A Finite Element and Experimental Analysis of Composite T-Joints Used in Wind Turbine Blades

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Abstract In this study, a finite element failure model was created using ABAQUS to determine the location where delamination is initiated and its subsequent propagation. The effect of fibre-reinforced structures on delamination behaviour was studied. The composite T-joints were made of glass fabric infused with epoxy resin using a vacuum assisted resin transfer moulding technique. The veil layer and 3D weave techniques were employed to improve the properties in the through-thickness direction that can delay or prevent delamination when in service. All the pull-out tensile tests were conducted in an Instron testing machine using a specially designed test fixture. The 3D weave T-joints were found to have improved performance under both static and fatigue loading. Increasing the static properties increases fatigue life performance. The location for the through-thickness reinforcement plays an important role in extending fatigue life of the T-joints.

Keywords Composite · T-joint · Finite element analysis · Fatigue · Delamination · 3D fabrics

1 Introduction

Modern wind-turbine blades are made of composite materials due to their low density and excellent mechanical properties combination of strength, stiffness, fatigue performance and better corrosion resistance than metals [1]. Wind turbine blade failures, when in service are due to various complicated reasons but blade failures account for most accidents and damage to wind turbines [2]. The composite materials used in blade construction are typically woven fabrics containing a variety of configurations. The formation of internal detailed shapes within the blade, allowing features such as spars, shear webs and other connections, inevitably requires these 2D material configurations to be formed into three-dimensional (3D) shapes.

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This introduces sites within the structure where load transfer occurs across regions with little or no fibre reinforcement. These weak areas become natural positions for the initiation of delamination. To overcome this problem, through-thickness reinforcements are widely considered to be an efficient way to increase the cracking resistance of laminated composites. Various techniques, such as stitching/tufting [3–7], interlaminar veils [8, 9], braiding, knitting [10], 3D weaving [3, 11, 12] and z-pining [13–15] have been developed to improve the properties in the through-thickness direction.

Many researchers [6, 9, 13, 14, 16–19] have developed finite element (FE) models to simulate the delamination of a composite T-joint. Failure of composite T-joints has also been studied experimentally from different point of view by many investigators [3, 4, 20–29]. The initiation of delamination in the composite T-joint is almost always initiated on the joint's corner due to the maximum stresses developed in this region. After crack initiation, the cracks may propagate along the flange-skin bond line only or along both the central line of the web and the flange-skin bond line, depending upon the T-joint reinforced configurations. The properties of these composite T-joints and possible toughening methods to improve thorough-thickness properties very much depend on the manufacturing method of the part [11].

The mechanical properties of composite materials have been widely studied, there are no in depth studies on failure of composite T-joints containing various reinforcement architectures. A number of scientific and technical issues still need to be resolved, for example, predictive FE models for determining the strength of composite T-joints have not been satisfactorily developed [11]. Therefore, it is important to understand the way a composite T-joint fails and develop methods of improving fatigue life performance to enhance the durability of wind turbines.

In this study, a finite element (FE) model was developed which is used to determine the initiation and propagation of delamination crack in the composite T-joints with various reinforcement architectures. The T-joints were made of glass fabric infused with epoxy resin using a vacuum assisted resin transfer moulding (RTM) technique. Mechanical tests on different T-joint configurations were conducted and used to validate the FE model. FE analysis and experimental measurements are presented and discussed in the following sections.

2 Finite Element Modelling of Composite T-joints

2.1 Description of T-joint FE Model

Figure 1 shows the geometry and layup detail of the composite T-joint used as the baseline configuration in the study. The flange and skin parts consist of five layers of equal thickness arranged in a stacking sequence of $[45^\circ/-45^\circ]_5$ while the web consists of 10-layer $[45^\circ/-45^\circ]_{10}$ plate. The outer stiffener consists of 5-layer unidirectional (UD) $[0^\circ]_5$, which is used to prevent large deflection that may not be representative of the larger structure.

Two types of local coordinate systems are used to describe the orientations of each ply (Fig. 2). On the corner the cylindrical coordinate system is used. In this coordinate system, the 1, 2, and 3 directions refer to the radial (R), circumferential (T), and axial directions (Z), respectively. In the web, flange, skin and stiffener the rectangle coordinate system is used and the 1, 2, and 3 directions refer to the X, Y and Z, respectively. For both coordinate systems, the fibre direction is oriented along axis 2 while directions 1 and 3 correspond to thickness and

Fig. 1 Geometry, layup and loading condition of a composite T-joint (all dimension in mm). The outer stiffener is used to constrain larger displacement

width directions, respectively. Under this coordinate system the engineering constants for the composite material are: the elastic moduli $E_1 = E_3 = 9$ GPa, $E_2 = 38$ GPa; Poisson's ratios $\nu_{13} = \nu_{23} = 0.3$, $\nu_{12} = 0.071$; the shear moduli $G_{12} = G_{23} = 3.6$ GPa, $G_{13} = 3.46$ GPa, respectively. The elastic modulus and Poisson's ratio for the epoxy resin are equal to 4 GPa and 0.34, respectively.

The T-joint is subjected to tensile pull-out loading along the web. The skin part is considered to be supported near the two ends of the T-joint, as indicated in Fig. 2. The FE model was created using ABAQUS. The FE simulations were run under displacement-controlled mode by applying an increasing tensile displacement along the web. Three elements were used in the thickness direction and an eight-node linear brick element (C3D8R) was utilised. The detailed mesh of the model with the kinematic and loading boundary conditions is shown in Fig. 2.

2.2 Modelling Delamination

Delamination in the composite T-joints is modelled using cohesive zone elements that are applied to the regions (e.g. central line of the web, interface between resin and corner, skin-flange bonding line) where the delamination is expected to occur. Linear elastic traction-separation behaviour is used to model the interface where the delamination is expected to occur. The traction-separation model in ABAQUS assumes initially linear elastic behaviour followed by damage initiation and evolution.

Fig. 2 FE mesh, boundary conditions and local coordinate system of the T-joint numerical model

The initiation of delamination damage can be estimated using the quadratic nominal stress criterion defined by the following expression [30].

$$\left\{ \frac{\langle t_n \rangle}{t_n^0} \right\}^2 + \left\{ \frac{t_s}{t_s^0} \right\}^2 + \left\{ \frac{t_t}{t_t^0} \right\}^2 = 1 \quad (1)$$

where t_n^0 is the interlaminar normal tensile strength, t_s^0 and t_t^0 are shear strengths in the two transverse directions.

Delamination propagation is described using a linear softening fracture-based law, where a mixed mode fracture energy criterion is used. Failure under mixed-mode conditions is governed by a power law interaction of the energies required to cause failure in the individual modes. It is given by [30].

$$\left\{ \frac{G_n}{G_n^c} \right\}^a + \left\{ \frac{G_s}{G_s^c} \right\}^a + \left\{ \frac{G_t}{G_t^c} \right\}^a = 1 \quad (2)$$

where G_n^c is the normal strain energy release rate, G_s^c and G_t^c are shear strain energy release rates in the two transverse directions; α is assumed to be equal to 1 in this study. The effect of α value on the load-deflection curve was studied and the variation of α values shows less effect [6]. Selecting ‘appropriate’ stress-based or fracture-based remains a debating issue.

3 Results and Discussion

3.1 Interlaminar Stresses

The stress fields of the T-joint subjected to a tensile pull-out loading provide useful information to understand the way delamination occurs. In this section a brief description of stress analysis of T-joints is given. Further details can be found in references [6, 9]. The regions of interest are: line AB (the central line of the web); arc BC (the interface between the corner and epoxy resin rich pocket); line CD (the bonded connection between skin and flange), as shown in Fig. 3a. The stresses developed in those regions were computed and then are plotted against the paths to obtain their distributions along those identified critical paths, shown in Fig. 3b.

It can be seen from the figure, in the web region (path AB), the stresses are hardly seen until near the corner where a sudden increase in the stresses is seen. There is a big stress jump in the region of the corner (path BC) and after the corner only the shear stresses are seen except near the end of the flange where there is a discontinuity. The higher stresses developed at the corner will initiate delamination when the damage criterion of Eq. (1) is met.

The shear stresses (σ_{12}) and (σ_{13}) are almost the same. The normal tensile stress (σ_{11}) is much larger than shear stresses and consequently the stress (σ_{11}) will dominate the initiation of delamination. The numerical analysis has confirmed that the maximum stresses are developed at the interface between the corner and resin. The magnitude of these stresses is influenced by the geometrical parameters of T-joints as described in Fig. 4a.

The distribution and magnitude of the stress (σ_{11}) is significantly influenced by the curvature of the corner and the calculated results are shown in Fig. 4b, c. As can be seen from the figure, the sharper corner (smaller R) T-joint shows a larger normal stress value compared with the blunt corner (larger R) T-joints, e.g., the maximum σ_{11} value is increased from 25 MPa to 35 MPa when the radius R is reduced from 2 mm to 0.5 mm as shown in Fig. 4b. However, there is no significant effect on the shear stresses (σ_{12}) as shown in Fig. 4c.

3.2 Effect of Through-Thickness Reinforcement in the Web

Experimental observations show that the crack always is initiated at the corner and then propagates along: (i) the central line of the web and flange-skin bonding line for

Fig. 3 Diagram showing: **a** paths where the stresses are measured; **b** the distribution and magnitude of the stresses (σ_{11} , σ_{12} and σ_{13}) along the paths

Fig. 4 Effect of radius (R) on stress distributions: **a** geometry of T-joints with different radius; **b** the distribution of normal tensile stress σ_{11} and **c** the distribution of shear stress σ_{12}

baseline and interlaminar veil specimens as shown in Fig. 5a; (ii) flange-skin bonding line for 3D woven specimen as shown in Fig. 5b. When the web contains the through

Fig. 5 Crack path depending upon the reinforcement configurations: **a** crack propagation along the central line of the web and flange-skin bonding line for Baseline and Interlaminar veil specimens; **b** crack propagation along flange-skin bonding line for 3D-woven specimens only

thickness reinforcement the tensile pull-out strength is significantly increased in both static and fatigue loading. With this reinforced structure, crack propagation was only along the bonded connection between skin and flange and the crack is inhibited to propagate in the web due to the nature of through-thick reinforcements.

To model crack growth in the T-joint with the through thickness reinforcement (e.g. 3D-woven T-joint), a tie constraint was imposed between pairs of surfaces (the central line of the web), instead of cohesive zone element, to simply represent its structural features. In this way, there is no crack propagation along the central line of the web and the crack propagation is along the flange-skin bonding line only. This approach reflects the experimental observations from the 3D woven T-joints.

The FE simulation shows that the maximum load to failure is increased dramatically when the web is reinforced in the through-thickness direction. The calculated results are presented in terms of the maximum bending stress developed due to the pull-out force on the base plate section to remove the effect of the base thickness variation. This applied stress was calculated using Eq. (3) in Section 4.2 and the result is shown in Fig. 6a. As can be seen from the figure, the pull-out strength is increased by 89% when the through-thickness reinforcement is applied into the web. Figure 6b presents the stress-deflection curves from the experimental observations, indicating that the FE prediction is consistent with experimental measurements, although it remains difficult to accurately capture all the non-linearities and fluctuations seen in the measured load-deflection response.

It can be concluded that the tensile pull-out strength will be significantly improved if the web contains the through thickness reinforcements.

Fig. 6 Stress-deflection curve showing the effect of through-thickness reinforcements in the web: **a** FE simulations; **b** experimental observations. The applied stress is calculated using Eq. (3)

4 Experimental Measurements

4.1 Test Materials and Conditions

Test specimens were made of glass fabric infused with epoxy resin. The geometry and layout detail of the specimen (see Fig. 1) was used as the baseline configuration in the study. The flange and skin parts consist of five layers of equal thickness arranged in a stacking sequence of $[45^\circ/-45^\circ]_5$ while the web consists of 10-layer $[45^\circ/-45^\circ]_{10}$ plate. The outer stiffener consists of 5-layer unidirectional (UD) $[0^\circ]_5$. The sample specifications are listed in Table 1.

The resin is an epoxy based on Araldite LY 564, and the associated hardener used is a formulated amine based on XB 3486. Both resin and hardener were supplied by Huntsman.

Table 1 Test sample specifications

Type	Architectures	Descriptions
Baseline	Web: $[\pm 45]_{10}$ Flange-Skin-Stiffener: $[\pm 45]_5[\pm 45]_5[0]_5$	T-joint made from glass fibre and epoxy matrix
Interlaminar veil (Polyester veil)	Web: $[\pm 45]_{10}$ Flange-Skin-Stiffener: $[\pm 45]_5[\text{Veil}][\pm 45]_5[0]_5$	Type Baseline T-joint + polyester veil added between the flange and the skin
3D-Woven (Angle interlock)	Web: 3D-Woven Flange-Stiffener: 3D-Woven $[0]_5$	T-joint made from 3D Woven fabric (3D Angle Interlock)

Two different types of fibre glass were used in this experiment. Unidirectional E glass fibre (FGE664) was used for the outer stiffener (support plate) and $\pm 45^\circ$ glass fibre (FGE104) was used in the fabrication of the web, flange and skin of the T-joint. Both of these fabrics were manufactured by Formax. The areal density for $[\pm 45^\circ]$ and UD fabrics is 609 and 594 g/m², respectively.

A polyester veil (non-woven fabric) was added between the flange and the skin to make interlaminar veil specimens with the aim to increase interlaminar fracture toughness. The thickness of the polyester veil is 0.055 mm and the areal density is 15 g/m².

A 3D fabric (angle interlock) was selected to make the 3D-woven type T-joint. It was weaved as a flat panel and from halfway in width the middle layer was removed during the weave process and a gap in thickness produced. The woven panel was then opened up from this gap and the two flange sections of the joint were formed on each sides of the web. The fibre type used in the 3D weaves is E-glass. The aim is to investigate the effect of through-thickness reinforcements in the web.

An Instron testing machine was employed to perform the mechanical tests at a loading rate of 2 mm/min. The static behaviour of the T-joints was tested under tensile pull-out loading to obtain the ultimate failure load of the T-joints. Fatigue test was performed in a load control mode with a stress ratio of $R = \sigma_{\min}/\sigma_{\max} = 0.1$. The cyclic loading pattern was a sinusoidal wave at a frequency of 6 Hz. Fatigue load levels were chosen with regard to maximum pull-out strength of samples obtained in the static tensile test. Constant fatigue load versus life data for each T-joint type were produced at various constant maximum applied loads. Failure criteria for fatigue tests were either crack length of 25 mm on each side of the web or one million stress cycles.

4.2 Static Behaviour

For fatigue testing it is necessary to determine the ultimate tensile pull-out strength under static loading. The test results were normalised on the base plate (flange-skin-stiffener) to remove the effect of thickness variation of the base plate. Taking into account the effect of bending, the maximum nominal stress in y- direction occurring in the base plate is calculated using the beam bending theory [31] and the maximum nominal stress(σ_2) is given by

$$\sigma_2 = \frac{3L}{2b} \left(\frac{P}{h^2} \right) \quad (3)$$

Here P is the applied load, L is the span of T-joint, h is the total thickness of the base section and b is the width of T-joint. When the span ($L = 100$ mm in this case) and the width ($b = 50$ mm) is fixed the magnitude of the stress occurred on the surface is inversely proportional to

the square of the thickness (h). In other words, the stress value is sensitive to the change of the base plate thickness.

The nominal stress (σ_2) is plotted against the deflection (δ), shown in Fig. 7. As can be seen from the figure, the stress – deflection behaviour is sensitive to the reinforced configurations used in the composite T-joints. The 3D woven specimen shows the best performance among these three types, its pull-out strength is increased by 171%, compared to the type Baseline specimen. The specimen with the interlaminar veils shows an increase of 44% in the tensile pull-out strength.

The through thickness reinforcement (3D woven specimen) in the web significantly increases the strength to failure comparing to other type specimens and the deflection is significantly increased as well. The specimen with the veil layer also show higher strength compared to the Baseline specimen due to the increase of the interlaminar fracture toughness in the veil specimen.

4.3 Fatigue Behaviour

Figure 8 shows the S - N data along with a regression fit for each. The R^2 values for the regression lines are 0.78 for Baseline, 0.84 for interlaminar veil and 0.97 for 3D-Woven, respectively. The static test result was also plotted together, indicated by the box in the y -axis (at the cycle number $n = 1$). As expected, the number of cycles to failure is decreased with the increase of fatigue load. Fatigue life performance of composite T-joints is significantly improved when the through-thickness reinforcement is applied into the web. The best performance is seen in the 3D woven specimen with almost 40% improvement of fatigue life at one million stress cycles. The specimen with the interlaminar veil also shows an increase in fatigue life, but not very significant. Taking to account the deviation of data and statistical analysis, it was found that there is no significant difference in fatigue life performance for Baseline, PE veil T-joints as the 95% confidence limit bands of these data were overlapped quite significantly. However 3D woven T-joints show a good improvement in fatigue properties.

Fig. 7 Stress-deflection curves of composite T-joints with different toughening architectures

Fig. 8 *S-N* data and regression fits for all type T-joint specimens

The use of 3D woven fabric significantly improves the mechanical properties both static and fatigue. There is a good correlation between the static and dynamic behaviour, see Fig. 8. This is because crack propagation largely depends upon the interlaminar fracture toughness (G_{IC}) as delamination is actually an energy dependant mechanism. Therefore, increasing interlaminar fracture toughness or reducing crack propagation driving force by changing structural feature (e.g. using 3D weave) will enhance the mechanical properties significantly.

5 Concluding Remarks

An FE model was created using ABAQUS to determine the delamination strength of composite T-joints. The FE predictions were validated by experimental measurements. The results show that the FE predictions are highly consistent with experimental observations. The 3D woven T-joint was found to have the best performance in both static and fatigue loading.

Fatigue life performance is significantly improved when the web is reinforced in the through-thickness direction. The techniques that increase the strength in the through thickness direction of the web enhance the static tensile pull-out strength by desisting or delaying delamination initiation that also improve fatigue life performance.

The use of interlaminar veil increases by more than 40% the maximum static load to failure with no significant improvement in fatigue life performance.

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