EFFECT OF THICKNESS ON INTERLAMINAR STRESSES IN COMPOSITE LAMINATE WITH BOLT JOINTS

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ABSTRACT

The main objective of this paper is to investigate the effect of thickness on interlaminar stresses in a composite laminate when it is subjected to bolt joint loads. Composite materials are considered as the desirable choice in manufacturing of parts where high strength and stiffness are required besides low weight. As an example, thick laminates are used as the yoke of the helicopter. The yoke is the part which connects the main rotor blades to the hub. It is connected to the rest of the assembly via bolts. This study compares the interlaminar stresses between plates made of 2 to 80 unidirectional layers of glass/epoxy when they are subjected to bolt clamping loads. Finite element simulation results show the significant difference between the stress distributions patterns in plates with different range of thickness.

1 INTRODUCTION

The reduction of structure weight has been the most challenging endeavor from the very first flying objects. Steel and aluminum were the first choices in order to manufacture the aerospace structures. During past few decades, efforts have been focused on development of materials which have both the high strength and light weight characteristics. The result of such efforts was creating components from composite materials which are currently the most popular in aerospace industry. The specific strength and specific stiffness of composite materials and their design flexibility to generate desired structural properties in specific directions, make them an appropriate choice in aerostructural applications. Carbon fiber composite parts were the first generation of this materials in this industry.

For several years great efforts have been devoted to the study of thin composite plates because of their wide range of applications. Theories to analyze thin composite laminates have been significantly developed. In addition different manufacturing methods have been introduced and adapted to thin composites. Recently, more modern methods have been utilized to manufacture thick laminates [1]. More advanced manufacturing methods direct industries attention towards utilizing thick laminates as a replacement for common heavier materials where appropriate. In the literature several approaches have been proposed to perform stress analysis on thick composite laminates [2–6].

The aerospace structures consist of several components which are assembled using different methods. The most common method is bolt joint because of they can be disassembled to be inspected, repaired and replaced. Bolt joints are currently used to assemble composite parts in a wide range of thicknesses such as wing to fuselage joint in Boeing/MDD Harrier, Boeing/Bell V-22 Osprey, Boeing 777 and Grumman X-29 (NASA) [7]. One of the applications of bolt joints is the connection used for the yoke of helicopter. In general, the yoke is made of glass/epoxy and has two ends, one is attached to the main rotor blade and the other is fastened to the mast using bolt joints. One of the major concerns during the design process of the yoke is stress analysis of the bolt joints, since they are one of the most vulnerable parts of the system.

In the literature, some proposed methods are based on two dimensional analysis of the laminate but it is shown by Tomas Ireman [3] that in vicinity of the bolt the stress distribution along the thickness is not uniform. To perform stress analysis of composite bolt joint, researchers have proposed various numerical and experimental methods. In most of the cases three dimensional finite element simulation and experimental validation have been incorporated to investigate the effect of washer size, bolt clearance, hole diameter, bolt or bolts configuration, clamping torque and layers sequences on the interlaminar stress distribution and joint strength [8-15]. However, previous studies do not take into account the effect of the thickness of the plate on the structural behavior of the laminate. Studies on the definition of a thick composite laminate versus thin composite laminate are still lacking, especially in the presence of bolt joints.

The principal goal of this paper is to study the difference in the interlaminar stresses distribution between thin and thick composite laminates when they are subjected to clamping bolt loads. At a first step a three dimensional finite element model is developed and verified by experimental method. For the next step, the stress analyses are performed on plates with different thicknesses from 0.018 inch (0.45 mm) to 0.72 inch (18.3 mm). The results indicate the significant difference in interlaminar stresses distributions in plates with different range of thicknesses.

2 FINITE ELEMENT

2.1 Model Development

A three dimensional finite element model was developed to find stress distributions in laminates with different thicknesses in the presence of the bolt joint. In order to verify the accuracy of the model, Digital Image Correlation (DIC) method and strain gages were utilized to find the strain over the area around the washer and along the thickness. Figure 1 shows the finite element model which was created using ANSYS 16.2. The plate, washer and bolt were partitioned in order to provide a full control on mesh pattern and sizing. Similar meshing was generated in areas which were in contact, in order to provide more accuracy for contact modeling. TARGE170 and CONTA174 elements were used to create contacts. Surface to surface contact was modeled between bolt head-washer, washer-plate and bolt shaft-hole inner side.

The plate, washers and bolt were all meshed using the solid element solid185 which is a three dimensional, 8 nodes brick element. Solid185 can be used to model both isotropic and orthotropic materials. To define the fiber orientations and thicknesses of different layers, a section was defined and associated with the solid element. A thick laminate made of 80layers of unidirectional Glass/Epoxy was manufactured for experimental validation of the finite element model. The model created for experimental validation consisted of 20 elements along the thickness each of them associated with the defined section which included 4 layers per element. Eighty elements were created around circumference of the washer, the hole and the bolt head. As the solid element does not have the rotational degree of freedom, it is not possible to apply the clamping torque to the bolt head directly. Therefore a bolt equipped with a load transducer was utilized to find the relation between tension force at the stud of the bolt and the clamping torque. Figure 2 illustrates the results found from the bolt load experiments. As it is introduced by Speck [16], this relation is linear. A pretension section was created in the middle section of the shaft and the pretension load was applied at this section.

Table 1 summarizes the basic parameters which were used for experimental validation of the finite element simulation. Regarding the application of the plate as the yoke of the helicopter, this study focuses only on the unidirectional plates. The clamping torque for the plate with 80 layers was 70 lb-ft (≈90 N.m.). Since the finite element model was created using APDL language programming and it is fully parametric, simulation of the composite bolt joints with different plate thicknesses, layer orientations, joint configurations and material properties can be established by changing the corresponding parameters.

2.2 Experimental Validation

Two experimental methods were utilized in order to validate the finite element simulation. First, using Digital Image Correlation (DIC) method in order to find the strain field around the washer and along the thickness. DIC is a method to find in-plane and out-of-plane displacements. This method is based on comparison between images taken before and after applying load. From the displacement field it is possible to find strain. The second method for verification was using strain gages. Several strain gages were installed around the washer and along the thickness of the laminate. The results obtained from strain gages and DIC were compared with the finite element results. The detail process of finite element modeling and experimental validation using strain gages and DIC has been explained in [17].

2.3 Configurations Selection

As it was mentioned before, this study considers the effect of the thickness on interlaminar stresses distributions in unidirectional glass/epoxy laminates when they are subjected to clamping load of bolt joints. Since the interlaminar stresses are the main subject of this study, the meshing model was refined. Therefore, the number of elements along the thickness of each plate was equal to the number of the layers of the plate. In this simulation the joint is the major source of the load and the washers are responsible to transfer the load from bolt to the laminate at the top and bottom surfaces. It was intended to produce models which can be practically used, therefore, plates with different thicknesses were associated with different joints with suitable characteristics.

Table 2 summarizes the configuration of created models. The hole diameter, “D” is selected based on the available bolts in the market which are able to tolerate a pretension force of 8700 lb. All the analysis performed considering the same pretension force of 8700 lb. which results in different clamping torques based on the bolt size. The distance of the hole center to the edge of the plate, “e” is considered to be twice of the hole diameter. The washer sizes (inner diameter “Din” and outer diameter “Dout”) were selected based on the market availability. In addition it was desired to keep almost the same Din/D and Dout/D ratios in different configurations. As Table 2 represents the ratio of Dout/D varied between 2.04 to 2.25 and the ratio of Din/D changed between 1.04 to 1.10.

In order to facilitate results interpretation, a coordinate system was defined. The origin of the coordinate system was placed at the hole center on the top surface. Positive X is in fibers direction, positive Y is transverse to the fibers and positive Z was considered to be away from the top surface. Figure 3 illustrates the defined coordinate system. To indicate the Z coordinate, the percentage of thickness has been used in the following sections of the paper. Points S1 to S3 on X axis and T1 to T3 on Y axis were selected to compare the interlaminar stresses distribution along the thickness between plates with different thicknesses. The position of these points are illustrated in Figure 3. In addition two points (S4 and T4) were selected at the radial distance of 1.25 times of the hole diameter in axial (X) and transverse (Y) axis, to investigate the stresses outside the clamping area.

3 Results

Figure 4 shows the distribution of the interlaminar stresses Sz, Sxz and Syz along the thickness of the laminates (from top surface to the half thickness) at inner edge of the washer (points S1 and T1, refer to Figure 3). Following observations were noticed at the inner radius of the washer:

1. The difference in stresses distributions between plates with 2 and 10 layers is more significant than the plates with 10 or more number of layers.
2. All three interlaminar stresses are significantly higher for the thinnest plate.
3. As it was expected the interlaminar stresses (Sxz and Syz) merged to zero at mid-thickness for all plates with different thicknesses.

4. In general, as the plate thickness increases the interlaminar stresses find a uniform distribution over a greater percentage of the total thickness.
5. It can be seen that the plate with 2 layers showed linear distribution of the interlaminar stresses along the thickness.
6. All plates experience compression on the top surface at the inner edge of the washer except the plates with 10 and 20 layers. It seems that for these two plates a change of stress behavior happened at the first top layer (5% of thickness for 20 layers plate and 10% of thickness for 10 layers plate) for all interlaminar stresses. As it is indicated in Table 2, the average thickness of the washer utilized for plates with 30 to 60 layers was 65% higher than the washer used for 10 and 20 layers plate. Therefore, for plates with 10 and 20 layers the washer has a lower stiffness and it can deform easier. Lower stiffness of the washer will provide more freedom for the material below the washer to flip up at the inner edge which cause tension at this area for plates with 10 and 20 layers.
7. In mid-thickness (50% of the thickness) the interlaminar normal stress (Sz) reduces by increasing the number of layers.

Figure 5 illustrates the interlaminar stresses distributions along the thickness for the point located between the inner and outer edges of the washer. As it is obvious from this figure, the thinnest plate showed a significant difference comparing to all the other laminates. For plates with 10 and 20 layers the change in the stresses behavior which was observed at the inner edge of the washer did not occur for this point. Similar to the first point located at the inner edge of the washer, the interlaminar normal stress (Sz) reduced by increasing the number of layers.
In Figure 6, the distributions of the stresses at the outer edge of the washer are shown. Similar to what was observed at the previous two points the behavior of the plate with 2 layers is significantly different from other plates especially for the normal stress (Sz). Results showed that the trends of the stresses variation changed first between 10 and 20 layers and second, between 50 and 60 layers. For example, the compressive normal stress (Sz) reduced from 2 to 10 layers, then increased between 10 and 20 layers. Between 20 up to 60 layers, there is constant reduction in compression stress (Sz), while at 60 layers it increased and finally for 70 and 80 layers the distribution changed totally.
The stresses distributions at the radial distance equal to 1.25 times of the hole diameter are shown in Figure 7. As it can be observed from Figure 7, the stresses distributions out of the contacted region are completely different from what it was observed for the points located inside the clamped area. For interlaminar normal stress (Sz), there was a transition from tension to compression stresses between plates consist of 10 and 20 layers. As it is obvious from Figure 7, the maximum normal stress occurred at the mid-thickness for all plates. The interlaminar stresses do not follow a predictable trend of variation with respect to the number of layers. For example, the interlaminar stress, Sxz, increases between 10 and 20 layers and then decreases up to 60 layers and then increases again from 60 to 80 layers. It can be identified that at this point, Sz and Sxz at the top surface vanished for plates with 40 to 80 layers while only plate with 2 layers had zero Syz at this radial distance.

4 Summary

In this study a three dimensional finite element model of composite bolt joint was introduced. The developed model was programmed fully parametric using ANSYS APDL language in order to perform further parametric studies. Several finite element analyses were done to find the interlaminar stresses distributions around the bolt joint at critical radial distances from the hole center.
Although some trends observed for the distribution of the interlaminar stresses along the thickness, in general the stress behavior highly depends on the thickness and the radial distance and no general conclusion on the effect of number of layers on interlaminar stresses distribution can be derived. Some local trends are as following:

- For all selected points the plate with 2 layers showed totally different interlaminar stress distribution.
- At the inner edge of the washer plates with 10 and 20 layers showed a different stress behavior while this phenomena was not noticeable in other points.
- For both of the points located at inner edge of the washer and between inner and outer edges, the compressive stress at mid-thickness reduced by increasing the thickness of the plate.
- At the outer edge of washer, a change in stresses variation trend was obtained between plates with 10 and 20 layers and 50 and 60 layers.
- At the point located outside of the clamping area the stresses distribution were totally different. Sz and Sxz vanished at the distance of 1.25×Diameter of the hole for plates with 40 or more layers while Syz was zero only for thinnest plate at this radial distance.

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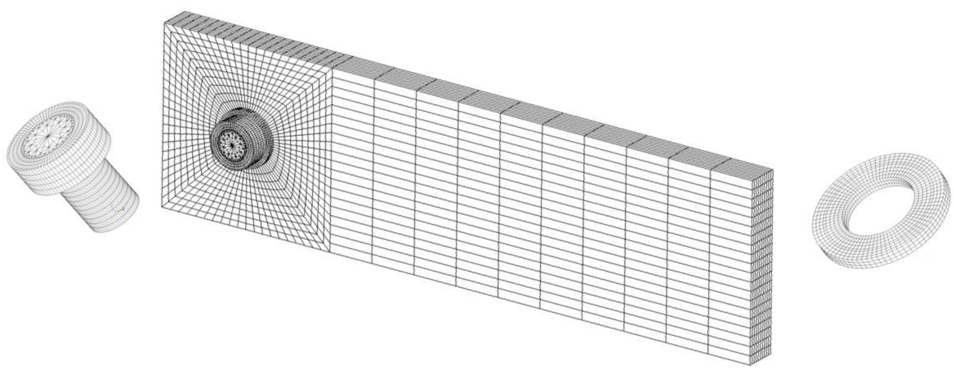

Figure 1: Developed finite element model.

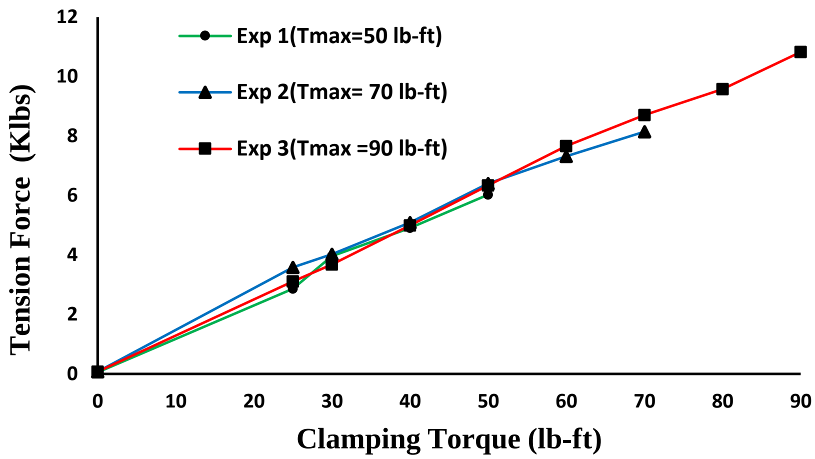

Figure 2: Tension force at bolt shaft vs clamping torque\

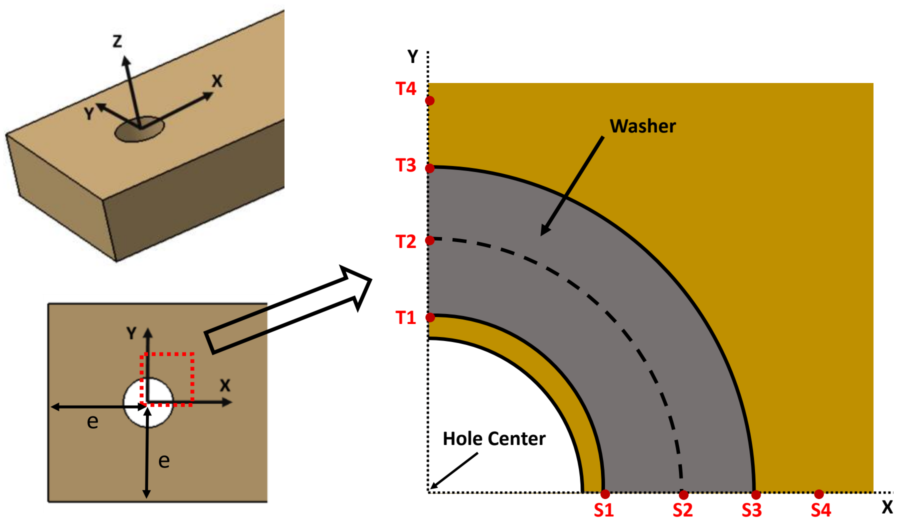

Figure 3: Defined coordinate system and selected points position

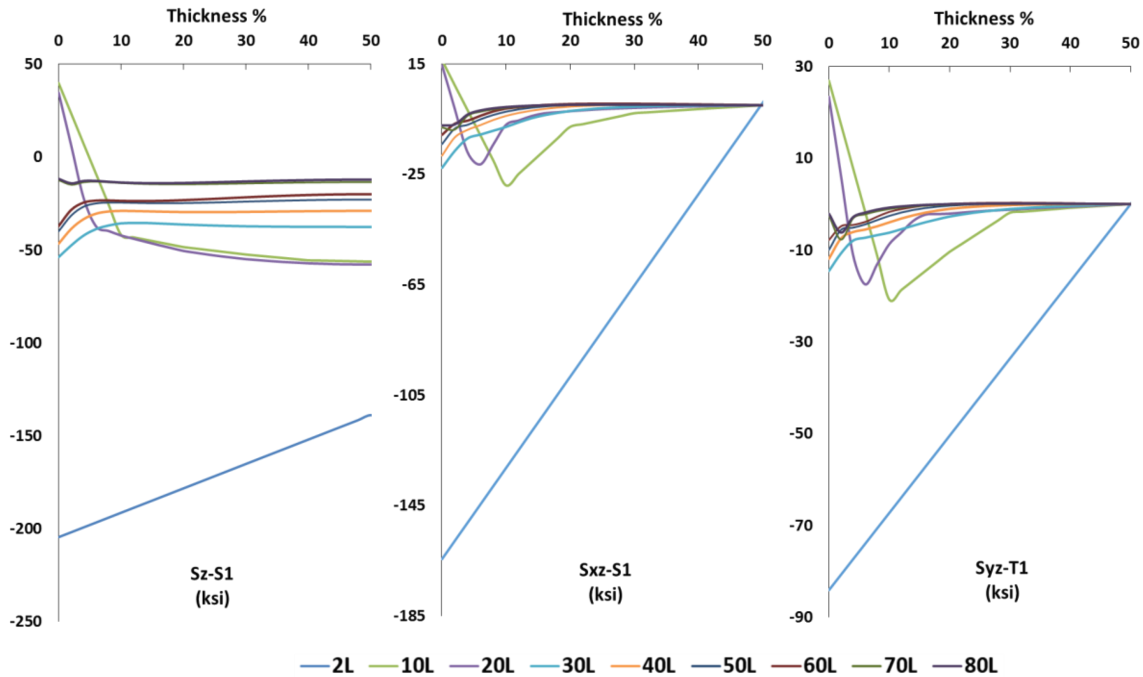

Figure 4: Interlaminar stresses distributions along the thickness at the inner edge of the washer

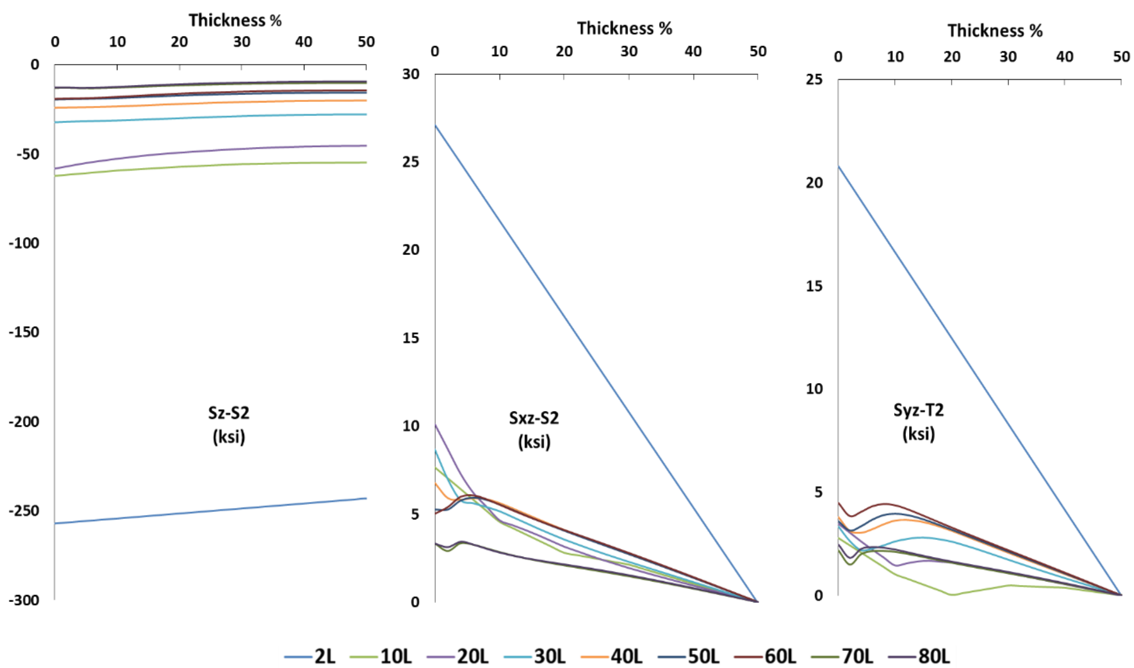

Figure 5: Interlaminar stresses distributions along the thickness between inner at outer edge of the washer

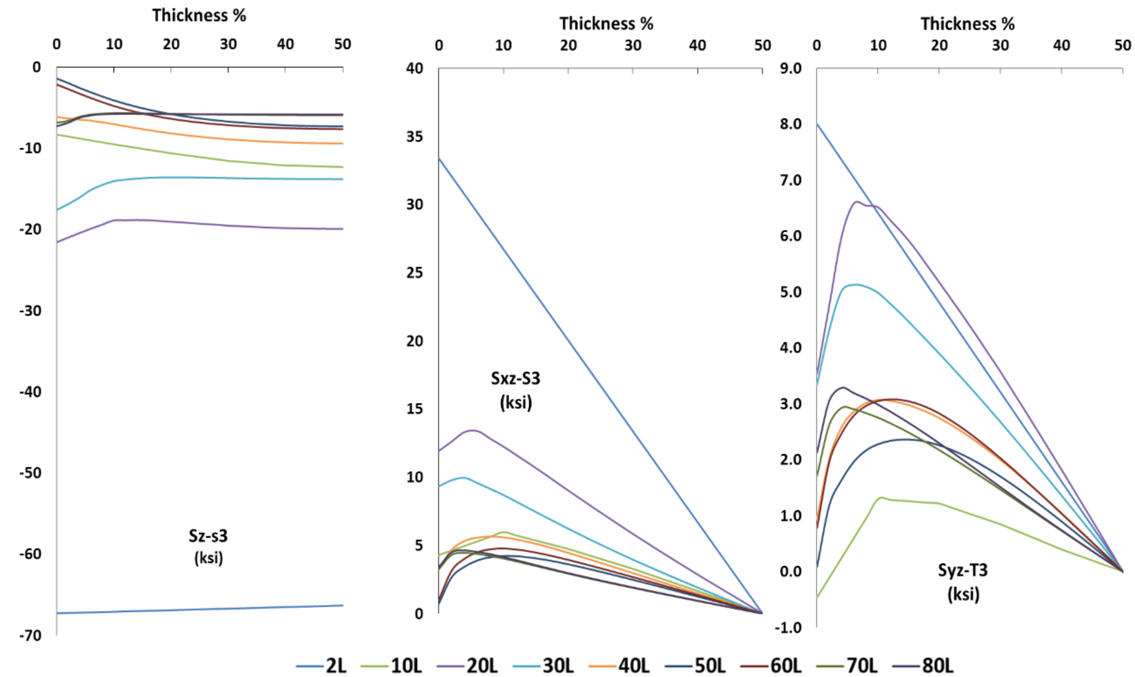

Figure 6: Interlaminar stresses distributions along the thickness at outer edge of the washer

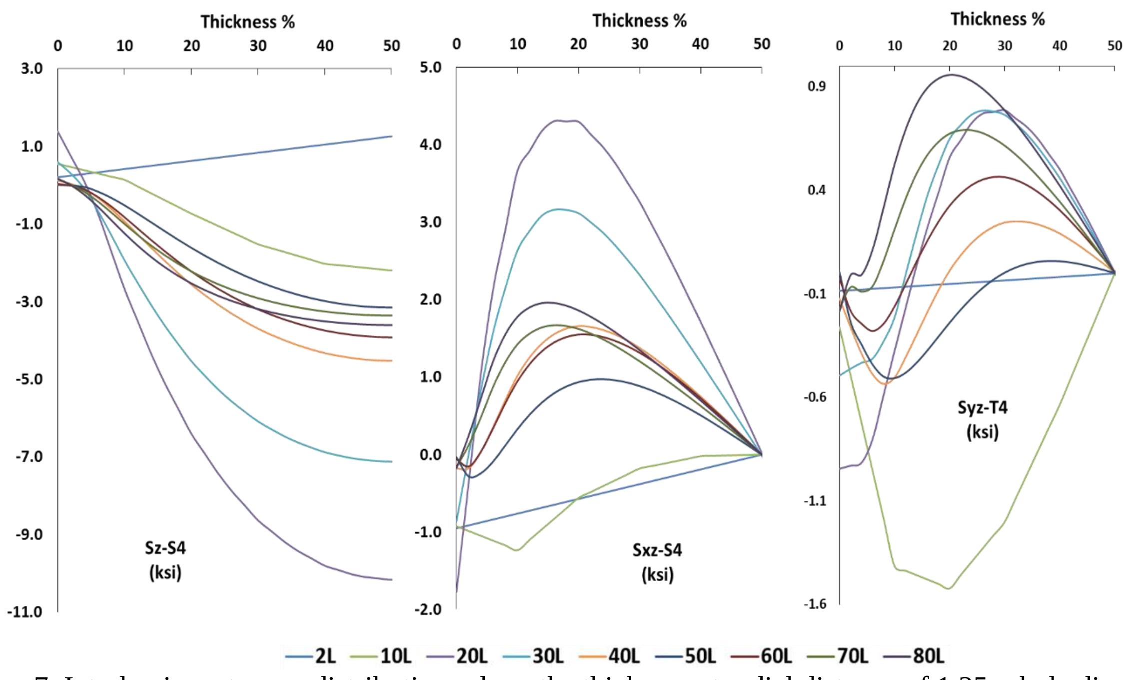

Figure 7: Interlaminar stresses distributions along the thickness at radial distance of 1.25 × hole diameter

Material	
Composite laminate	Glass Epoxy
Bolt, washer and nut	Steel
Geometry	
Lamina thickness	0.009 inch (0.23 mm)
Hole (bolt) diameter	0.5 inch (12.7 mm)
Washer inner diameter	0.53 inch (13.46 mm)
Washer outer diameter	1.06 inch (29.62 mm)

Table 1: Simulation parameters.

NOL	t (inch)	e (inch)	D (inch)	Dout/D	Din/D	WTH (inch)	T (lb-ft)
80	0.72	1	0.5	2.12	1.06	0.074-0.121	70
70	0.63	1	0.5	2.12	1.06	0.074-0.121	70
60	0.54	0.875	0.4375	2.11	1.07	0.051-0.08	62
50	0.45	0.875	0.4375	2.11	1.07	0.051-0.08	62
40	0.36	0.75	0.375	2.17	1.08	0.051-0.08	53
30	0.27	0.625	0.3125	2.20	1.10	0.051-0.08	44
20	0.18	0.5	0.25	2.25	1.04	0.03-0.05	35
10	0.09	0.5	0.25	2.25	1.04	0.03-0.05	35
5	0.045	0.276	0.138	2.04	1.09	0.018-0.032	20
2	0.018	0.276	0.138	2.04	1.09	0.018-0.032	20

Table 2: Different configurations used for modeling
NOL: number of layers, t: thickness of composite plate, e: distance between hole center and plate edge (refer to Figure 3), D: hole diameter, Dout: washer outer diameter, Din: Washer inner diameter, WTH: washer thickness, T: Required clamping torque.

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