stiffener. This study has shown that the optimisation of the ply stacking sequence of the laminate material within the bend radius reduces the interlaminar tension and in-plane shear stresses which results in a large improvement to the damage initiation load.

Finite element analysis and experimental testing of a bio-inspired T-joint has proven the hypothesis that a more uniform stress distribution translates into improved structural performance, with a reduction in the maximum interlaminar and in-plane shear stresses of 15% and 19% and an improvement in the failure initiation load and elastic absorbed strain energy of over 40% and 75%, respectively. Based on this research, bio-inspired design is an effective and innovative method of improving the structural properties of bonded composite T-joints without weight or cost penalties.

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