Yan Tan, Yong Li*, Dajun Huan, Xiangyang Zhang and Qiyi Chu

Failure analysis and strengthening mechanism of Z-pinned composite T-joints under tensile loading

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Abstract: Z-pinning technology is applied to composite T-joints in this paper to explore the strengthening mechanisms. The structural properties of T-joints with skin thickness values at 2 and 4 mm were determined under stiffener tensile load. The results revealed that the initial failure strength and failure modes of T-joints were affected by the thickness of skin. Under stiffener tensile load, the actual stress situation of Z-pin tends to be complicated with the deflection of skin. As a result, a mixed mode I/II stress condition exists at the delamination crack tip during tensile loading, and an enhanced frictional zone is located near the delamination surface. When the deflection of skin is indispensable, the snubbing effect acts as a significant factor to strengthening. As the pullout process of pins from the flange is limited by snubbing, pins could fail by split. This paper discusses the strengthening mechanism of Z-pinning and elaborates a potential enhancing effect of Z-pins resulting from the complicated loading condition due to different structure dimensions.

Keywords: bridging; composite; snubbing; T-joints; Z-pinning.

1 Introduction

As basic units of stiffened panels, composite joints improve the structural efficiency of skins, save many mechanical fastenings, and achieve a significant reduction to weight [1]. Currently, composite joints are extensively used in many structural applications. T-joints, as a kind of typical composite joints, link skin and stiffener to transfer the load between perpendicular planes. However, the bond line between skin and stiffener is susceptible to

crack delamination when subjected to out-of-plane loads, impact, or environmental deterioration of the bonded region due to moisture ingress [2, 3].

A solution to this problem is to introduce through-the-thickness reinforcement to bridge delaminated cracks. Z-pinning is the mostly suitable method that can be applied to composite joints made from prepreg. Studies [2, 4–10] reveal that this method can effectively improve the structural properties of composite joints due to the bridging traction zone generated by pins. Many experimental and analytical studies have been carried out on Z-pinned T-joints. Emile et al. [4] tested the tensile performance and measured the damage tolerance of Z-pinned T-joints. Results showed that the damage tolerance increased by 229%. The pullout, shear, and bending tests on Z-pinned T-joints and L-joints were carried out by Vazquez [5] to investigate improvements of Z-pin on joints under different conditions. Park et al. [6] measured an increase to the ultimate strength of T-joints of 70%, which linearly increased with the bonding surface between Z-pin and laminates. Most of the available information for Z-pinned T-joints is based on the work of Koh et al. [2, 7–10]. They have provided systematic investigation on the influence of different parameters of Z-pin on the mechanical properties for T-joints and single lap joints, and also have explored strengthening mechanisms and failure modes. Recent studies show that Z-pins eventually fail along the bond line by debonding and pullout from the adherends. The strengthening mechanism and failure modes of Z-pinned T-joints are explained by the bridging traction laws under mode I loading. However, recent results indicate that the mechanisms by which Z-pin contribute to mechanical properties are complicated, depending considerably upon the loading conditions, parameters of Z-pin, configuration of structures, etc. Various failure processes of Z-pin such as deformation, splitting, breakage, pullout, and ploughing of Z-pin through the laminate can occur [11]. Thus, it is necessary to extend their research to study the strengthening mechanisms of Z-pinned T-joints comprehensively.

Under stiffener tensile load, the actual stress situation of Z-pin tends to be complicated with the deflection of skin and flange. The thickness of skin is an important factor affecting the deflection. The paper aims to present an experimental and analytical study into the bridging

*Corresponding author: Yong Li, Academy of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China, e-mail: lyong@nuaa.edu.cn

Yan Tan, Dajun Huan, Xiangyang Zhang and Qiyi Chu: Academy of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China

mechanisms of Z-pins inserted into different sizes of T-joint structure. In the second part, the Z-pinned T-joints with different thickness skins were tested under tensile load. Next, the improvement of structural properties and failure process were displayed. In the fourth part, the bridging mechanisms were analyzed theoretically and parametric analysis was displayed to evaluate the influence of skin thickness on failure modes subsequently. We suggest that, with deflection of the flange due to crack tip opening displacement, the enhanced friction zone (snubbing effect) extending over the segment of pin that has been laterally deflected by mode II loading could act as a significant factor in strengthening.

2 Materials and experimental techniques

2.1 Manufacture of Z-pinned composite T-joints

Z-pins improved the joint properties by creating crack bridging tractions between the stiffener and skin after the presence of crack along the bond line. The capacity of Z-pins to improve the ultimate load of T-joints increased with the embedded length of Z-pins [10]. The geometry of T-joint specimens was designed concerning composite design method [12], shown in Figure 1.

T-joint specimens were made of unidirectional T300 carbon/epoxy prepreg tape (USN12500 from Weihai Guangwei Group Co., Ltd.). The ply thickness after curing was 0.125 mm. The unidirectional plies in L-shaped stiffener were stacked in the pattern of $[45/0/-45/90]_{25}$, resulting in a thickness of 2 mm. Skins were fabricated in the pattern of $[45/0/-45/90]_{25}$ and $[45/0/-45/90]_{45}$ respectively, the thickness of skins being 2 and 4 mm. In other words,

the skin and flange of the thin specimen were each 2 mm thick and a combined thickness of 4 mm was obtained. In the case of the thick specimen, the combined thickness was 6 mm.

T-joint specimens were fabricated by co-curing two L-shaped stiffeners back-to-back with a flat skin. The fillet region was filled with a unidirectional prepreg roll before curing to avoid the formation of a weak resin-rich zone. Specimens were manufactured using flat-bed press (QingdaoXLB-50Z, Qingdao Jiarui Rubber and Machinery Co., Ltd.) at 120°C and 1 MPa for 2 h. Moreover, the curing process of T-joints was accomplished with specially designed molds to guarantee the shape and quality. The skin-flange section to the T-joint specimens was Z-pinned. Z-pins were made of pultruded rods of unidirectional T300/epoxy produced by our laboratory. The properties of the pins were determined by experiments, and the axial tensile strength, shear strength, and tensile modulus were 1.5 GPa, 65 MPa, and 150 GPa, respectively. The volume content and diameter of Z-pins used to reinforce the skin-flange connection was 1.2% and 0.5 mm. T-joint specimens without Z-pins were manufactured as control specimens.

The introduction of Z-pins to uncured specimens was realized by the UAZ method (Ultrasonically Assisted Z-Fiber). Pins were inserted in the stiffener direction of the skin-flange region manipulated by an ultrasonic handheld device (Center for Composites Industry Automation, Nanjing University of Aeronautics and Astronautics, Nanjing, China) at the frequency of 40 kHz.

2.2 T-joint testing

A stiffener tensile test was conducted on the T-joint specimens to assess the structural properties. The ends of the skin were clamped to a rigid plate. Two clamps were spaced 110 mm away. A tensile load was applied using

Figure 1: Dimension of T-joint specimens.

a 5 kN Instron machine (MTS SYSTEMS Co., Ltd., China) under stroke control at a constant crosshead rate of 0.5 mm/min (Figure 2). Axial displacements were measured by the machine stroke.

3 Experimental results

3.1 Failure mode of T-joints

Figure 3 presents the curves of load against vertical displacement for thin-skin specimens with or without Z-pins.

The curves show that both unpinned and pinned T-joints experience a load drop in the range of 1100–1300 N. The load drop was caused by crack initiation within the fillet region of the joint. Cracking occurred first in the region because of the high-stress concentration and being a resin-rich zone. In the case of unpinned joints, cracks

Figure 2: Configuration of the stiffener tensile test.

Figure 3: Load-displacement curves for the unpinned and pinned T-joints with thin skin.

grew along the interface between the skin-flange bonding section and the center line of stiffener to release energy. The bending of the skin-flange section occurred with the orthogonal displacement of stiffener. Moreover, the final load drop was caused by rapid delamination crack growth along the skin-flange interface, which led to complete detachment of the stiffener from skin. For Z-pinned T-joints, the load-bearing capacity recovered after the first load drop because the bending rigidity of the stiffener and skin was sustained longer by the bridge effect of Z-pinning. The formation of crack bridging zone in Z-pinned T-joints under tensile loading has been reported in Ref. [13].

Figure 4 presents the failure of thin-skin T-joints. Large-scale delamination cracking was suppressed in Z-pinned T-joints. Failure occurred through the skin when strained beyond the ultimate load point with this specific pin content, shown in Figure 4B. It indicates that pins are effective at maximizing the ultimate load capacity of the joints by suppressing complete separation of the stiffener from the skin. Furthermore, the 2 mm skin was relatively thin and demonstrated lower bending rigidity, which resulted in large deflection of the skin with applied tensile load. Furthermore, Z-pinning brought in resin-rich zones at each pin location, which results in fiber waviness, crimp, and breakage shown in Figure 5 [14]. After the first row of pins debonded, holes occurred so that the loading path was cut off, and the bending performance of skin was weakened significantly. Thus, the final failure was presented as breakage of the skin.

The load-displacement curves for thick-skin joints with and without Z-pins are shown in Figure 6, and the points where load drops are marked. During fracture process, the pictures corresponding to these points are presented in Figure 7.

As shown in Figures 6 and 7A, the curve rises linearly up to point A, at which Z-pinned joints suffered the first slight load drop when crack initiated in the fillet region. The load-bearing capacity for Z-pinned joints recovered after the initial load drop, and they could withstand greater loading until the ultimate load. This was because the Z-pin bridging effect was valid when the crack tip first extended to the first row of pin, shielding opening stress on the crack tip and inhibiting crack propagation. The applied load was transmitted through the pin vertically, and the traction load increased by elastic deformation with crack opening displacement until a certain level (point B). The energy accumulated at the crack tip was released after the sudden load drop. The first row of pin opening displacement on both sides of the stiffener increasing, pin debonding occurred. Finally, pin failed at point C and the load was borne by the rest of the pins.

Figure 4: Failure of unpinned and pinned T-joints with thin skin: (A) unpinned; (B) pinned.

Figure 5: Defects of Z-pinned laminate.

Figure 6: Load-displacement curves for unpinned and pinned T-joints with thick skin.

The curve of unpinned joints also rises linearly up to point D according to Figures 6 and 7B. Moreover, sawtooth fluctuations presented at point D are due to a plurality of microcracks appearing in succession in the fillet region,

which did not directly lead to a sudden drop in carrying capacity. With a certain amount of microcracks, visible cracks occurred in the fillet region (point E), and a sudden load drop took place. Point F still has residual bonding properties because interlaminar fiber between the layers overlapped so that the crack did not extend completely through the bonding interface.

3.2 Comparison of T-joints with thin and thick skin

The load-displacement curves for T-joints with thin and thick skin are shown in Figure 8. The rigidity of the joints, which was determined by the slope of the initial linear segment of the curve, increased with the thickness of skin. However, the rigidity was not affected by pins because the elastic modulus of carbon fiber-epoxy laminates were slightly changed by pins (<10%) [15].

The tensile traction loads for thick-skin joints with and without Z-pins are shown in Table 1. The initial failure load P_0 corresponds to points A and D in Figure 6; ultimate failure load P_m corresponds to points B and E; and the final failure load P_f corresponds to points C and F. As can be seen from Table 1, the initial failure strength of thick-skin joints was improved slightly, the ultimate load increased, and the failure load was significantly improved. The pin may play a potential role on the slight increase of the initial load. The significant increase of ultimate load was due to (i) bending rigidity of skin sustained by pinning; (ii) the function of crack opening stress on the crack tip was shielded so that crack propagation was inhibited; and (iii) extra energy was required to failure of pinned specimens, including pin deformation, friction consumption, and split. This manifests enhanced traction load in the limited displacement.

Figure 7: Failure of pinned and unpinned joints with thick skin: (A) pinned; (B) unpinned.

Figure 8: Comparison of load-displacement curves for unpinned and pinned joints with thin and thick skin.

Meanwhile, the improvement to the initial load of Z-pinned joints increased with thickness of skin. This was because thick skin showed higher bending rigidity as the elastic modulus was not affected by pins, which demonstrated smaller displacement under the same load (Figure 9). While the cracks initiated in the fillet region so that the energy (the product of displacement and load) for initial failure was

assumed to be constant. As a result, the thick-skin T-joints showed a higher initial load than thin-skin ones.

Compared to the fracture in skin as the failure mode for thin-skin joints, the deflection of skin in thick-skin joints was in the allowable range (2%). The final failure was observed as Z-pin rupture (Figure 10). The change in failure mode between thin- and thick-skin T-joints was also because the bending rigidity increased and the deformation of skin could not occur easily.

Assuming that mode I bridging traction force is dominant, the total elastic bridging traction is related to the ultimate load of T-joints. Koh et al. [8] suggested that the traction could be expressed as

$$P_{\text{total}} = N \int \tau(l) \pi d_p dl \quad (1)$$

where N is the number of pins and $\tau(l)$ is the interfacial shear strength. The equation suggests that the bridging force increases with the contact area between pins and matrix, resulting in higher bridging traction load of T-joints. Observations turned out that the failure mode changed when the deflection of flange was indispensable. Pins failed by shear rupture (Figure 10) followed by partial pullout (concluded from visual voids in Figure 11), while

Table 1: Comparison of traction load of unpinned and pinned joints.

		Initial load P_0 (N)	Amplification (%)	Ultimate load P_m (N)	Amplification (%)	Failure load P_f (N)	Amplification (%)
Thin-skin joints	Unpinned	1286	5.1	–	–	796	58.6
	pinned	1352				1264	
Thick-skin joints	Unpinned	2720	9.9	2881	18.3	1303	68.6
	pinned	2990		3409		2198

Figure 9: Comparison of thick-skin and thin-skin specimens: (A) thin skin; (B) thick skin. **Figure 10:** Failed flange of Z-pinned thick-skin specimen.

they were expected to fail by debonding and pullout from the matrix. Therefore, Eq. (1) is insufficient to explain this case, and further analysis of the strengthening mechanics of thick-skin T-joints is necessary.

Figure 11: Failed skin of Z-pinned thick-skin specimen.

4 Analysis and discussion

The stress condition of Z-pinned T-joints with thick skin under tensile load was more complicated. The schematic representation for the loading process of a pin in thick-skin specimens is shown in Figure 12. S is the slip length.

Initially, Z-pin was bonded to the matrix perfectly and the traction load increased by elastic deformation. Debonding initiated from the delamination surface into the

Figure 12: Schematic of the loading process for a pin in the thick-skin specimen.

bonding surface around the pin until its end. The elastic traction load generated by a fully bonded pin aligned in the orthogonal direction is calculated by Eq. (2) [16]:

$$P = \tau \pi d_p h \quad (2)$$

where τ is the interfacial stress strength between the pin and matrix, d_p is the pin diameter, and h is the length of the pin carrying load before debonding.

The bridging load generated by a pin during the pullout phase is expressed in Eq. (3) [16]:

$$P = (H - S) \tau_f \pi d_p \quad (3)$$

where τ_f is the frictional stress generated at the pin-laminate interface, which opposes pin pullout. This can be calculated using [17]

$$\tau_f = \frac{P_{\max}}{\pi l_r d_p} \quad (4)$$

where $P_{\max}$ is the maximum traction load (which is measured) and l_r is the half-length of the pin that is pulled out.

The skin was slightly bended followed by the separation between skin and flange. Furthermore, the deflection of flange was more obvious than skin so that pin itself began to incline at an angle φ from the direction of tensile load. An elevated compressive stress was generated due to shear deformation of pin into the laminate near the delamination crack plane (as shown in Figure 12), known as pin snubbing [18]. Moreover, this increased the friction stress opposing further pin pullout. The angle φ between the pin orientation and the applied load P increased during tensile loading, and the component of applied force in the shear direction increased with the angle.

For the case in which mode I traction is dominant, which results in the pin pullout, the axial load P generated by pins can be calculated by modifying Eq. (3) [10]:

$$P_1 = \pi d_p \left[\left(\frac{H - S - z_0}{\cos \varphi} \right) \tau_f + z_0 \tau_e \right] \quad (5)$$

where z_0 is the length of the pin deflected into the laminate and τ_e is the snubbing shear stress. This equation takes into account the snubbing friction stress. Cartié et al. [17] reported that τ_e is between 3 and 10 times higher than τ_f . The axial load is predicted to increase with the angle φ .

While in the case that the axial load is dominated by mode II traction load, which results in the pin split, the load P can be approximated using the maximum failure stress criteria for unidirectional laminates [19]:

$$P_2 = \frac{S_{12} \pi r_p^2}{\sin 2\varphi} \quad (6)$$

where S_{12} is the shear strength of the pin. As shown in Eq. (6), the traction load drops with increasing angle φ .

Samples show delamination planes with failed pins protruding marginally from delamination surfaces before final failure (Figure 11). After initial debonding, competition exists about which failure mode will occur for a single pin. As shown in Eqs. (5) and (6), P_1 increases with angle φ while P_2 decreases with angle φ . The lower one determines the failure mode of the pin. This explains that the final failure of pin is split inside the pin due to shear stress.

In brief, the failure process of Z-pinned T-joints with thick skin could be concluded. In the initial stage, load was transmitted through the pin in the vertical direction. The crack propagated under mode I load, and traction load increased by elastic deformation and debonding. Z-pinned T-joints failed progressively by delamination cracking along the skin-flange interface. While the loading on pins was predominantly mode I, a mixed mode I/II stress condition existed at the delamination crack tip due to bending of the flange under tensile loading. The mode II load appeared. When the mode II load on the pin reached its shear strength, the pin split into several fragments and its bending rigidity decreased significantly. Failed pin was pulled out from matrix gradually.

Moreover, the pins were pulled out partially during initial loading from skin (concluded from the excess length of pin in Figure 10 and visible voids shown in Figure 11). It is presumed that the flange suffered bigger displacement, which resulted in greater friction limiting the pullout at the top end of a pin due to snubbing; hence, protruding marginally from skin was easier than from flange. The stress condition changed during loading, and the pin failed by shear rupture finally at some segment of the pin through the skin, and the pullout length of the broken

Figure 13: Partial pins failed by pullout.

pin was longer farther away from the stiffener (along the direction of the arrow in Figure 10).

Additionally, the pin orientation inclined to the stiffener (Figure 10), which conformed to presumption. There are two main causes: (i) the lateral deflection of the pin occurred due to mixed mode I/II load condition; (ii) the configuration of specimens were limited to the designed size with a programmed gap, which inevitably brought in layers sliding due to flow of resin when heated. This enabled inserted pins to incline slightly during curing.

Moreover, partial pins failed by pullout, as shown in Figure 13. This is probably due to the uneven force during the insertion process. Some pins were inserted so deep to penetrate the flange, leaving excessively large pores in the pin location where a resin-rich zone was formed after cure. Hence, the end of the pin was fixed in the matrix due to the resin zone and could not be pulled off from the matrix. When subjected to tensile load, pins were pulled out of the skin smoothly.

5 Conclusions

This paper investigated the strengthening mechanisms and failure process of Z-pinned T-joints. The mechanics of strengthening for thick-skin T-joints still needs further verification.

The initial failure load of thin-skin joints was not changed by Z-pinning because the fillet region was not reinforced by pins. Moreover, the improvement to the

ultimate strength by pinning was 18.3%. Pins can sustain the traction capacity when the crack occurs due to the formation of bridging traction. From the failure analysis of T-joints, the failure modes of T-joints were affected by the thickness of skin. Within limited deformation displacement, thicker skin showed higher failure initiation strength. Great bridging traction due to pins bonding with the adherent may exceed the bending property of the skin when the skin was too thin. In the case of thick-skin ones, Z-pin bridging traction was fully expressed in the initial loading. As stress conditions tended to be complex, a mixed mode I/II stress condition existed at the delamination crack tip. To some extent, mode II stress could make the pin split into several fragments. Finally, the pin failed as it is pulled out from the matrix marginally and sheared off.

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