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Design and investigation of composite bolted π-joints with an unconventional configuration under bending load

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ABSTRACT

In this present investigation, a novel design scheme for composite bolted π-joint is proposed, which is mainly improved in layup design. A set of joints are manufactured by resin transfer moulding (RTM) process based on the design above. A detailed investigation by experimental and numerical analysis is conducted on them to study their mechanical behavior and failure mechanism under bending load. In this work, computational models are developed by ABAQUS/Standard, with 3D progressive damage model to predict multiple damage modes in two components of joint. By validation of experimental results, it is indicated that the numerical analysis captures the failure mechanism and provides reasonable accuracy in predicting ultimate load. It is shown that the shear-out failure of lug bolt holes is the failure mode of joints. Besides that, decreasing the thickness of base panel properly will probably cause additional damage to base panel, though it has no significant effect on ultimate load of joints. Also, the location of lug bolt hole is proved to be one of the factors that will influence the load carrying ability of joints.

1. Introduction

The fiber-reinforced composite structures are increasingly taking place of metal structures in modern aerospace industry due to their favorable lightweight material properties. In this case, the composite structures should be designed and utilized on the basis of replacement design rules which require that the composite structures have at least equivalent stiffness, strength and reliability compared with metal ones. With the development of manufacturing technology, the application of composite has extended from secondary structures to primary aircraft structures such as joints [1,2]. Among these joints, π-joint can achieve the connection of composite structural components at a right angle and has become an advanced research hotspot in the field of joint design.

In recent years, many research efforts by experimental and numerical analysis have been made to study the design scheme and mechanical behavior of π-joints. By comparison of all these investigations in open literatures [3–8], it is found that the vast majority of π-joints studied are connected with the connected components with pure adhesive bonding. And these bonded π-joints have been applied to the connection of skin-stringer, skin-rib and skin-spar in aircraft structures. Indeed, bonding can significantly reduce the quantity of various components and simplify the assembly process correspondingly. But the load carrying ability of joints is largely dependent upon the bonding quality and material properties of adopted adhesive [9,10]. Also, to ensure the bonding quality needs strict manufacture process supervised by solid quality inspection system [11], thereby increasing manufacture costs. In contrast, bolting has many advantages such as better reliability and durability, greater load carrying ability and remains the first choice for the connection particularly between separation surfaces [12]. For example, the wing can be connected to the fuselage by using bolted π-joints. In this case, the π-joint sustains heavy bending load derived from aerodynamic force applied on the wing surface. Given these reasons above, the issue of bolted π-joints subjected to bending load needs to be further studied.

In a previous study, a typical bolted π-joint designed for wing to fuselage connection was manufactured [13]. And the configuration of joint is shown in Fig. 1. By experimental and numerical investigation, it indicated that the final failure mode of the π-joint under

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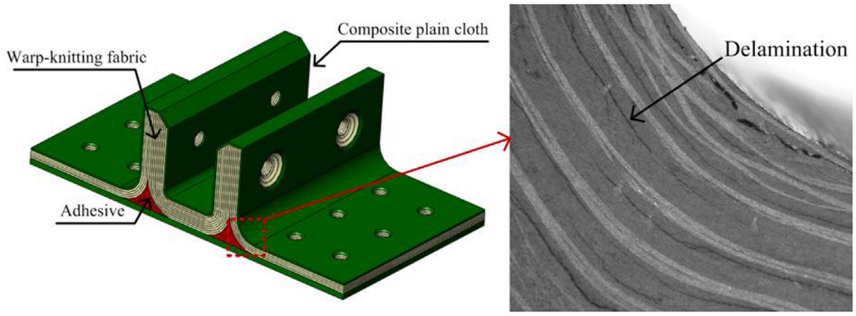

Fig. 1. Conventional configuration of bolted π-joint.

bending load was the delamination of the fillet region. Once the delamination initiated at the region, the damage area would rapidly extend to the surrounding material with the applied load increasing, thus leading to the structural failure within very short time. From the failure mechanism above, it is concluded that the joint configuration goes against the design principles about damage tolerance because of its too fast growth speed from initial damage to final failure. Furthermore, the bolt holes of lugs and base panel almost kept intact because of the quasi-isotropic layups, which showed their excessive strength in comparison with other portion of the joint. Taking all this into consideration, this conventional configuration has some obvious shortcomings and also a lot of room for the improvement of structural performance. To this end, the authors optimized the layup design based on the configuration above and proposed a novel alternative design scheme. The same-sized bolted π-joint with the new design is shown in Fig. 2. Especially, the internal warp-knitting fabric of the joint is stacked along the direction 3 and the structure surface is covered with multi-layer composite plain cloth with a total thickness of 1 mm. For the mechanical behavior of the joint in terms of bolting connection, the extraordinary layup design of internal warp-knitting fabric has pros and cons. On the one hand, the structural stiffness of the joint subjected to bending load will supposedly increase compared with the conventional one. As pointed out in the literatures, the in-plane properties are relatively stronger than interlaminar properties in composite laminate. For this reason, the new layup design will change the load transmission path to make the in-plane stress rather than interlaminar ones dominant in the internal fabric of joint, thus taking advantage of its in-plane properties. But on the other hand, the failure modes of bolt holes are closely related to fiber inclination angle which influences the stress distribution around the holes [14–16]. When the joint undergoes the bending load from the insert, the bolt holes of base panel and lugs are susceptible to exhibit shear-out failure or splitting failure because they are subjected to the applied force from the bolts in the direction parallel to the layer plane of internal fabric [17]. Conventionally, the two undesirable failure modes should be avoided as far as possible in joint design due to their catastrophic effect on the load carrying ability of bolt holes [18]. In order to make up for the adverse effect, the external composite plain cloth is used herein. The composite plain cloth has considerable fracture strength in warp and weft directions and is able to apply to complicated surfaces of structures [19,20]. In this case, it not only suppresses free edge delamination of the internal layers, but also shares a portion of extrusion load from bolts with the adjacent internal fabric around the bolt holes. More importantly, the application of composite plain cloth can partly retard the progress from initial damage to final failure, which is favorable to enhance the structural damage tolerance.

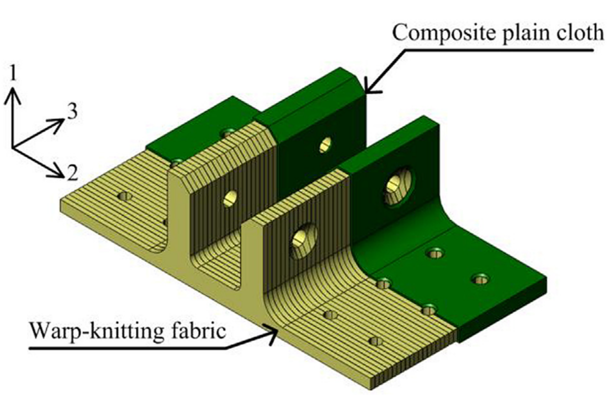

Fig. 2. Novel configuration of bolted π-joint.

In this current investigation, three joint specimens based on the new design were manufactured and tested by the self-designed experimental facility. And the superiority of new design scheme to the conventional one was certified by test data. To further analyze the failure mechanism of the joints, a 3D progressive damage FE model was established and validated by the experimental results. Based on good correlation of failure mechanism and failure load between numerical and experimental results, the investigation was extended into the effect of two geometric parameters on the mechanical behavior of joints, which aimed to improve the connection efficiency of bolting and achieve weight reduction of the joint.

2. Experimental procedure

2.1. Materials and specimens

The dimensions of specimens are given in Fig. 3. The joints were made by RTM technology, which comprised the internal warp-knitting fabric and the external composite plain cloth. Compared with prepreg technology, RTM shows a superior adaptation for complicated composite structures such as the joints investigated [21]. In details, the internal part of the joints was made of T300/6808 warp-knitting fabric in a quasi-isotropic layup of $[45/0/-45/90]_{ns}$. And the external overlaminate consisted of two-layer G814/6084 plain cloth with a total thickness of 1 mm. The material properties are shown in Table 1. Then drilling was conducted after the co-curing process of RTM. For aerodynamic reasons, countersunk was used in lugs to meet the requirement of surface smoothness. Based on the configuration in the design scheme, three specimens with different dimensions in two locations were manufactured, which were summarized in Table 2. The labeling of the joint specimens refers to the variations in the thickness of base panel (T) and the distance between lug hole center and the top of