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Numerical analysis and experiment of composite sandwich T-joints subjected to pulling load

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ABSTRACT

This paper presents an investigation into the failure mechanism and alternative design of composite sandwich T-joints subjected to pulling load. Based on a conventional design of sandwich T-joint as the baseline, numerical modeling and analysis using finite element (FE) method was performed to assess the strength against pulling load. The effect of a cutout in the web panel near the joint has been considered. To validate the models, sandwich T-joint samples were manufactured and tested. Detailed FE analysis and inspection of the experimental results indicated that the failure was mainly due to the excessive stress in the adhesive between the cleat flange and the T-joint base panel. The manufacture defects, which reduced the strength of the T-joint test samples had also been investigated. This has been further demonstrated by experimental results of repaired T-joint samples. A very good correlation between the test data and FE results were obtained. An unconventional design of T-joint for simpler manufacture process was proposed. Based on the design, T-joint samples were modeled, manufactured and tested to demonstrate the manufacture process and evaluate the improved strength.

1. Introduction

Adhesive bonding provides an efficient technique for composite structures especially sandwich structure assembly without riveting or bolting. However the structural integrity and manufacture cost are largely dependent upon the design and bonding quality of the components. T-joint is a typical type of connection of composite structural components. Examples of T-joint in a wing primary structure include the connection of skin–stringer, skin–rib and skin–spar joints. Because of the dramatic change of geometry and discontinuity of the reinforcement fibers of the structure in these connection rejoins, the T-joint is potentially a weak point affecting the overall structure efficiency and integrity.

Therefore many research efforts have been made to study the behavior and in particular the failure mechanism of composite joint structures. In 1990, Shenoi and Violette studied the failure of a T-joint for a small boat by using a method combining sandwich beam and laminate theory [1]. The study of T-joints was continued in numerical modeling and analysis by Kumari and Sinha [2], progressive damage analysis by Blake et al. [3]. Yap et al. [4] and Vijayaraju et al. [5] further extended the study to the skin–stringer joints by FE analysis and experiment. Kesavan et al. made investigation into the damage detection of a GFRP T-joint structure by numerical approach [6]. The work by Shenoi et al. [7] presented a study of load transfer mechanism in sandwich T-Joint structures under pull-off load. It was concluded that failure can occur in any of the constituent elements at the root of the T-joint. The parametric study demonstrated that a larger fillet radius and cleat thickness had favorable effect on both the joint strength and stiffness. Turaga and Sun [8] made further study of the failure mode and load transfer of sandwich T-joints. Theotokoglou [9–11] studied in depth the sandwich T-joints by experiment and FE analysis taking into account the non-linearity effect. Based on the correlation between the FE and experimental results, two failure modes under pull-out load were identified with the first failure in web core and the second being base panel core crack. The joint strength is obviously depends upon the core strength. They also observed that there is significant scatter in the measurement. Hence manufacture quality of the test samples is essential to produce reliable results. In 2009, Diler et al. [12] presented a study on the performance of various T-joint design in a strain based assessment. A similar conclusion to the earlier study by Shenoi [7] on favorable effect of large fillet radius was obtained. However the assessment was limited to a simple T-joint configuration of flat sandwich base panel and strain evaluation. Zhou et al. [13] extended the study to the sandwich T-joint behavior under dynamic loading by numerical analysis only.

The previous research focus is on the failure mechanism analysis of existing type of joints by the means of numerical modeling or experiment. Little attention was paid to the manufacture defect

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Nomenclature

E	Young's modulus of isotropic material	Y_t, Y_c	tensile and compressive strength in off-fiber direction
ν	Poisson's ratio of isotropic material	S	ply shear strength
E_1, E_2	ply modulus in the 1 and 2-direction	σ_1, σ_2	ply stress in the 1and 2-direction
G_{12}	ply shear modulus in the 1–2 plane	τ_{12}	ply shear stress in the 1–2 plane
ν_{12}	ply Poisson's ratio in the 1–2 plane	ε_1, ε_2	ply strain in the 1and 2-direction
X_t, X_c	tensile and compressive strength in fiber direction	γ_{12}	ply shear strain in the 1–2 plane

and design improvement of conventional sandwich T-joint. As cutout is unavoidable in aircraft structures, the effect of cutout on composite panels and T-joint also needs attention. Guo et al. [14] studied the cutout and reinforcement of sandwich panels under shear load. It was followed by a study of optimal core to face thickness ratio against shear buckling of a sandwich panel with cutout [15]. The study was then extended by Guo and Morishima [16] to investigating the strength of a sandwich T-joint of conventional configuration under shear load. The study was performed by FE analysis validated by experimental. Cutout effect on the T-joint strength was also considered. In the conventional configuration of sandwich T-joint, the core of the base panel has a drop-off to merge the upper and lower composite faces into a monolithic laminate in the joint region. This type of construction increases the strength for through thickness load transfer between the base panel and the web panel. However, this design feature reduces the local bending stiffness and adds complexity and cost of manufacture process. An improved design of T-joint was presented and evaluated under pulling load [17,18].

In this current investigation, the authors have extended the above study of sandwich T-joint strength in three study cases. It was started with the numerical modeling and analysis of a sandwich T-joint of the conventional design. The effect of a cutout in the web panel close to the joint has also been evaluated. To validate the numerical models, sandwich T-joint samples with and without the cutout on the web panel were manufactured and tested. A pulling load was applied until the pull-off failure of the T-joint test samples. Very good correlation between the test data and FE results was obtained. A detailed FE analysis and inspection of the pull-off test samples indicate that the failure was mainly due to the excessive stress of the adhesive between the cleat flange and the T-joint base panel. Minor manufacture defect in the T-joint triangle also affected the strength and load carrying capability of the T-joint. This result has been further approved by rebonding and testing the pull-off T-joint test samples in the second case of study. Based on the failure mode of the conventional sandwich T-joint, investigation was extended into the design, modeling and experiment of an unconventional sandwich T-joint in the third study case. It is aimed at improving the manufacture process and load carrying capability of the sandwich T-joint. The investigation was conducted in the approach of numerical modeling, analysis, manufacture and experiment. Their mechanical behavior and strength were assessed and compared with the conventional baseline T-joint.

2. The conventional sandwich T-joint and FE analysis

2.1. The conventional sandwich T-joint

The sandwich T-joint structure studied in the current investigation was made of two flat sandwich panels including a base panel and a web panel. The two panels are joined at a right angle to each other by two L-shape cleats. The T-joint geometric and material details are shown in Fig. 1a. The first baseline T-joint has no cutout in the web panel. The second version has a circular cutout of diameter 40 mm in the centre of the web panel close to the joint as shown in Fig. 1a. Both the web panel and base panel were made of 5 mm thick foam core sandwiched by bonding a composite face on each side. For the web panel, each of the laminate faces was made of four plies of carbon–epoxy prepreg (MTM46/HTS) in a symmetrical layup $[\pm45]_S$ of 1 mm thickness. For the base panel, each of the composite faces was made of eight plies of the same carbon–epoxy prepreg in a symmetrical layup of $[\pm45/0/90]_S$ with a thickness of 2 mm. In the conventional T-joint configuration, the sandwich base panel had foam cut off in the joint region where the upper face was dropped down and co-cured together with the lower face to form a monolithic laminate. Two L-shape cleats were used to bond the web panel to the base panel in the monolithic laminate join region. The cleats were made of composite plain wave cloths (HTA Fibre Plain Weave Cloth-193 gsm) with a total thickness of 2 mm. In the process of bonding, the T-joint triangle gap between the web, base panel and cleats were filled with epoxy resin called paste adhesive. The details of the T-joint components are shown in Fig. 1b. The material properties of the carbon fiber prepreg used for the sandwich faces and cleats of the T-joints are listed in Table 1. The foam and adhesive material properties are shown in Table 2.

2.2. FE modeling and stress analysis of the sandwich T-joint

FE modeling and stress analysis of the T-joint structure was carried out by using the commercial package MSC PATRAN/NASTRAN. 2D shell element (QUAD4) was chosen to model the sandwich composite faces, the cleats and the adhesive layers between the core and the composite faces. 3D solid element (Hex8 Isomesh) was used to model the sandwich core and the epoxy resin used to fill the gap of the joint triangle. By using uniform mesh, the mesh density was chosen to ensure the FE result converged. In this case, 5880 shell elements were taken for the sandwich web panel face model; 5880 elements also for the film adhesive model; 2448 elements for the monolithic composite base panel; 2664 elements for the cleat laminate; 2988 solid elements for the sandwich core model; 3792 elements for the clear adhesive model; 96 elements for the epoxy resin in the joint triangle gap.

Fig. 2a shows the FE model mesh including the test rig with the loading and boundary conditions to simulate the actual test setup as shown in Fig. 2b. The pulling load was applied to the test rig through one bolt at both ends of the test rig. For the web panel model, the load was transferred from the upper test rig panel through five bolts modeled in pin connection. The base panel was connected to the T-shape test rig through pin connection and displacement constraint to represent the bolting and clamp condition. The same condition was also set in the FE model of the T-joint with a cutout in the web panel.

In the investigation, geometric nonlinear analysis was carried out to take into account the relatively large deformation especially at the T-joint region of the base panel in bending. When the pulling load was applied up to 22 kN for the T-joint without cutout, the base panel was bent up in the T-joint region of core drop-off with