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A qualitative comparison of stresses at aircraft bolted joint holes under initial clamping force

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Abstract

The stress state around the middle (skin) plate hole of double-lap single bolted joints are investigated under an initial clamping force. Two different materials are considered for the middle plate: a quasi-isotropic carbon fiber reinforced plastic (CFRP) composite laminate and an aluminum alloy 7075-T6 plate. The outer (splice) plates are aluminum alloy 7075-T6 for both cases. The noncommercial FE code ANSYS v12.0 is used for the analyses [1]. Linear solid brick elements are used to model the aluminum plates and the composite laminate. One element per layer approach is employed in through-the-thickness direction to model the laminated composite plate. The bolt and the washer are modeled as a single linear elastic deformable solid body. Surface-to-surface contact elements are used to define the contact behavior between the joint members including the effect of friction. Comparison of the stress results show that the clamping force has a significantly different effect for composite and aluminum plates. Initial clamping force introduces beneficial compressive stresses for aluminum plate whereas both tensile and compressive stresses occur for the composite laminate. The stress analysis results are used to explain the phenomena behind the different clamping force responses.

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Keywords: Bolted joints; clamping force; composite materials; finite element analysis.

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1. Introduction

Aluminum alloys and carbon fiber reinforced plastic (CFRP) composite materials have been widely used in aircraft structures due to their superior specific material properties. Bolted joints are the most commonly used fasteners for these materials. They are easy to assemble, tolerant to severe environmental effects, and allow component disassembly for inspection/maintenance requirements. They also meet some special requirements such as the structural integrity under heavy loads [2-4]. Although aluminum alloys have been used in last decades in primary structures, the introduction of the CFRP composites in the heavily loaded structures is relatively new, e.g. the center wing box of Airbus A380. The use of composites in primary structures entails the connections between composite-to-composite and/or composite-to-metallic structures. However, the mechanical response of the CFRP bolted composite joints can differ significantly from metallic materials due to the different elastic material properties of the layers. Out-of-plane clamping force further complicates the stress state around the bolt hole in three-dimensions. A previous study showed that the initial clamping force introduces compressive stresses around the net section plane (*Figure 1*) of the bolt hole boundary in aluminum alloy joints [4]. These compressive stresses increase the tensile strength and fatigue life of the aluminum alloy bolted joint. Conversely, the application of the clamping force introduces both tensile and compressive stresses around the net section plane of the CFRP composite bolt hole due to the different material properties of each layer. A three-dimensional finite element model is developed in this study in order to explain the significantly different clamping force responses of the quasi-isotropic CFRP composite and aluminum alloy plates.

2. Problem description

A double-lap, fully clamped (no washers between top/bottom and middle plate) bolted joint is considered as shown in Figure 1 with dimensions in mm [4]. All the aluminum and CFRP composite plates have the same dimensions. The effect of the bolt clamping force on the stress distribution around the middle plate bolt hole is the interest of the present paper.

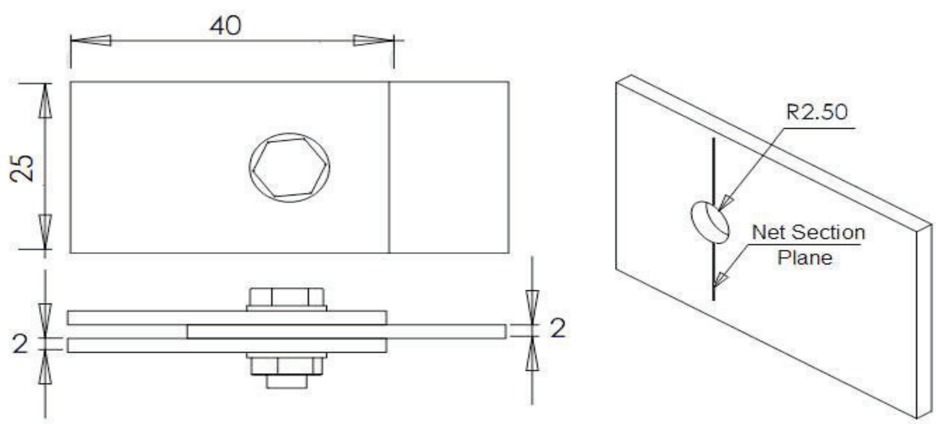

Fig.1. Bolted joint geometry and dimensions in mm.

Top and bottom plates are considered to be aluminum alloy 7075-T6 with a Young's modulus *E=71000 MPa* and Poisson's ratio *ν=0.33* [4]. The middle plate is considered to be either aluminum alloy 7075-T6 or a $[45/90/\text{-}45/0]_s$ quasi-isotropic CFRP composite plate with the elastic properties given in Table 1. Each composite layer (ply) has a thickness of *0.25 mm* which gives a total laminate thickness of *2 mm*. All 7075-T6 alloy plates are also *2 mm* thick. The steel bolt and washers have the elastic modulus of *E=210000 MPa* and *ν=0.30.*

Table 1. Unidirectional CFRP composite material elastic properties [5]

E_{11} (MPa)	E_{22} (MPa)	E_{33} (MPa)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)	ν_{12}	ν_{13}	ν_{23}
129000	9500	9800	4700	4700	3200	0.34	0.34	0.52

3. Finite element modeling

A three-dimensional finite element analysis of the double-lap bolted joint is performed using the non-commercial version of ANSYS v12.0 finite element software [1]. The advantage of the geometrical symmetry with respect to two orthogonal planes (*xy - xz*) of the model is used to simplify the analysis in terms of CPU times (*Figure 2*). Symmetric boundary conditions are applied to both symmetry planes, i.e. out-of-plane translations and in-plane rotations are set to zero.

One element per composite layer thickness is used to model the CFRP laminate. This approach gives quite acceptable stress/strain predictions [5]. Each CFRP layer is modeled separately by using SOLID185 linear 8-noded brick elements with reduced integration option. All layers are then glued together and shared nodes are generated at the interfaces. Three steps are taken to define the layer orientation angles. First, unidirectional material elastic properties (*Table 1*) are assigned to each layer individually in the global coordinate system. Second, local coordinate systems are generated for each different orientation angle (±45, 90). Third, the specific local coordinates are assigned to the associated laminate layers. The fiber direction of the 0˚ layer coincides with the global *x* direction. The single bolt/washer body, which will be referred to as fastener hereafter, is also modeled using SOLID185 linear 8-noded brick elements with reduced integration option. For simplicity, the bolt head also modeled as a circular body with the same diameter as the washer;a 0.1 mm clearance is set between the fastener and the laminate.

The finite element mesh aspect ratio at the hole boundary is set to 1.0 in order to capture the high stress/strain gradients as it is suggested for an accurate stress analysis [1]. Mesh density away from the hole is reduced to decrease the required computation time and storage space for the solution data. Surface-to-surface deformable contact behavior between the fastener and the laminate surfaces is modeled with CONTA174 and TARGE170 elements. Friction coefficient between all the contacting surfaces is set to 0.2. The contact pair is created by contact wizard. It should be noted that CONTA174 contact element is a high order element with mid-side nodes and the contact wizard drops the mid-side nodes of this element for convenience with linear SOLID185 elements. The clamping effect is simulated by applying a negative displacement at the bottom surface of the fastener. The clamping force is then obtained from the resulting reaction force at the bolt body. More detailed explanation on the clamping force simulation is available in [4]. The quarter finite element model of bolted joint is shown in Figure 2.

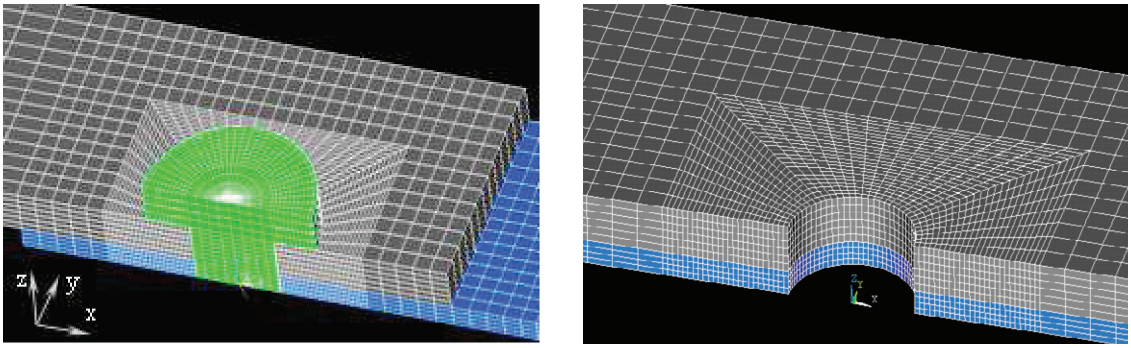

Figure 2. Finite element model of the bolted joint and close-up view of the hole circumference

4. Results and concluding remarks

The middle plate in a double-lap bolted joint carries the total load experienced by two outer plates. The integrity of the joint relies heavily on the strength of the middle plate and so the stress state around the middle plate bolt hole is of great importance. The longitudinal stress distribution (σ_x) of the 7075-T6 aluminum alloy middle plate under 6kN (~7Nm) clamping force is shown in Figure 3(a). The compressive stresses around the net section plane at the hole boundary are almost uniform through the thickness of the plate. It is well known fact that the net section plane is a critical failure initiation and propagation region for the bolted joints subjected to uniaxial tensile loads due to the high local tensile stresses developed at that plane. Thus, the clamping force induced compressive stresses increase the ultimate strength of the bolted joint by retarding the formation of these tensile stresses.

The understanding about the formation of these compressive stresses is a crucial step to make further explanation about the different joint behaviors. Let us consider a reference element at the hole boundary net section plane of the 7075-T6 aluminum alloy middle plate, where the maximum compressive stress occurs (*Figure 3*). When the out-of-plane (*z direction*) clamping force is applied, the material under the clamped area tries to expand in the two in-plane directions (*x and y*) due to Poisson's effect. While trying to expand, this element receives reaction forces from surrounding elements. These reaction forces cause compressive stresses on the element. They are of the same magnitude in the tangential circle trajectories around the hole boundary because of the isotropic nature of the aluminum alloy and the same clamping force effect exerted by the outer plate. The magnitude of the radial reaction forces decreases gradually with the distance from the hole boundary and the maximum develops at the hole boundary of the net section plane. The reduction of the radial reaction forces with the distance can be explained as follows. The solid-deformable fastener head (*Figure 2*) tends to bend under the clamping force. This causes a change on the through-the-thickness compressive stresses between the fastener head and the outer plate proportional to the amount of the bending. The outer plates transmit the same mechanical effect to the middle plate of interest. The contour circles around the holes in Figure 4 show the gradual decrease in the through-the-thickness normal compressive stresses. The less through-the-thickness compressive stresses lead to the less expansion in the in-plane directions so to the less reaction forces. As a conclusion, we observe the maximum compressive stresses at the hole boundary. The clamping effect also forces the middle plate to bend as well as the outer plates. The tapered compressive stress field at the net section plane (*V shape*) is the result of that slight bending of the middle plate.

Conversely to the aluminum plate, the longitudinal stress distribution (σ_x) is not uniform through-the-thickness of the CFRP composite middle plate hole under the same applied clamping force of 6kN. Both compressive and tensile stresses are developed as shown in Figure 3(b), mainly due to the different elastic modulus of each composite layer. Tensile stresses are developed at the 0˚ layer (*bottom layer in the figure*). It is evident under clamping force that CFRP layers tend to expand more in transverse-to-fiber 90˚ direction (*y direction*) than 0˚ fiber direction (*x direction*) because of the lower elastic modulus in 90˚. Let us consider again an element of the 0˚ layer at the hole boundary net section plane. This particular element tries to expand under the clamping force and it receives different reaction forces from surrounding elements depending on the direction as well as the distance from the hole. The relatively high displacement tendency of that element through the low modulus 90˚ direction is restricted by high modulus 0˚ direction to satisfy the compatibility. Tensile stresses at the 0˚ layer are result from this constraining effect. Similar explanations can be made for other laminate orientation angles. The joint with CFRP also requires relatively more through-the-thickness displacement in order to maintain the same clamping force due to the lower elastic modulus of CFRP in *z* direction. Increased through-the-thickness displacement causes a more pronounced bending effect in the plates which contribute to the increased magnitude of the tensile stresses at the bottom and compressive stresses at the top of the middle plate.

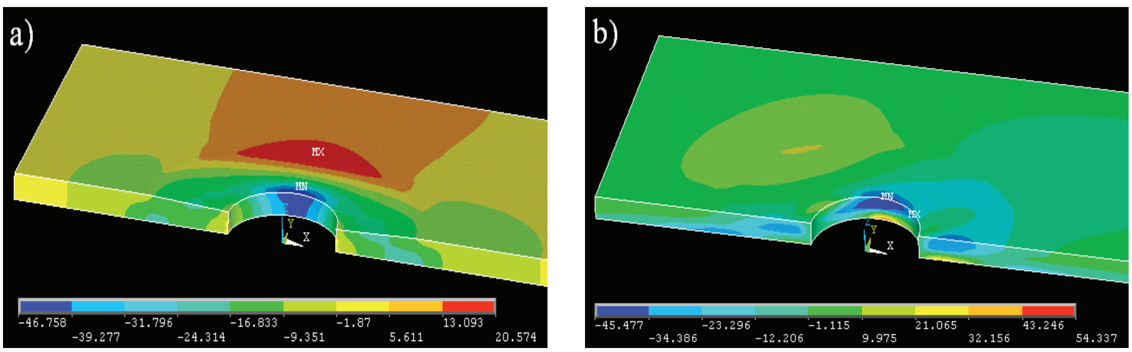

Figure 3. σ_x stress distribution of middle plate due to 6kN clamping force: a) aluminum alloy 7075-T6, b) $[45/90/-45/0]_s$ CFRP laminate

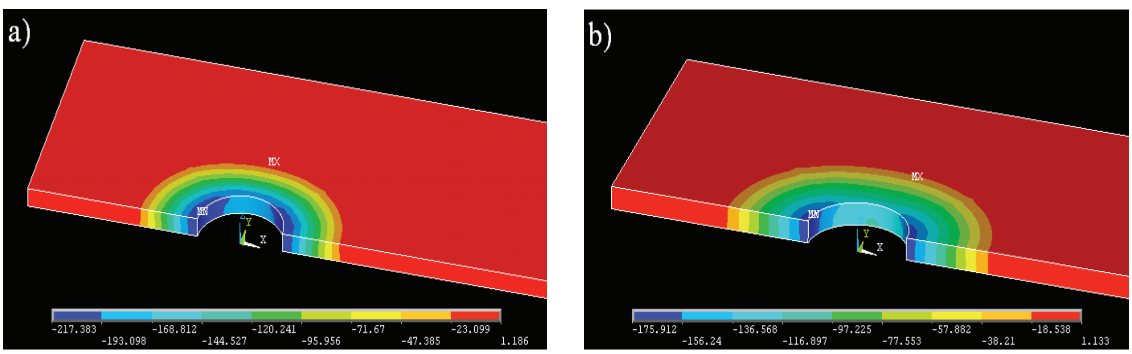

Figure 4. Through-the-thickness normal stress distributions of middle plate due to 6kN clamping force: a) aluminum alloy 7075-T6, b) $[45/90/-45/0]_s$ CFRP laminate

In conclusion, the CFRP composite and 7075-T6 aluminum alloy bolted joints give significantly different response for initial clamping forces. Experiences from metallic material joints should be used carefully when designing with composite materials due to their anisotropic nature.

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