Parametric Study of Single Bolted Composite Bolted Joint Subjected to Static Tensile Loading

L.V. Awadhani
Research Scholar ZCOER Narhe, Associate Professor PCCOE, SPU
Dr. Anand Bewoor
Professor, CCOEW, Pune

Abstract: The use of composites is increasing in the engineering applications in order to reduce the weight, building energy efficient systems, designing a suitable material according to the requirements of the application. But at the same time, building a structure is possible only by bonding or bolting or combination of them. There are limitations for the bonding methods and problems with the bolting such as stress concentration near the neighborhood of the bolt hole, tensile or shear failure, delamination etc. Hence the design of a composite bolted structure needs a special attention. This paper focuses on the performance of the composite bolted joint under static tensile loading and the effect of variation in the parameters such as the bolt pitch, plate width, thickness, bolt tightening torque, composite material, coefficient of friction between the bolt and plate etc. A simple spring mass model is used to study the single bolted composite bolted joint.

The influencing parameters are identified through the developed model and compared with the results from the literature. The best geometric parameters for the applied load are identified for the composite bolted joints.

Keywords: Bolt hole clearance, single lap, single bolted joint behavior, Secondary bending, Spring mass model.

1. INTRODUCTION

Use of the advance composites is increasing day by day in structural applications. The main benefit of using composite materials in structural applications is its high strength to weight ratio and high stiffness to weight ratio. Hence it is important to know the behavior of the advanced composites to the applied load [5]. Bolted joints have a major contribution to the static and dynamic performance of the assembled structures; hence it is important to design the joint with caution [3]. The bolted joint subjected to tensile load may exhibit the failure modes such as bearing, net tension, shear, cleavage. The secondary bending influences various macroscopic failure modes and hence may initiate a different failure mode and affect the failure load [4]. The secondary bending increases the bending of the plates and generates severe net tension stresses. The main objective of this paper is the identification of significant parameters of the secondary bending influencing the joint stiffness of the single lap, single bolted composite bolted joint. The spring based model was developed by Nelson for the analysis of the composite bolted joint with neat fit. McCarthy et al [2] have applied it to a single column multi bolt composite bolted
joint with an extension to it to analyze the effect of bolt hole clearances in a multi bolt composite bolted joint. Olmedo et al [1] included the friction, clearance effects and extended the use of the spring model for the prediction of secondary bending in case of a single lap single bolted joint. The inclusion of flexural elastic modulus using the classical laminate theory made the prediction more reliable. In this work, implementation of the spring mass model introduced by Olmedo et al [1] has been done.

2. SPRING MASS MODEL

A single lap single bolted composite bolted joint was modeled by Olmedo et al [1] considering the effect of the friction, clearance in bolt hole, the torque applied for tightening, secondary bending etc. According to his hypothesis, the load displacement curve of a single lap, single bolted composite bolted joint (shown in Fig. 2), is split in three parts, in the first region, the applied force is utilized to overcome friction between the bolt and the plates, in the second region the clearance in the hole is taken and in the third region, the actual load sharing of the joint starts. The third region includes the tensile shear load bearing and secondary bending also. The model is described below.

The single lap single bolted composite bolted joint is shown in Fig. 1. This joint is replaced by the springs and masses as shown in Fig 3. The load is applied at mass 3 and reacted at the clamped end of the joint. The stiffness of composite plate 1 under tensile loads is represented by $K_{pl1}$, and composite plate 2 by $K_{pl2}$. During the first region, the joint stiffness is dominated by the upper branch, where $K_{sh-pl1}$ and $K_{sh-pl2}$ is the stiffness under shear load of composite plates 1 and 2 respectively. If the value of the load in upper branch reaches the maximum value of the

![Figure 1 Single lap Single bolted joint][2](image)

![Figure 2 Load Displacement diagram for single bolted composite bolted joint][1](image)

![Figure 3: Spring mass model of single lap single bolted joint][1](image)
friction forces that the joint can transmit, a relative displacement between laminates is produced without increasing loads until the clearance is taken up. This phenomenon is represented by a friction element, $F_{\text{fric}}$. When the contact between bolt shank and laminates is established, the joint stiffness is controlled by the bottom branch, where $K_{\text{bolt}}$ includes the shear and bending stiffness of the bolt, the bearing stiffness of composite plates, and the secondary bending effect.

Considering that masses are free to move in the x-direction only, the system shown in Fig. 3 leads to a system of linear equations of the form:

$$[M] \ddot{\{x\}} + [K] \{x\} = \{F\}$$

For quasi static loading neglecting acceleration; $$[K] \{x\} = \{F\}$$

Free body diagrams for each mass during the first and third regions are shown in Figs. 4 and 5 respectively. Where $c$ is the clearance between bolt diameter and hole, and $u_f$ is the maximum displacement reached during the first region. The resulting linear equations during first and second regions are expressed in Equations (1) and (2) respectively. Calculation of the displacements is straightforward by pre-multiplying the load vector $F$ by the inverse of stiffness matrix $K$.

Combining equations (1) and (2), as the springs representing plate stiffness and bolt spring are in series.
\[
\begin{pmatrix}
(K_{pl1} + K_{bol1} + K_{shear}) & (-K_{bol1} - K_{shear}) & 0 \\
(-K_{bol1} - K_{shear}) & (K_{bol1} + K_{bol2} + K_{pl2}) & -2K_{pl2} \\
0 & -2K_{pl2} & 2K_{pl2}
\end{pmatrix}
\begin{pmatrix}
 x_1 \\
x_2 \\
x_3
\end{pmatrix}
= \begin{pmatrix}
(-K_{bol1}c - K_{bol1}u_f + F_{frict}) \\
(K_{bol1}c - K_{bol1}u_f + F_{frict}) \\
2F
\end{pmatrix}
\]

Equation (3) is solved using the various stiffness values as given below

### 3. Calculations of Various Stiffness Values

#### 3.1 Plate Stiffness:
The composite plate stiffness, in each plate i, can be found considering a composite laminate subjected to uniform tensile load:

\[
K_{pli} = \frac{E_{lc}W_{ci}t_{ci}}{p_c - D/2}
\]

Where, \(E_{lc}\) is the equivalent elasticity modulus in longitudinal direction calculated using the laminate theory. \(W_c\) and \(t_c\) are width and thickness of the composite plate respectively. \(p_c\) is the distance between the hole centre and the plate free end where load is applied, and D is the hole diameter.

#### 3.2 Shear Stiffness:
The shear stiffness \(K_{shear}\) is found as the shear stiffnesses of the two composite plates in series.

\[
K_{shear} = \left[ \frac{1}{K_{sh-pl1}} + \frac{1}{K_{sh-pl2}} \right]^{-1}
\]

Where, the stiffnesses under shear load of composite plates 1 and 2, \(K_{sh-pl1}\) and \(K_{sh-pl2}\), are found considering the inter-laminar stiffness of the laminate \(G_{xz}\), the washer area in contact with the composite plate \(A_{wpli}\), and the plate thickness \(t_{ci}\).

\[
K_{sh-pli} = \frac{A_{wpli}G_{xz}}{t_{ci}}
\]

#### 3.3 Bolt Stiffness:

\[
K_{bol-b} = \frac{3G_bA_b}{2(t_{c1} + t_{c2})}; \quad K_{bolend-b} = \frac{E_b(t_{c1}t_{c2})}{2(t_{c1} + t_{c2})}; \quad K_{bol-pl1} = t_{c1}\sqrt{E_{lec1}E_{fc1}}; \quad K_{bol-pl2} = t_{c2}\sqrt{E_{lec2}E_{fc2}}
\]

Where, \(G_b\) is the bolt shear modulus, and \(A_b\) the bolt transverse section area, \(E_b\) is the bolt Young modulus, \(E_{lec}\) is the equivalent elasticity modulus of composite plate in transverse direction calculated using the classical laminate theory.

\[
K_{bol} = \frac{2L_{epli}^2E_{Fc1}^2I_{c1}^2 + 2L_{epli}I_{epli}^2E_{Fc1}E_{Fc2}I_{c1}I_{c2}(2L_{epli}^2 + 3L_{epli}I_{epli}^2 + 2L_{epli}^2) + L_{epli}E_{Fc2}^2I_{c2}^2}{t_{c1}t_{m}L_{epli}^2I_{epli}^2(t_{c1}E_{Fc1}I_{c1} + L_{epli}E_{Fc2}I_{c2})}
\]
\[ K_{\phi 2} = \frac{2L_{z_{1}z_{2}}E_{z_{1}z_{2}}I_{z_{1}}}{t_{z_{2}}I_{z_{2}} + 2L_{z_{1}z_{2}}E_{z_{1}z_{2}}I_{z_{1}} + \left(2L_{z_{1}z_{2}}E_{z_{1}z_{2}}I_{z_{1}} + 3L_{z_{1}z_{2}}E_{z_{1}z_{2}}I_{z_{1}} + 2L_{z_{1}z_{2}}E_{z_{1}z_{2}}I_{z_{1}}\right)} \]

\[ K_{\text{bolt}} = \left[ \frac{1}{K_{s-h-b}} + \frac{1}{K_{\text{bend}-b}} + \frac{1}{K_{\text{bend}-\text{pl}1}} + \frac{1}{K_{\phi l}} + \frac{1}{K_{\text{bend}-\text{pl}2}} + \frac{1}{K_{\phi 2}} \right]^{-1} \]

The data used for the determination of stiffnesses is given in Table I.

| Various Parameters of the model                  |       |
|------------------------------------------------|-------|
| Diameter of bolt \( d \)                        | 4.8 mm|
| Pitch of the bolt \( p \)                       | 30 mm |
| Width of the plate \( w \)                      | 30 mm |
| Length of plate                                 | 140 mm|
| Bolt hole clearance                             | 0 to 200 microns |
| Bolt tightening Torque                          | 1 Nm to 8 Nm  |
| Thickness of composite plates                   | 3 mm  |
| Modulus of Elasticity of Bolt \( E_B \)        | 110 GPa|
| Shear Modulus for bolt                          | 44 GPa|
| Shear Modulus for composite plate               | 4.14 GPa|
| Transverse and Longitudinal Modulus of Elasticity of Skin plate | 8.27 and 38.6 GPa |
| Coefficient of friction                         | 0.1   |

4. Results and Discussions

The equation (3) is solved using a MATLAB code which gives the load displacement relationships. The model is validated with the published result [1]. It can be seen that the slope of the load displacement curve i.e. stiffness of the joint in fig 6 (a) is 10169.49 N/mm while in the fig 6 (b) it is 10344.82 N/mm. The region I and II shown in fig 6 (a) are not seen in fig. 6 (b). The use of these diagrams is to be done for the determination of joint stiffness. A good correlation is seen between the two load displacement curves in terms of joint stiffness. Hence it can be said that the spring mass model solved here is validated.
The parametric study based on the validated model is carried out where effect of various parameters in the model is determined using MATLAB code. The parameters such as Material, Tightening torque, coefficient of friction, Length, Width, Bolt hole clearance and bolt diameter were varied and the effect of variations is studied. The effect is represented in Fig. 7 to Fig. 13.

Effect of variation in bolt hole clearance is represented in Fig. 7. It is seen that the load take up by the joint is delayed with increase in the clearance. The torque applied for bolt tightening which in turn decides the frictional force used in equation (3) has no significant effect on the joint stiffness.
Moreover, it is seen from Fig. 9 that variation of coefficient of friction is not affecting the joint stiffness. While the length of the composite plate and distances of the bolt hole are the significant parameters which varies the joint stiffness. The joint stiffness decreases with increase in the length of plate is seen in Fig. 10. The joint stiffness reduces as the diameter of bolt increases is evident from Fig. 12. Also the joint stiffness increases with increase in the width of the composite plate is seen from Fig. 11. The effect of changing the composite material is represented in Fig. 13. It is evident that the carbon/ Epoxy and Boron/ Epoxy composites have highest joint stiffness and the Glass/ Epoxy polymer composite has the minimum joint stiffness in the material group studied.

Figure 9: Effect of variation of Coefficient of friction
Figure 10: Effect of variation in Length of plate

Figure 11: Effect of Varying plate width.
Figure 12: Effect of varying bolt diameter.
5 CONCLUSION

A spring mass model introduced by Olmedo et al has been implemented in this work and parametric study is carried out on the model. This study revealed that the spring mass model is predicting the performance of the joint in the second and third region of the load displacement curve, while the prediction in the first region the effect of the friction has not been reflecting in comparison with Fig. 6 (a).

With this model the significant parameters of the joint stiffness were identified such as length and width of the plate, bolt diameter and the composite material. Non-significant parameters include the coefficient of friction and the tightening torque applied on the bolt. This work will be useful for the parametric optimization of the single lap single bolted composite bolted joints.

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Name: L. V. Awadhani  
Designation: Assistant Professor at PCCOE and Research Scholar at ZCOER  
Qualification: M. Tech. (Design)  
Area of Interest: Design Engineering, Composite Structures
Email Id: laxman.awadhani@pccoepune.org
Name: Dr. Anand Bewoor
Designation: Professor at CCOEW, Pune
Qualification: PhD Mech. Engineering
Area of Interest: Quality Engineering, Operations Engineering, Optimization.
Email Id: anand.bewoor@cumminscollege.in