11th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2021-018**
8-10 September 2021 - METU, Ankara TURKEY

INVESTIGATION OF THE EFFECT OF LAMINATE STIFFNESS ON BEARING/BYPASS LOADS FOR BOLTED COMPOSITE JOINTS

Korhan Candan[1]
Middle East Technical University
Ankara, Turkey

Altan Kayran[2]
Middle East Technical University
Ankara, Turkey

ABSTRACT

A bolted joint is considered as the weakest point in a structure and its strength determines the overall load capacity of that structure. For a safe structural design, engineers have to understand and predict the behavior of the joint; hence bearing and bypass loads of every bolt in a joint must be calculated. In this paper, a study is conducted to investigate the laminate stiffness on the load distribution of the bolts in a composite joint. Bearing and bypass loads are calculated utilizing analytical solution with different bolt constant calculation methods and Finite Element Method (FEM).

INTRODUCTION

Joint design is an important topic for structural engineers. With the advent of composite materials, composite joints are also increasingly used in composite structures and therefore, a lot of research has been conducted on bolted joints. Many researchers predicted the possible failure modes of composite bolted joints by calculating the bearing and bypass loads [Sharos, 2016; Liu et al., 2018; Ekh and Schön, 2006; Kabeel et al., 2015; Feo et al., 2012]. Calculation of the bearing and bypass loads for a bolted composite joint, allows one to predict the failure modes of the joint. Some of the studies performed to determine the parameters that effect bearing/bypass loads; hence possible failure modes of the joint include works of [Park, 2001; Pakdil, 2009; Acione et al., 2010; Aktas and Dirikolu, 2003; Sen et al., 2009; Okutan, 2002].

In the literature, there are many ways to calculate the bolt constant. Some of them are analytically derived formulas but most of them are empirical formulas that are derived from experimental results.

There are two commonly used methods which are the Tate and Rosenfeld method and the McCarthy method to calculate the bolt load in a bolted joint configuration [Tate and Rosenfeld, 1946; McCarthy and Gray, 2011].

In this study, bolt loads are calculated first for a metallic plate and then for composite plates with different laminate stiffnesses generated by different stacking sequences. For these calculations, analytical solution and finite element method are used, and results are compared. For the analytical solution, first plate and bolt constants are calculated then bearing loads of each bolt is calculated for the problem defined. For the finite element method, ANSYS

[1] Graduate Student in Aerospace Department, Email: korhan.candan@metu.edu.tr
[2] Professor in Aerospace Department, Email: altan.kayran@metu.edu.tr

Workbench R19.1 is used. For the bearing load of a bolt, total reaction forces for all nodes on the bolt contact surface are added up.

Bearing/Bypass Loads

In multi fastener joints, fastener holes may be subjected to both bearing loads and loads that bypass the hole as illustrated in Figure **1**. The bearing load is the force that is transmitted through the bolt to the other load carrying elements. The bypass load is the force that bypasses the bolt. Bypass loads are transmitted the other load carrying elements via other bolts in the joint.

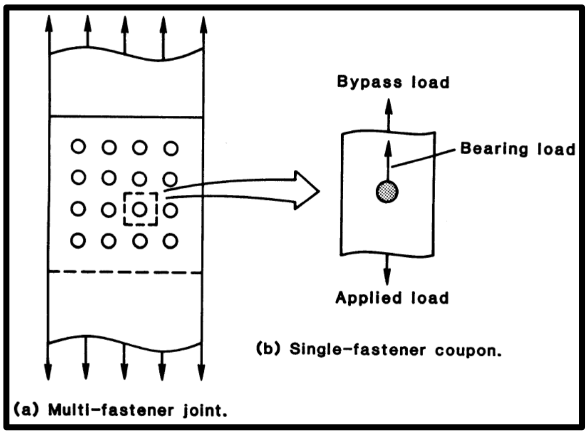

Figure 1. Bearing/Bypass loads within a multi fastener joint [Crews and Naik, 1987]

METHOD

In this section, the problem definition is given first. Then, calculation of plate and bolt constants are explained and calculation method of material properties for different composite laminate configurations is described. Lastly, details of analytical methods and the finite element analysis for the calculation of the individual bolt loads are explained.

Problem Definition

For both hand calculation and finite element analysis, ASTM D7248 is taken as the reference for the dimensions of the test specimen for which analyses are conducted. Figure 2 shows the analysis geometry comprising 3 bolts based on ASTM D7248.

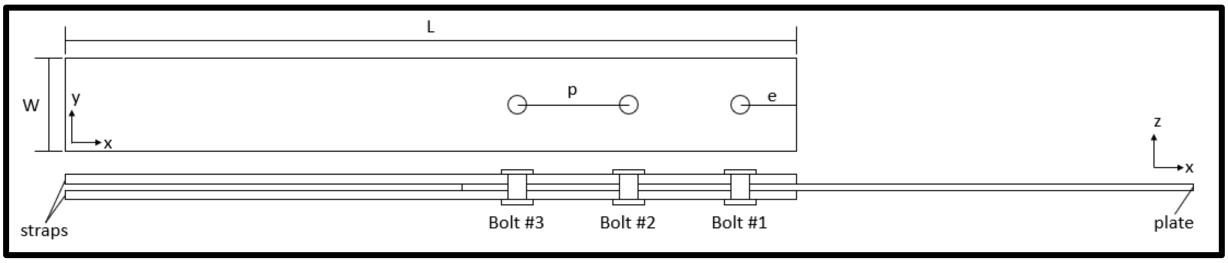

Figure 2. Analysis geometry

Table 1. Parameters of the analysis geometry

Parameter	Value	Unit
L (Length)	236	mm
W (Width)	30	mm
e (Edge Distance)	18	mm
d (Bolt Diameter)	6	mm
p (Pitch Distance)	36	mm
Steel bolts		
Parameter	**Value**	**Unit**
E (Elasticity Modulus)	200000	MPa
v (Poisson’s Ratio)	0.3	
Aluminum straps		
Parameter	**Value**	**Unit**
E (Elasticity Modulus)	71000	MPa
v (Poisson’s Ratio)	0.33	
Strap Thickness	3.0	mm
Aluminum plate for Metallic Analysis		
Parameter	**Value**	**Unit**
E (Elasticity Modulus)	71000	MPa
v (Poisson’s Ratio)	0.33	
Plate Thickness	2.08	mm
Carbon/Epoxy UD (230Gpa) Prepreg plate for composite material analysis		
Parameter	**Value**	**Unit**
E_x (Elasticity Modulus x-direction)	121000	MPa
E_y (Elasticity Modulus y-direction)	8600	MPa
v_{xy} (Poisson’s Ratio)	0.27	
v_{yx} (Poisson’s Ratio)	0.019	
Lamina thickness	0.13	mm
Laminate thickness (16 plies)	2.08	mm

In the analyses, straps are fixed, and 100 N axial load is applied to the plate in the x direction.

Calculation of Plate/Strap Constants

Plate constant is in fact the plate flexibility which is the inverse of plate stiffness. There are two different calculation methods for the plate/strap constant in the literature given by Eqs. (1) and (2). These formulas are essentially the flexibility of an axially loaded bar because both methods solve the problem by simplifying plate structures to 1D structure. Tate and Rosenfeld (1946) and McCarthy and Gray (2011) calculated the plate and strap constants by Eqs. (1) and (2) respectively,

$$K_p = \frac{p}{wt_pE_p} \qquad K_s = \frac{p}{wt_sE_s} \tag{1}$$

$$K_P = \frac{p-d}{wt_pE_p} \qquad K_s = \frac{p-d}{wt_sE_s} \tag{2}$$

where,

K_p is the plate constant,

K_s is the strap constant,

p is the pitch distance,

d is the bolt diameter,

w is the width of the plate and strap,

t_s is thickness of strap,

t_p is thickness of plate,

E_s is the longitudinal (or load) direction modulus of the straps,

E_p is the longitudinal (or load) direction modulus of the plate,

The only difference between these two calculation methods is the length of 1D bar element. Tate and Rosenfeld method uses the distance between two consecutive bolt centers and McCarthy and Gray method uses the distance between two consecutive bolt centers minus bolt diameter as the length of the 1D bar element.

Calculation of the Bolt Constant

Bolt constant (C) is the bolt flexibility which the inverse of bolt stiffness. It is dependent upon the elastic properties, geometric shape, dimensions, manner of loading of bolts, bearing properties and thickness of plates. While determining the bolt constant, it is assumed that the bolt is a fixed end beam. The load on the bolt is distributed equally along the length of plate thickness and on the other direction the bolt load is distributed equally along the total length of two strap thicknesses. This means that, shear stiffness of the bolt is considered not the axial stiffness because the load only acts in the shear direction.

There are many ways to calculate bolt constant in literature. Tate and Rosenfeld, Nelson, Huth and Boeing methods for the calculation of bolt constants are used in this study.

<u>Method of Tate and Rosenfeld:</u> This method assumes that a linear relation exists between the bolt deflection and the bolt load. To determine the bolt constant (C), the factors which are affecting the deflection are considered. These factors are the shearing, bending, bearing of bolt and the localized effect of bearing of the plates (plate bearing). Tate and Rosenfeld generated a bolt constant formula for metallic materials given by Eq. (3).

$$\boldsymbol{C = \frac{1}{K} = \frac{2t_s + t_p}{3G_bA_b} + \frac{8t_s^3 + 16t_s^2t_p + 8t_st_p^2 + t_p^3}{192E_bI_b} + \frac{2t_s + t_p}{t_st_pE_b} + \frac{1}{t_sE_s} + \frac{2}{t_pE_p}} \tag{3}$$

C is the bolt constant (flexibility),

K is the bolt stiffness,

t_s is thickness of straps,

t_p is thickness of plate,

E_b is Young's modulus of the bolt,

I_b is geometric moment of inertia of bolt

G_b is shearing modulus of elasticity of the bolt,

A_b is cross-sectional area of the bolt,

E_s is Young's modulus of the straps,

E_p is Young's modulus of the plate,

Method of Nelson: Nelson et al. tested more than 180 composite specimens and obtained load and deflection curves for these specimens. They found that the linear part of these curves could be accurately captured by minor modification of the Tate and Rosenfeld's formula which was derived for metallic materials. Nelson's formula for the bolt constant is given by Eq. (4).

$$\boldsymbol{C}=\frac{\boldsymbol{1}}{\boldsymbol{K}}=\frac{2t_s+t_p}{3G_bA_b}+\frac{8t_s^3+16t_s^2t_p+8t_st_p^2+t_p^3}{192E_bI_b}+\frac{2t_s+t_p}{t_st_pE_b}+\frac{1}{t_s\left(\sqrt{E_LE_T}\right)_s}+\frac{2}{t_p\left(\sqrt{E_LE_T}\right)_p} \quad (4)$$

where,

C is the bolt constant (flexibility),

K is the bolt stiffness,

t_s is thickness of straps,

t_p is thickness of plate,

E_b is Young's modulus of the bolt,

I_b is geometric moment of inertia of bolt

G_b is shearing modulus of elasticity of the bolt,

A_b is cross-sectional area of the bolt,

E_L is the longitudinal (or load) direction laminate moduli,

E_T is the transverse (or lateral) direction laminate moduli.

Huth's Method: Based on extensive testing on different types of joints and materials, a formula for fastener flexibility (bolt constant, C) was fitted to the load-displacement curves as,

$$\boldsymbol{C}=\left(\frac{t_s+t_p}{2d}\right)^a\frac{b}{n}\left(\frac{1}{t_sE_s}+\frac{1}{nt_pE_p}+\frac{1}{2t_sE_b}+\frac{1}{2nt_pE_b}\right) \quad (5)$$

where,

C is the bolt constant (flexibility),

E_s is the longitudinal (or load) direction modulus of the straps,

E_p is the longitudinal (or load) direction modulus of the plate,

d is the diameter of the bolt,

t_s is thickness of straps,

t_p is thickness of plate,

and a, b, and n are parameters defining the joint type as seen in Table 2.

Table 2. Parameters Defining the Joint Type

Single Shear	n=1
Double Shear	n=2
Bolted Metallic Joints	a=2/3 and b=3.0
Rivetted Metallic Joints	a=2/5 and b=2.2
Bolted Graphite/Epoxy Joints	a=2/3 and b=4.2

Boeing's Method: Whitman (2012) gives the Boeing bolt constant formula as,

$$\boldsymbol{C = \frac{1.25^{\left(\frac{t_s}{d}\right)}}{t_s}\left(\frac{1}{E_s}+\frac{3}{8E_b}\right)+\frac{1.25^{\left(\frac{t_p}{d}\right)}}{t_p}\left(\frac{1}{E_p}+\frac{3}{8E_b}\right)} \quad (6)$$

where,

C is the bolt constant (flexibility),

t_s is thickness of straps,

t_p is thickness of plate,

E_s is the longitudinal (or load) direction modulus of the straps,

E_p is the longitudinal (or load) direction modulus of the plate,

d is the diameter of the bolt,

E_b is Young's modulus of the bolt.

Calculation of the Material Properties for Different Laminate Configurations

The methodology used to calculate the laminate properties from a single lamina and laminate configurations is based on the following steps [Nettles, 1994],

- Calculation of the reduced stiffness matrix (Q Matrix),
- Calculation of the lamina stiffness matrix ($\bar{Q}$ Matrix),
- Calculation of the extensional stiffness matrix (A Matrix), coupling stiffness matrix (B Matrix) and bending stiffness matrix (D Matrix),
- Calculation of equivalent elastic moduli; material properties such as E_x and E_y

In this study only symmetric laminates are considered; thus B (coupling stiffness matrix) is equal to zero.

The calculation methodology assumes that,

- The laminate thickness is very small compared to its other dimensions.
- The laminae (layers) of the laminate are perfectly bonded.
- Lines perpendicular to the surface of the laminate remain straight and perpendicular to the surface after deformation.
- The laminae and laminate are linear elastic.

- Through-the-thickness stresses and strains are negligible.

These assumptions are valid if the laminate is not damaged and undergoes small deflections.

Selected Stacking Sequences: In the first part of the study, three composite material stacking sequences are selected as $[0_{16}]_T$, $[90_{16}]_T$, $[\pm45_4]_S$ for the ease of calculation and modelling.

In the second part, by using the guidelines of Bailie et. al (1997) three different configurations are determined. The stacking sequences of all six specimens are given in

Table 3.

Table 3. Stacking sequences for the six composite specimens

Specimen No	**Stacking Sequence**
1st Specimen (SS*_1)	$[0_{16}]_T$
2nd Specimen (SS_2)	$[90_{16}]_T$
3rd Specimen (SS_3)	$[\pm45_4]_S$
4th Specimen (SS_4)	$[+45 / +15 / -15 / 0_3 / -45 / 90]_S$
5th Specimen (SS_5)	$[+45 / +75 / -75 / 90_3 / -45 / 0]_S$
6th Specimen (SS_6)	$[+45 / +15 / 0 / -15 / -45 / -75 / +75 / 90]_S$

*SS: Stacking Sequence

Composite material is selected from the ANSYS database and mechanical properties of a single lamina is given in Table 1. Mechanical properties of the laminates calculated are given in Table 4.

Table 4. Mechanical properties of composite laminates

Mechanical Property	1st Specimen (SS*_1)	2nd Specimen (SS_2)	3rd Specimen (SS_3)	4th Specimen (SS_4)	5th Specimen (SS_5)	6th Specimen (SS_6)	Unit
E_x	121000	8600	16501	79401	29068	52359	MPa
E_y	8600	121000	16501	29068	79401	52359	MPa
v_{xy}	0.27	0.019	0.76	0.35	0.13	0.22	
v_{yx}	0.019	0.27	0.76	0.13	0.35	0.22	
Lamina thickness	0.13	0.13	0.13	0.13	0.13	0.13	mm
Laminate thickness	2.08	2.08	2.08	2.08	2.08	2.08	mm

Hand Calculation of Bolt Loads

Method of Tate and Rosenfeld: This solution is the first method used for the analytical solution of bolt loads. Plate and strap constants (K_p and K_s) are calculated via Eqn. (1) For the bolt constant (C), Tate and Rosenfeld, Huth and Boeing formulas are used as given by Eqns. (3), (5) and (6).

Relation between the loads acting on two successive bolts (bolts in rows i^{th} and $(i+1)^{th}$) in a bolted joint is given by Tate and Rosenfeld as in Eqn. (7).

$$R_{i+1} = \frac{C_i}{C_{i+1}} R_i + \frac{2K_p + K_s}{C_{i+1}} R_i - \frac{2K_p}{C_{i+1}} P + \frac{2K_p + K_s}{C_{i+1}} \sum_{1}^{i-1} R \tag{7}$$

where,

R_i is load of the bolt in i^{th} row,

C_i is bolt constant of the bolt in i^{th} row,

P is total applied load (100N in the x direction in this study),

K_p is the plate constant,

K_s is the strap constant.

Derivation of Eqn. (7) is described in Tate and Rosenfeld (1946). For the three bolted problem described in Figure 2, having calculated the bolt, plate and strap constants, the loads acting on the three bolts are calculated as,

$$R_1 = R_1 \tag{8}$$

$$R_2 = \frac{C_1}{C_2} R_1 + \frac{2K_p + K_s}{C_2} R_1 - \frac{2K_p}{C_2} P + \frac{2K_p + K_s}{C_2} R_1 \tag{9}$$

$$R_3 = \frac{C_2}{C_3} R_2 + \frac{2K_p + K_s}{C_3} R_2 - \frac{2K_p}{C_3} P + \frac{2K_p + K_s}{C_3} (R_2 + R_1) \tag{10}$$

$$P = R_1 + R_2 + R_3 \tag{11}$$

where Eqn. (11)) gives the total load acting on the plate.

McCarthy's Method: This solution is the second method used as the analytical solution of bolt loads. Plate and strap constants (K_p and K_s) are calculated via Eqn. (2). For the bolt constant, Nelson's formula given by Eqn. (4) is used for composite materials. For metallic materials, Tate and Rosenfeld's bolt constant given by Eqn. (3) is used. This method solves the bolted joint problem by idealizing the bolted joint as a simple spring-mass system as shown in Figure 3.

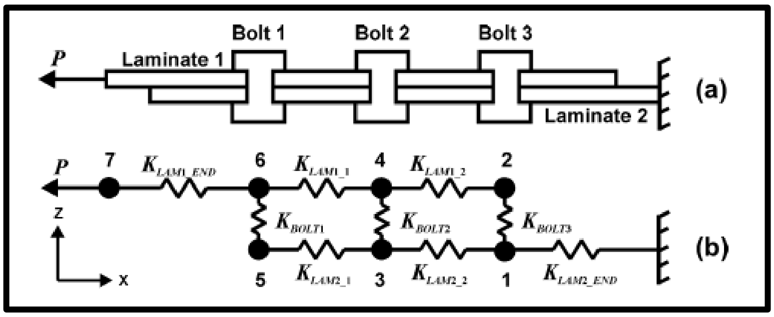

Figure 3. McCarthy's Approach to the Bolted Joint Problem

This spring-mass system examined each mass using free body diagrams and equations of motions. For example, the corresponding equation of motion for mass 4 is given as,

$$m\ddot{x}_4 - K_{LAM1\_2}x_2 - K_{BOLT2}x_3 + \left(K_{LAM1\_2} + K_{BOLT2} + K_{LAM1\_1}\right)x_4 - K_{LAM1\_1}x_6 = K_{BOLT2}c_2$$

where x is the displacement, c is bolt-hole clearance (in this study bolt hole clearance is equal to 0) and $\ddot{x}$ is the acceleration. In this study, only the static response of the joint is considered, thus the nodal accelerations ($\ddot{x}$) are set to zero. This results a system of linear equations of the type,

$$[K]\{x\} = \{F\} \tag{12}$$

where, K is the stiffness matrix, x is the displacement vector and F is the load vector.

When considering double-lap joints as in this study, only half the spring stiffness for Laminate 1 (plate) and half of the total joint load (P) has to be used for the McCarthy's approach. Figure 4 shows the application of McCarthy's approach to the problem in Figure 2.

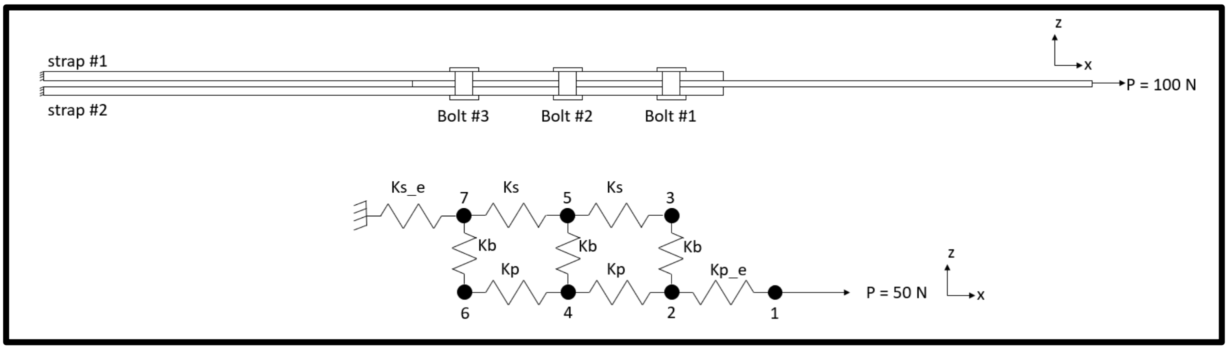

Figure 4. Application of McCarthy's Approach to the Problem

Displacement and load vectors are defined as follows,

$$\{x\} = \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{Bmatrix}, \{P\} = \begin{Bmatrix} 50 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

and the stiffness matrix in Eqn. (12) is given by,

$$[K] = \begin{bmatrix} K_{s\_e} + K_p + K_b & -K_b & -K_s & 0 & 0 & 0 & 0 \\ -K_b & K_b + K_p & 0 & -K_p & 0 & 0 & 0 \\ -K_s & 0 & K_s + K_s + K_b & -K_b & -K_s & 0 & 0 \\ 0 & -K_p & -K_b & K_p + K_p + K_b & 0 & -K_p & 0 \\ 0 & 0 & -K_s & 0 & K_s + K_b & -K_b & 0 \\ 0 & 0 & 0 & -K_p & -K_b & K_b + K_p + K_{p\_e} & -K_{p\_e} \\ 0 & 0 & 0 & 0 & 0 & -K_{p\_e} & K_{p\_e} \end{bmatrix}$$

where,

K_{s_e} is strap stiffness for the straps between bolt 3 and the fixed end,

K_s is strap stiffness for the straps between bolt 1-2 and bolt 2-3,

K_{p_e} is plate stiffness for the plate between bolt 1 and free end,

K_p is plate stiffness for the plates between bolt 1-2 and bolt 2-3,

K_b is bolt stiffness for each bolt.

Calculation of each stiffnesses are described above and in McCarthy and Gray (2011). Solution of Eqn. (12)) yields the displacement vector, and utilizing the displacement vector, bolt loads are calculated as given in Eqns. (13) – (15).

$$R_1 = K_b(x_2 - x_3) \tag{13}$$

$$R_2 = K_b(x_4 - x_5) \tag{14}$$

$$R_3 = K_b(x_6 - x_7) \tag{15}$$

Finite Element Solution of Bolt Loads

ANSYS Workbench R19.1 was used for the Finite Element Analysis (FEA) for the bolt load solution. In Figure 5 the geometry of the finite element model is presented. The materials used for the FEA of bolted joints with metallic material and composite materials are given in

Table 5.

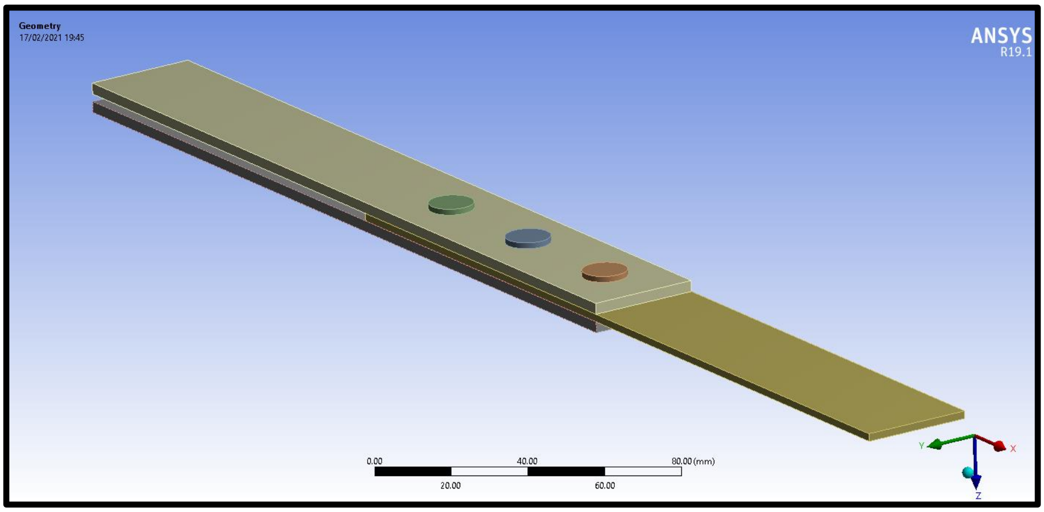

Figure 5. Geometry model of the finite element model

Table 5. Finite Element Analysis Materials

For Metallic Analysis	
Bolts	Steel
Straps	Aluminum
Plate	Aluminum
For Composite Analysis	
Bolts	Steel
Straps	Aluminum
Plate	Composite

Finite element mesh created for the metallic problem is given in Figure 6. Element size for bolts is 1 mm and element size for plate and straps is 1.5 mm. Solid 186 homogeneous structural solid element which has 20 nodes per element is used for the straps and the plates, and Solid 187 tetrahedral structural solid element which has 10 nodes per element is used for the bolts in the analysis. There are 40961 elements and 160551 nodes in the analysis for the metallic material.

For the analysis of the composite material, solid 185 homogeneous structural solid element which has 4 nodes on each element is used for the composite plate. Element types are the same with the metallic analysis for the steel bolts and the aluminum straps. Total number of elements is 485044 and total number of nodes is 612300 for the solid finite element analysis of bolted joints with composite material.

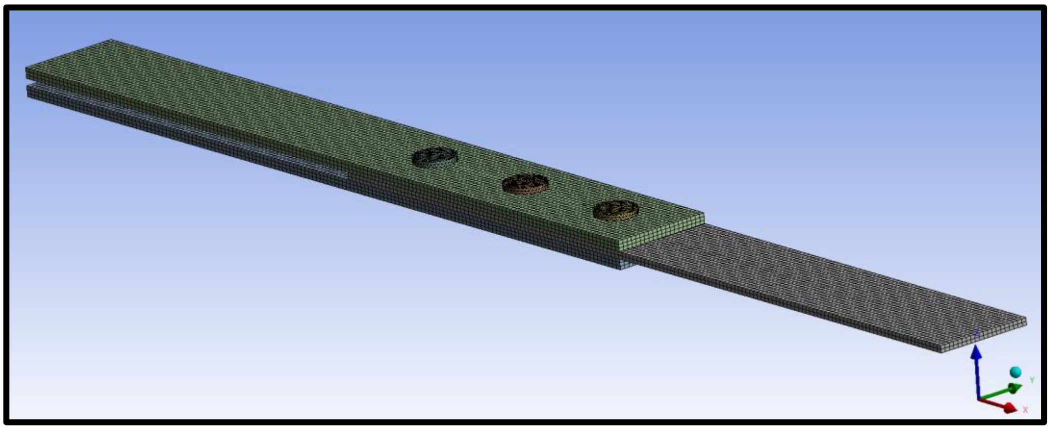

Figure 6. Finite element mesh created for FEA

Load and boundary conditions of the problem defined in Figure 7. As seen from Figure 7, straps are fixed support at the end and 100 N force in the x-direction is applied to the plate.

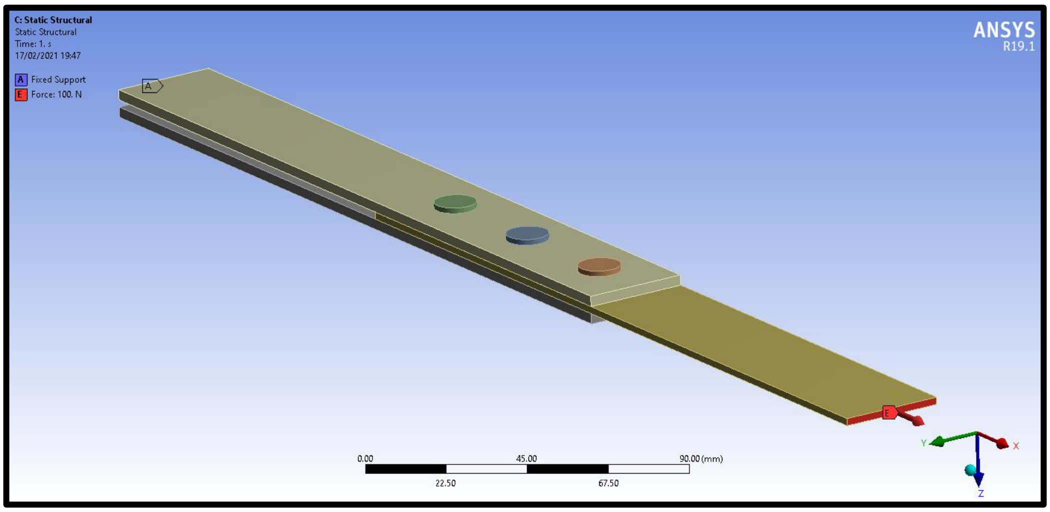

Figure 7. Load and BCs of FEA

Result obtained for the 1st bolt from finite element analysis is presented in Figure 8. For each bolt, bearing loads of the bolts are calculated and in ANSYS these loads are calculated as the sum of the reaction forces on the nodes of the contact surface between the bolt and the plate. Total load vector for the 1st bolt load is shown in Figure 8.

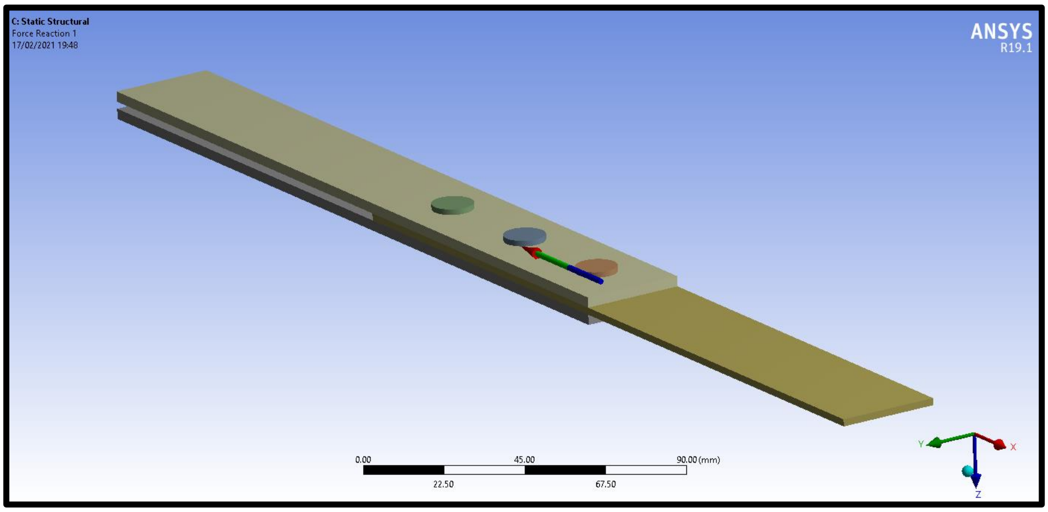

Figure 8. Bolt load of the first bolt

Comparison of the Bolt Loads

<u>Bolted joint with metallic material:</u> In this section results for the bolted joint with metallic materials are presented. Tate and Rosenfeld, Huth and Boeing methods are used to calculate the bolt constants. Both Tate and Rosenfeld and McCarthy methods are used for the analytical bolt load calculation. The results are given in Table 6.

Table 6. Bolt loads for the bolted joint with metallic material plate and straps for the 100 N input force

Bolt loads	Bolt #1 (N)	Bolt #2 (N)	Bolt #3 (N)
Tate and Rosenfeld	48.0	26.1	25.9
Huth	57.9	18.5	23.6
Boeing	50.9	24.1	25.0
McCarthy	46.4	27.1	26.5
ANSYS - Solid	57.8	18.7	23.5

These results show that bolt #1 carries most of the load for the defined problem when the strap and plate stiffnesses are equal. When Huth bolt constants are used in the Tate and Rosenfeld's bolt load relation Eqn. (7), it is seen that bolt load results are highly correlated with the ANSYS Workbench results.

<u>Bolted joint with composite material:</u> In this section, results for bolt loads in bolted joints with composite plates are presented. In this case, Nelson, Huth and Boeing methods are used to calculate the bolt constants. Both Tate and Rosenfeld and McCarthy methods are used for the bolt load calculation. Composite plate and aluminum strap constants are calculated differently for the Tate and Rosenfeld and McCarthy methods as defined by Eqns. (1) and (2), respectively. The mechanical properties of composite materials are defined in Table 4.

FEA is conducted for composite plate and aluminum straps which are meshed with solid elements. Bolt load results for composite plates are given in Tables 7-9.

Table 7. Bolt Loads for 1st and 2nd Composite Specimen in Table 3

	1st Composite Specimen (SS_1)			2nd Composite Specimen (SS_2)		
	Bolt #1	Bolt #2	Bolt #3	Bolt #1	Bolt #2	Bolt #3
Nelson	38.5	29.8	31.7	77.3	15.9	6.8
Huth	47.1	21.7	31.2	70.5	20.1	9.4
Boeing	43.6	25.4	31.1	70.2	20.2	9.6
McCarthy	37.8	30.3	31.9	75.0	17.4	7.6
ANSYS - Solid	49.0	20.4	30.6	82.4	12.2	5.4

Table 8. Bolt Loads for 3rd and 4th Composite Specimen in Table 3

	3rd Composite Specimen (SS_3)			4th Composite Specimen (SS_4)		
	Bolt #1	Bolt #2	Bolt #3	Bolt #1	Bolt #2	Bolt #3
Nelson	59.6	24.6	15.8	44.6	27.6	27.8
Huth	67.9	20.3	11.8	53.2	21.3	25.5
Boeing	66.5	21.1	12.4	49.3	24.4	26.3
McCarthy	57.1	25.7	17.2	43.3	28.5	28.3
ANSYS - Solid	77.1	14.3	8.6	57.0	18.0	25.0

Table 9. Bolt Loads for 5th and 6th Composite Specimen in Table 3

	5th Composite Specimen (SS_5)			6th Composite Specimen (SS_6)		
	Bolt #1	Bolt #2	Bolt #3	Bolt #1	Bolt #2	Bolt #3
Nelson	60.4	22.8	16.8	51.1	25.7	23.2
Huth	64.2	20.5	15.3	58.5	20.9	20.6
Boeing	61.7	22.1	16.2	54.9	23.4	21.7
McCarthy	58.1	24.1	17.8	49.3	26.7	24.0
ANSYS - Solid	74.1	13.3	12.6	64.9	15.8	19.3

As seen from Table 4 and Table 1, the relationship between the elastic modulus in the load direction of the specimens and aluminum is given by Eqn. (16),

$$E_{x\_SS1} > E_{x\_SS4} > E_{Al} > E_{x\_SS6} > E_{x\_SS5} > E_{x\_SS3} > E_{x\_SS2} \quad (16)$$

The results from Tables 7-9 are presented in Figures 9-14 as load percentage versus bolt number plots.

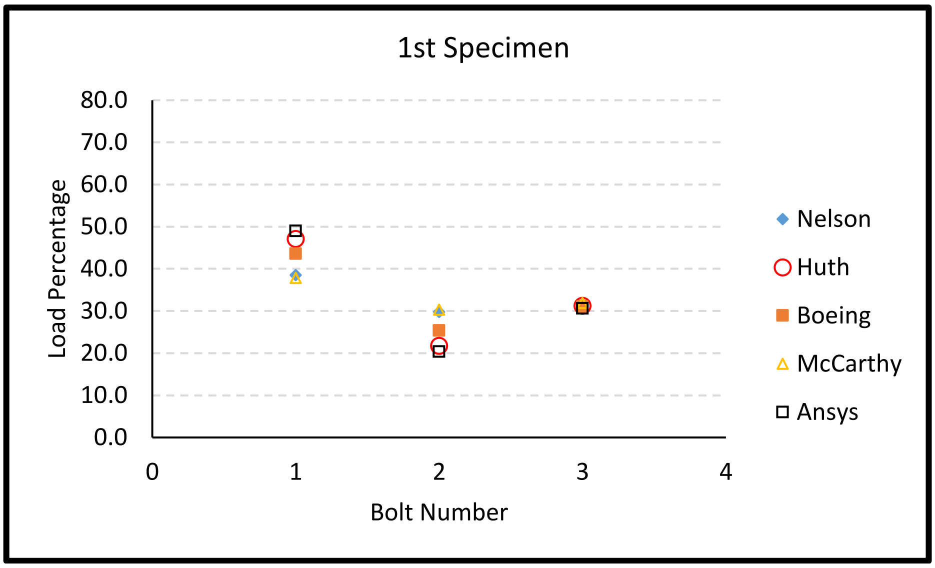

Figure 9. Results for the 1st Specimen (SS_1)

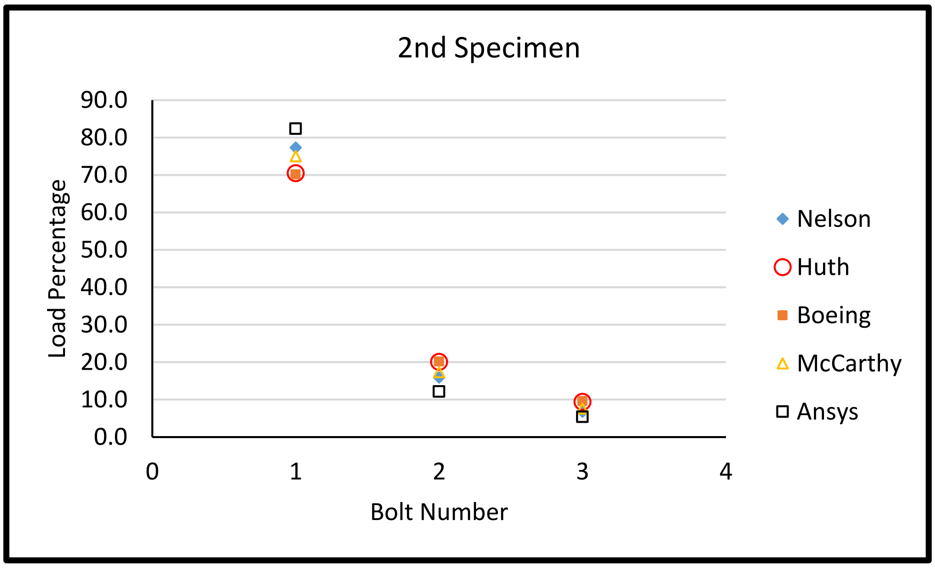

Figure 10. Results for the 2nd Specimen (SS_2)

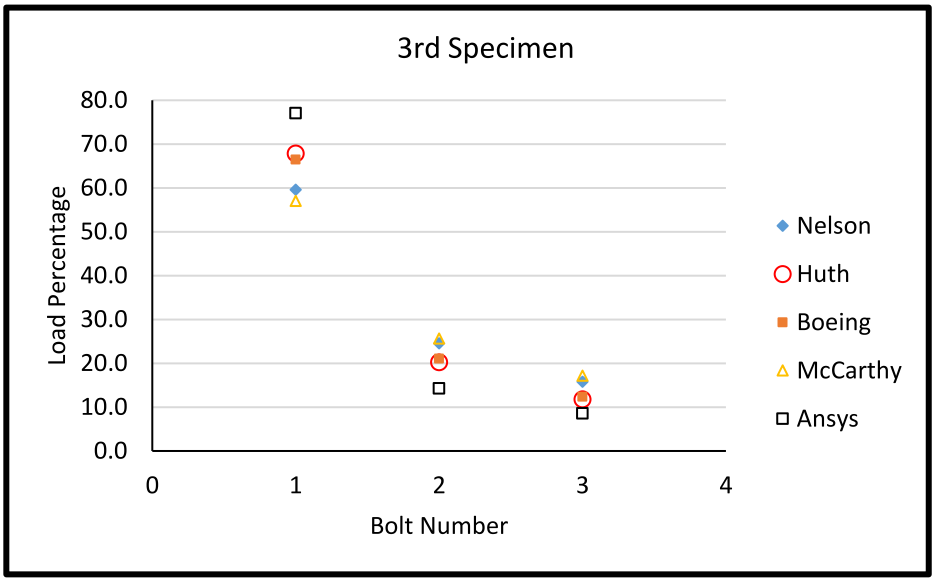

Figure 11. Results for the 3rd Specimen (SS_3)

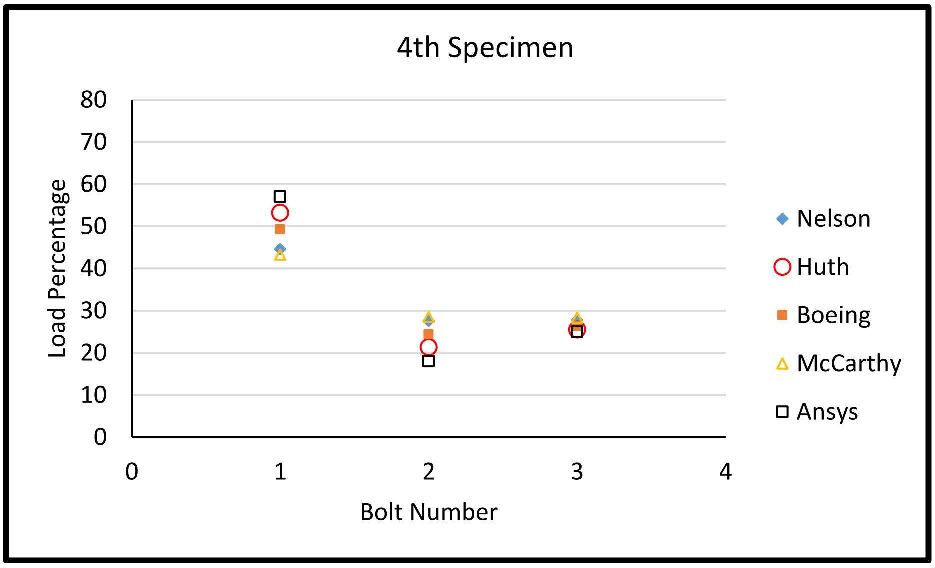

Figure 12. Results for the 4th Specimen (SS_4)

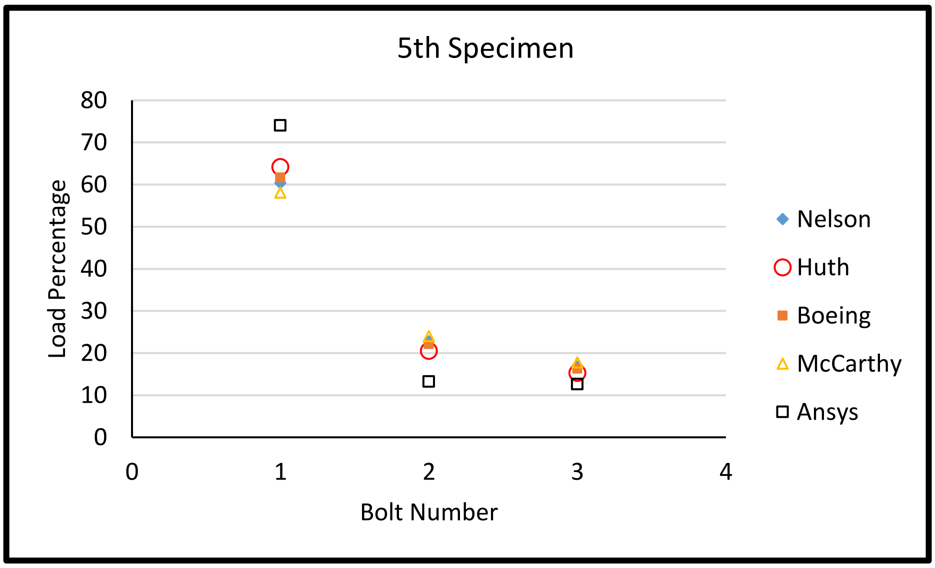

Figure 13. Results for the 5th Specimen (SS_5)

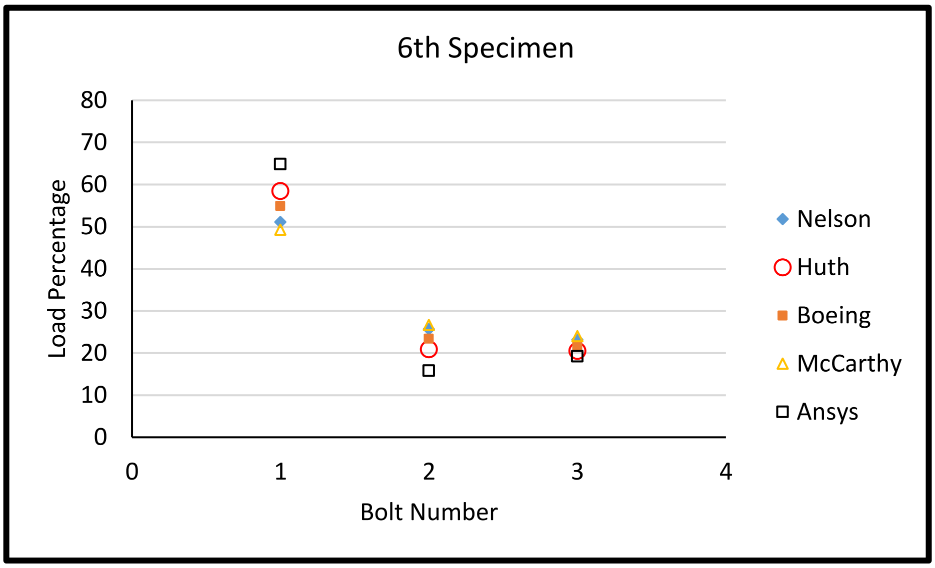

Figure 14. Results for the 6th Specimen (SS_6)

Close examination of the bolt load results given in Tables 7-9 and Figures 9-14 reveals that the following.

- If the stiffness in load direction decreases, the load on the first bolt increases. For the seven specimens (six composite and aluminum) and five calculation methods (Tate and Rosenfeld/Nelson – Huth – Boeing – McCarthy and ANSYS) there are only two cases for which the load on the first bolt did not increase. These two cases are the Nelson and McCarthy calculations for SS_5 and SS_3. In these cases, the load on the first bolt decreased slightly when the stiffness in the load direction decreased. For the SS_1 and SS_2 specimens, significant increase in the load of the first bolt is clearly seen in Figure 9 and Figure 10.
- The load on bolt number two (middle bolt) does not change significantly with respect to the plate stiffness in the load direction. For the seven specimens (six composite and aluminum) and five calculation methods (Tate and Rosenfeld/Nelson – Huth – Boeing – McCarthy and ANSYS), again there are only two cases for which the load on the second bolt changed somewhat substantially. These two cases are the Nelson and McCarthy calculations for SS_3 and SS_2. For these cases, the load on the second bolt changed more than 8% (this is the load change of the second bolt in the calculations made with Nelson and McCarthy methods for SS_3 and SS_2) whereas for all the other cases, the load change is less than 3% for the second bolt.
- For all cases, the load on the third bolt always decreases with the stiffness of the plate in the load direction with no exception.
- Trends in the bolt load versus bolt number plots are in agreement for the hand calculation methods (Tate and Rosenfeld/Nelson – Huth – Boeing – McCarthy) and Ansys FEA results. It is seen that when the major stiffness is in the load application direction such as in SS_1 laminate with all 0^{o} plies or SS_4, Ansys FEA and the Huth method results agree very well. For the third specimen SS_3, load application direction and transverse stiffness values are also equal, and for this specimen again bolt loads, determined by Ansys FEA and Huth methods, are closest to each other. It is concluded that except for specimen SS_2, bolt loads estimated by the Huth method are closest to the bolt loads determined by the 3D FEA. For specimen SS_2, for which the major stiffness direction is the transverse direction, bolt loads estimated by the method of Nelson are closest to the 3D FEA results. Considering that in bolted joints the major

stiffness direction and load application direction are usually the same, it can be concluded that the bolt loads estimated by using the bolt constant determined by the Huth method are the most accurate. For other bolt configurations, it is recommended that similar studies to be performed to determine the most accurate bearing/bearing bypass load calculation methodology.

CONCLUSION

A study to investigate the relation between the laminate stiffness and the load distribution of the bolts in a joint is conducted. Analytical solution utilizing different load calculation methods with different plate stiffness and bolt constant calculation methods and Finite Element Method (FEM) are used for the calculation of bolt bearing and by-pass loads.

All the results show that load carried by the 1st bolt is the highest both for metallic and composite materials. This is due to the geometric effects of the problem. If the thicknesses of the three plates are equal for metallic analysis (same material for straps and plate) the loads of three bolts should be equal to each other.

The results show that load carried by the 1st bolt decreases when the stiffness in load direction is increased. Hence bypass loads for the first bolt increase when the stiffness increases in the load direction.

Also, it seen that the bearing load for the 2nd bolt does not change significantly with respect to the laminate stiffness, and the bearing loads for the 3rd bolt always decreases when the stiffness of the plate decreases.

Finite element results and hand calculation results are very similar for metallic analysis. Particularly, Huth method and Ansys results are nearly the same for metallic analysis. The difference between these two methods is less than 0.5% for bolt#1 and bolt#3 and for bolt#2 the difference is 1.1%. These results show that for metallic joints, Huth method for bolt constant calculation and Tate and Rosenfeld method for bolt load calculation can be used to calculate the loads of individual bolts in the joint.

Finite element analysis and hand calculation results have similar trends for composite plate analysis also. Trends in the bolt load versus bolt number plots are in agreement for the hand calculation methods (Tate and Rosenfeld/Nelson – Huth – Boeing – McCarthy) and Ansys FEA results. It is concluded that except for specimen SS_2, bolt loads estimated by the Huth method are closest to the bolt loads determined by the 3D FEA. Considering that in bolted joints the major stiffness direction and load application direction are usually the same, it can be concluded that the bolt loads estimated by using the bolt constant determined by the Huth method are the most accurate. These results show that, for the defined problem (which has thinner plate than the straps) if the plate stiffness decreases, the load of the first bolt increases, the load of the second bolt does not change significantly and the load of the third bolt decreases.

References

Aktas A., Dirikolu M.H., (2003) The effect of stacking sequence of carbon epoxy composite laminates on pinned-joint strength, Composite Structures, Volume 62, Issue 1, 2003, Pages 107-111,

Ascione F., Feo L., Maceri F., (2010) On the pin-bearing failure load of GFRP bolted laminates: An experimental analysis on the influence of bolt diameter, Composites Part B: Engineering, Volume 41, Issue 6, 2010, Pages 482-490,

Bailie J.A., Ley R.P., Pasricha A. (1997), A summary and review of composite laminate design guidelines. Technical Report NASA, NAS1-19347

Crews J.H., Naik R.A. (1987) Bearing-Bypass Loading on Bolted Composite Joints, NASA Technical Memorandum 89153

Ekh J., Schön J., (2006) Load transfer in multirow, single shear, composite-to-aluminium lap joints, Composites Science and Technology, Volume 66, Issues 7–8, 2006, Pages 875-885,

Feo L., Marra G., Mosallam A.S., (2012) Stress analysis of multi-bolted joints for FRP pultruded composite structures, Composite Structures, Volume 94, Issue 12, 2012, Pages 3769-3780,

Huth H., (1984), Zum Einfluß der Nietnachgiebigkeit mehrriehiger Nietverbindungen auf die Lastübertragungs- und Lebensdauervorhersage, LBF Report No. FB-172, Dissertation, Technische Universität Munchen, Munich, Germany, 1984

Kabeel A.M., Maimí P., González E.V., Gascons N., (2015) Net-tension strength of double-lap joints under bearing-bypass loading conditions using the cohesive zone model, Composite Structures, Volume 119, 2015, Pages 443-451,

Liu F., Lu X., Zhao L., Zhang J., Xu J., Hu N., (2018) Investigation of bolt load redistribution and its effect on failure prediction in double-lap, multi-bolt composite joints, Composite Structures, Volume 202, 2018, Pages 397-405,

McCarthy C.T., Gray P.J., An analytical model for the prediction of load distribution in highly torqued multi-bolt composite joints, Composite Structures, Volume 93, Issue 2, 2011, Pages 287-298,

Nelson W.D., Bunin B.L., Hart-Smith L.J., (1983) Critical Joints in Large Composite Aircraft Structures, NASA Contractor Report 3710

Nettles A.T., (1994) Basic Mechanics of Laminated Composite Plates, Marshall Space Flight Center. NASA Reference Publication No: 1351

Okutan B., (2002), The effects of geometric parameters on the failure strength for pin-loaded multi-directional fiber-glass reinforced epoxy laminate, Composites Part B: Engineering, Volume 33, Issue 8, 2002, Pages 567-578, Pakdil M., (2009) Failure Analysis of composite single bolted-joints subjected to bolt pretension, Indian Journal of Engineering & Material Sciences, Volume 16, 2009, Pages 79-85

Park H.J., (2001) Effects of stacking sequence and clamping force on the bearing strengths of mechanically fastened joints in composite laminates, Composite Structures, Volume 53, Issue 2, 2001, Pages 213-221,

Sen F., Sayman O., Ozcan R., Siyahkoc R., (2009), Failure response of single bolted composite joints under various preload, Indian Journal of Engineering & Material Sciences, Volume 17, 2010, Pages 39-48

Sharos, P.A. (2016) Efficient Load Distribution Analysis and Strength Prediction of Bolted Composite Joints at Various Loading Rates, PhD Thesis, University of Limerick

Soderberg J., (2012) A finite element method for calculating load distributions in bolted joint assemblies, MSc. Thesis, Linköping University

Tate M.B and Rosenfeld S.J. (1946), Preliminary Investigation of the Loads Carried by Individual Bolts in Bolted Joints, NASA Technical Note 1051

Whitman Z.L., (2012), The Effect of Fatigue Cracks on Fastener Flexibility, Load Distribution and Fatigue Crack Growth, PhD Thesis, The University of Utah