Composite Structures 96 (2013) 207–215

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Improving the fracture resistance of sandwich composite T-joints by z-pinning

A.M. Nanayakkara, S. Feih, A.P. Mouritz *

School of Aerospace, Mechanical & Manufacturing Engineering, RMIT University, GPO Box 2476, Melbourne, Victoria 3000, Australia

ARTICLE INFO

Article history:
Available online 9 October 2012

Keywords:
Sandwich composites
Joints
z-Pins
Mechanical properties

ABSTRACT

This paper presents an experimental and analytical study into the strengthening and toughening of sandwich composite joints by z-pinning. Cleats connecting the vertical stiffener and horizontal base panel to T-shaped sandwich joints were reinforced in the through-thickness direction with pins. Tensile (stiffener pull-off) tests revealed that pinning increased the ultimate fracture load and fracture energy by resisting crack growth along the cleat–skin and skin–core interfaces, which were the weakest points in the unpinned joint. The peak fracture load and fracture energy increased with the volume content of z-pins. The strengthening and toughening effect of the pins was analysed using multiple pin pull-out tests performed on the sandwich composite material. It is shown that elastic deformation, debonding and pull-out of the pins from the face skins to the sandwich composite is the primary toughening mechanism of the pinned T-joints. The pin pull-out process, which is the cause for the high strengthening and toughening of the T-joints, is analysed using bridging traction modelling.

1. Introduction

The joints connecting sections of sandwich panels are often the weakest link in sandwich composite structures. Various designs are used to maximise the fracture load limit of sandwich joints, including T-shaped joints, U-channel joints and other bonded fillet designs as well as bolted connections (e.g. [1–4]). Sandwich joints are susceptible to interfacial cracking along the skin-stiffener connection and the face skin/core region within the sandwich material due to their low out-of-plane strength and fracture toughness properties. The usual method of increasing the interfacial fracture toughness is to use high-strength adhesive along the joint connections. An alternate approach that may be effective in the strengthening and toughening of sandwich joints is through-the-thickness reinforcement using z-pins, although this method has not been previously investigated.

z-Pins are thin fibrous composite or metal rods that are inserted through-the-thickness of composite materials to promote high interlaminar fracture toughness. Numerous research studies have shown that pinning is effective at increasing the structural properties (including the fracture load and toughness) of T-joints, L-shaped joints, stiffened panels and lap joints made of composite laminates [5–14]. Pinning can also promote large increases in the fatigue life of laminate joints by resisting interfacial cracking between the adherends. For example, Koh et al. [11] recently reported that the ultimate load and fracture energy of carbon/epoxy T-joints were increased respectively by up to 75% and over 600% with pinning. Chang et al. [7] measured a 40% increase in the fatigue strength of single lap joints when reinforced with pins. The properties were improved by the pins generating bridging traction loads which resist large-scale crack growth in the joints.

While the strengthening and toughening of laminate joints by pinning has been proven, it is not known whether pinning will significantly increase the fracture resistance of sandwich composite joints. The strengthening and toughening provided by pins is reliant on the formation of bridging traction loads along cracks within the joint [6–14], and it is not known whether the bridging response is different for sandwich composites due to the foam core and the skin–core interfaces. The aim of this study is therefore to experimentally determine the effect of pinning on the structural properties and strengthening mechanics of sandwich composite joints. The joint type examined was a traditional fillet T-joint, which is one of the most common designs for joining sandwich composite panels. The joint was made with thin face skins of carbon fiber/epoxy laminate and a thick core of polymer foam, and this sandwich material is used in aircraft structures. The effect of increasing the volume content of pins on the ultimate fracture load and fracture energy of the sandwich composite joint was determined. Also, the effect of pinning on the development of damage and final fracture of the T-joint was assessed. The strengthening and toughening mechanics of the sandwich joint were analytically and experimentally studied using pin pull-out tests which provide information on the bridging traction behaviour of pins in sandwich materials.

* Corresponding author. Tel.: +61 3 99256269.
E-mail address: adrian.mouritz@rmit.edu.au (A.P. Mouritz).

0263-8223/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2012.09.029

2. Sandwich joints and experimental methodology

2.1. Fabrication of sandwich T-joints

The design and geometry of the sandwich T-shaped joint used to assess the effectiveness of pins to increase the structural and fracture properties is shown in Fig. 1. The joint was constructed using two flat sandwich composite panels which formed the base and stiffener, and they were joined using two L-shaped laminate cleats. The cleats and face skins to the sandwich composite were made using eight plies of T700 carbon/epoxy prepreg (VTM264) arranged in a cross-ply stacking sequence $[0/90/0/90]_s$. The core material used in the base and stiffener panels was a closed-cell polymethacrylimid (PMI) foam (Rohacell Type 71RIST supplied by Evonik GmbH). The local regions where the cleats, stiffener panel and base panel connect were filled with unidirectional prepreg to avoid the formation of weak resin-rich zones. The cleats were bonded directly on to the stiffener panel and base panel by co-curing inside an autoclave operated at an overpressure of 276 kPa and temperature of 120 °C for 1 h. Adhesive was not used to aid the bonding of the joint components.

Before curing, the horizontal section of the cleats was joined to the base panel by z-pinning using 0.28 mm diameter rods of pultruded T300 carbon/bismaleimide (Albany Engineered Composites Pty Ltd.). The cleat/base panel connection was reinforced with a low (0.5%) or high (2%) volume content of pins. The pins were inserted using the Ultrasonically Assisted Z-Fiber (UAZ) process, which basically involved driving the pins from a foam carrier preform into the uncured sandwich joint using high frequency (20 kHz) ultrasonic vibrations [15]. The pins were inserted through the entire thickness of the horizontal section of the cleat and the sandwich base panel, as illustrated in Fig. 1a. The leading tip of the pin, which was forced into the sandwich material, was chamfered to ease the insertion process whereas the trailing end of the pin was blunt, as shown in Fig. 2. The pins were arranged in a square grid pattern with the rows aligned along and across the cleat-base panel sections. The pins were spaced 3.5 mm and 1.75 mm apart for the low and high density pinning, respectively. In addition to T-joint specimens being made with the low or high amounts of pin reinforcement, unmodified specimens were also produced without pins as the control joint. The geometry and fabrication of the unpinned T-joint was identical to the pinned joints, with the only difference being the absence of pins.

Many of the pins in the fully cured sandwich material were slightly offset from the orthogonal direction. Fig. 3 presents an X-ray tomography image of the sandwich composite showing that the pins were inclined at various angles. The inclined angle of the pins varied over a range up to 12° (Fig. 3b). Based on the work by Chang et al. [16] for carbon/epoxy laminates that were pinned with the same UAZ process used here for the sandwich joints, it appears that the cutting off of the excess pin length and consolidation of the material within the autoclave are the main causes for the pins being inclined at various angles from the orthogonal direction.

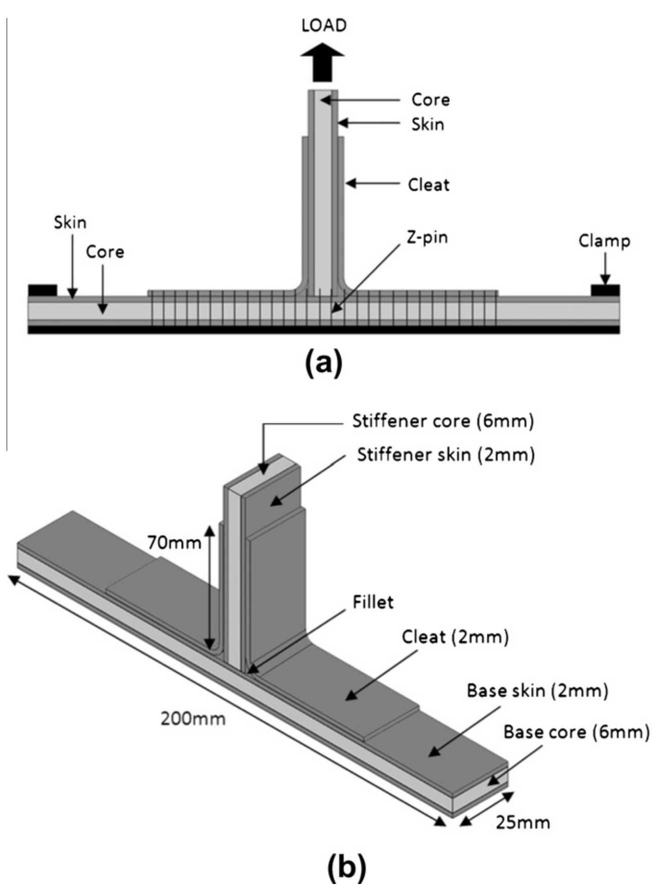

Fig. 1. Schematic of the design and dimensions of the sandwich T-joint used in the structural pull-off test. The region that was reinforced with z-pins and the direction of applied loading is indicated in (a).

2.2. Structural fracture testing of sandwich joints

The structural properties of the unpinned and pinned sandwich T-joints were measured by applying a pull-off load parallel with the stiffener (as indicated by the arrow in Fig. 1) until final fracture. The ends of the base panel were rigidly clamped, with an unrestrained length of 150 mm. A tensile force was applied to the stiffener end using a 50 kN Instron loading machine operated at a constant displacement rate of 1 mm/min. From these tests the peak fracture load and fracture energy of the T-joints were measured. Six specimens of each type of T-joint were tested under identical conditions to assess the variability in the fracture properties.

2.3. Pin pull-out tests on sandwich composites

Multiple pin pull-out tests were performed on flat panels of the sandwich composite material, as shown schematically in Fig. 4. These tests were performed to determine the bridging traction load and traction fracture energy generated by a single pin under mode I loading, which is similar (but not identical) to the tensile loading on the pins along the cleat-base panel connection in the structural pull-off tests performed on the sandwich joints. As explained later, the pins in the joint experience mixed mode I/II interlaminar loading as opposed to pure mode I interlaminar loading on the pin that occurs in the pull-out test.

The pin pull-out test specimen (measuring 40 mm × 20 mm) was reinforced with the same pins used in the joints. The entire area of the specimen was reinforced with about 80 or 260 pins, which is equivalent to the low and high volume pin contents, respectively. A tensile load was applied normal to the face skins of the sandwich composite at a displacement rate of 1 mm/min to final failure. Pull-out tabs were bonded to the face skins of the specimen using a high strength epoxy adhesive (Araldite 420). The measured load was divided by the total number of pins in the sandwich sample to determine the average traction load generated by each pin. Three samples of the sandwich materials reinforced with the low and high pin contents were tested under identical conditions.