Composites Part B 97 (2016) 216–225

Contents lists available at ScienceDirect

Composites Part B

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

Influences of thickness ratios of flange and skin of composite T-joints on the reinforcement effect of Z-pin

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ARTICLE INFO

Article history:
Received 23 January 2016
Received in revised form
25 March 2016
Accepted 1 May 2016
Available online 9 May 2016

Keywords:
A. 3-Dimensional reinforcement
B. Delamination
C. Finite element analysis (FEA)
D. Mechanical testing

ABSTRACT

Experiments along with the finite element model were used to analyze the influences of thickness ratio of flange and skin (hereinafter referred to as thickness ratio) of T-joint on the reinforcing effect of Z-pin. Results showed that the thickness ratio significantly influences the reinforcement effect of Z-pin. Whether or not Z-pin should be applied to a specific T-joint can be decided by the thickness ratio. For T-joints with large thickness ratios (larger than 0.32 for the studied T-joint), the application of Z-pin is an effective way to increase the carrying capacities of the T-joints, while for T-joints with small thickness ratios (smaller than 0.32 for the studied T-joint), the reinforcing effect of Z-pin is not obvious. Besides, the corresponding load value under large displacement in the load-displacement curves of T-joints with different thickness ratios are similar.

1. Introduction

Overall composite structure design technology is an effective way to achieve high performance and low cost. T-joint is a typical kind of overall composite structure used in the modern aircrafts. The laminates are laid up with unidirectional prepregs with a character of anisotropy and the properties in the directions perpendicular to the fiber direction are poor. As a result, delamination between the interfaces of skin and flange is a typical failure mode of composite T-joints.

Z-pin technique is the insertion of cured fiber/resin rods or metallic rods (usually fiber/resin rods) into the uncured laid up plies, effectively pinning the individual plies together [1,2]. Researches have showed that Z-pin can significantly improve the interfacial properties of laminates. The reinforcement effect of Z-pin is affected by several factors, such as the Z-pin content and diameter of Z-pin. Koh et al. [3] found that both the maximum load and absorbed energy capacity of the tested T-joint increased rapidly with the z-pin content and the ultimate load and absorbed energy capacity of a T-joint could be improved to over 75% and 600%, respectively. Park et al. [4] fabricated and tested several T-joints with different areal pin densities as well as pin diameters and results showed that the strength of the composite T-joints can be increased by more than 70% compared with the unpinned joints through the z-pinning technique. The authors also discovered that the enhancement is directly related to the total contact area between the pins and the laminate and a larger contact surface means a higher failure load of the z-pinned T-joints. Li et al. [5] showed that the bearing properties of composite joints increase at a quasi-linear rate with the Z-pin content, however, the bearing properties were not dependent on pin diameter. Z-pins improve the bearing properties by retarding the crack propagation through a bridging toughening mechanism that involves debonding and frictional sliding of pins within the damaged region. As the bridging force is proportional to the total contact area, the bearing properties of composite joints increase at a quasi-linear rate with the Z-pin content when the pin diameter remaining the same. Although with the same Z-pin volume content, pins with smaller diameter can provide larger bridging force than pins with larger diameter due to the fact that the total contact surface of smaller pins is bigger, smaller pins are more likely to be fractured under the bearing load. For this reason, the bearing properties show little or no dependence on the pin diameter. Cartié et al. [1,6] also found that the mode I (crack opening) energy release rate increase as the diameter and density of Z-pin increases. Park [4] and Cartié [6] both reported that with the same Z-pin volume content, pins with small diameter can provide larger bridging force than pins with larger diameter, which can be explained as the total contact surface of smaller pins is

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http://dx.doi.org/10.1016/j.compositesb.2016.05.007
1359-8368/

bigger.

In addition to above factors, which have been studied thoroughly, the inserting depth of Z-pin is also one of the main factors that would affect the reinforcement effect of the Z-pin. Mouritz and Koh [7] showed that the mode I bridging traction load generated by Z-pin increases with their length through the double cantilever beam (DCB) experiments. Pegorin et al. [8] pointed out that both the mode I fracture toughness and fatigue resistance increase with the z-pin length due to increased bridging traction loads generated by elastic stretching and pull-out of the pins through the DCB tests. This is easy to understand as the traction force of Z-pin is proportional to the inserting length [9–11]. Koh et al. [12] studied strengthening mechanics of thin and thick Z-pined composite T-joints with identical thickness of flange and skin and found that the joint properties increase at a quasi-linear rate with the skin or the flange thickness. While the thickness of flange is equal to that of skin in Refs. [12], skin is often thicker than flange in aircrafts engineering applications. Meanwhile, T-joints with large thickness ratio and small thickness ratio are both widely used. Therefore, research into the enhancement of Z-pin on T-joint with thickness ratio of 1 cannot provide sufficient guide to the design of Z-pin reinforcement on composite T-joints with thickness ratios smaller than 1 and those T-joints are most widely used in the aircraft engineering. For this reason, it is meaningful to study the reinforcement effect of Z-pin on T-joints with different thickness ratios, which is rarely studied before. When doing the parametric analysis on the thickness ratio, only one parameter is allowed to vary to keep the parametric analysis valid. This means the parametric study on the thickness ratio should be carried out through the parametric study on the flange thickness while with the skin thickness remaining unchanged or the parametric study on the skin thickness and with the thickness of flange remain the same. Although it seems that either changing the flange thickness while remain the thickness of skin unchanged or changing the skin thickness while remain the thickness of flange unchanged is feasible, changing the thickness of flange will lead to the change of radius of R-section or size of the filler (Fig. 2), which would make the parametric analysis on flange thickness complex and invalid. When there are more than one variables in a parametric analysis, it is invalid to analyze the influence of one of the variables on the results. In addition, changing the skin thickness will not lead to the change of any other structural parameters. Thus, it is valid to study the influence of the thickness ratio of flange and skin through parametric analysis on skin thickness. We observed that thickness ratio affects the reinforcement effects of Z-pin evidently through the analysis of experiment data and FEM results. Results of the effect of thickness ratio on the Z-pin reinforcement are instructive to the design of T-joints and the Z-pin reinforcement design.

In this paper, T-joints under tensile load were modeled and analyzed using cohesive behavior similar with cohesive element to simulate the delamination of interface and nonlinear spring element based on experiments to simulate the enhancement mechanism of Z-pin in ABAQUS. After comparing the FEA results with the experiments, the feasibility of FEM was proved. On this basis, the effects of thickness ratio were analyzed to make it clear how the thickness ratio affects the pull-off carrying capacities of T-joints. The results may have certain guiding significance for the design of Z-pined T-joints.

2. Material and experimental methodology

2.1. Single pin tensile test

Mode I bridging law (the relation between traction T and relative displacement u in the interface) of the Z-pin was measured in pure mode tension of the specimen containing a poured body bridged by a single Z-pin inserted vertically into the poured body (as shown in Fig. 1). The tensile load is applied on the free end of Z-pin through a loading jig. The loading speed was set at 0.5 mm/min. The poured body is a cylinder with a diameter of 30 mm. The material of the poured body is a kind of bismaleimide (BMI) resin called QY8911-IV and the properties of QY8911-IV is given in Table 1. The Z-pin with a diameter of 0.5 mm is a rod of 100 mm and the inserting length of Z-pin is 3 mm. The material of Z-pin is T300/NHZP-1. T300 is a kind of carbon fiber provided by the Japan Toray company and the properties are given in Table 2; NHZP-1 is a special kind of BMI resin which is developed by the Nanjing University of Aeronautics and Astronautics (NUAA). The resin mass content of Z-pin is 35.7%. The T300/NHZP-1 rods were linear elastic to failure with a strength of 1870 MPa.

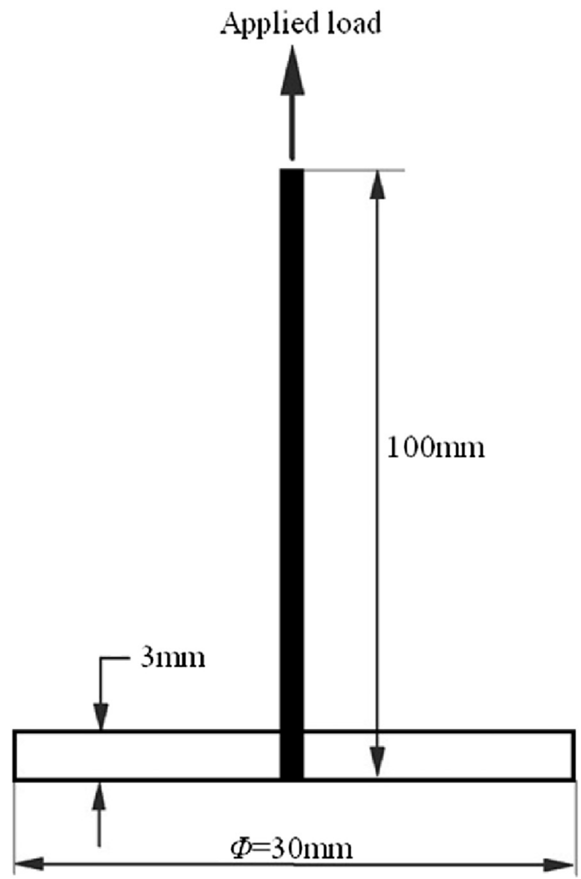

Fig. 1. Illustration of Z-pin pulling out of a poured body.

Test results are shown as Table 3. The maximum traction stress τ was calculated by:

$$\tau = \frac{T_{max}}{\pi \varnothing d} \tag{1}$$

where T_{max} is the maximum traction load, $\varnothing$ is the diameter of Z-pin, d is the inserting depth of Z-pin.

2.2. T-joint tensile test

Geometry and the coordinate systems of the plies of the T-joint specimen is shown in Fig. 2. W represents the width of the T-joints; R represents the radius of the R-section; F represents the span of the flange; H represents the height of the web; T_f represents the