A USER-DEFINED FINITE ELEMENT TO MODEL THE RESPONSE OF COMPOSITE BOLTED JOINTS UNDER STATIC LOADS

P. A. Sharos[1], C. T. McCarthy[1*]

[1]*Material and Surface Science Institute, Department of Mechanical, Aeronautical and Biomedical Engineering, University of Limerick, Limerick, Ireland*
**Conor.McCarthy@ul.ie*

Keywords: Bolted joints; efficient numerical analysis; analytical model; finite element analysis.

Abstract

A highly efficient user-defined finite element for modelling the response of composite bolted joints was developed. The element is a result of a combined analytical/numerical approach and is capable of representing the full non-linear load displacement behaviour of the joint up to and including failure. The elastic response of the joint is a closed-form extension of a spring-based method where the bolts and laminates are represented by a series of springs and masses. A semi-empirical approach is used to model failure initiation and energy absorption in the joint and this has been successfully applied in models of single-bolt single-lap joints. A series of tapered and non-tapered, single-bolt, single-lap joints were tested with various layup orientations. These joints were modelled using the user-defined finite element and yielded excellent correlation with the experimental results.

1 Introduction

Significant weight savings can be realised in composite aircraft structures in the region of bolted joints; however this relies on the ability to carry out design studies quickly and cheaply. To carry out a detailed finite element analysis of a composite bolted joint is computationally demanding. A method has been developed to retain the accuracy of the detailed model without a significant time penalty. The theory behind this model originates from Tate and Rosenfeld [1] who developed an analytical method of determining loads carried by individual bolts in symmetrical aluminium butt joints. This was later developed by Nelson et al. [2] for use in modelling single and double composite lap joints. McCarthy et al. [3] advanced Nelson’s model by including the effects of bolt-hole clearance. Finally McCarthy and Gray [4] accounted for the effects of bolt torque and friction between laminates. The finite element discussed in this paper implements the McCarthy-Gray model in ABAQUS commercial software through the use of its user element subroutine function.

The method used in this paper utilises a user-defined finite element to represent the bolt and joint foundation (i.e. the material in the vicinity of the bolt-hole) accurately. The user-defined element accounts for friction effects, bolt-hole clearance, and the contribution of the bolt to the stiffness of the joint. This eliminates the need to implement complex friction and contact algorithms to model the interaction between the bolt and the hole [4]. Further increases in model efficiency are obtained through the use of shell finite elements to represent the composite laminates. This technique yields a mesh-independent method for modelling the response of composite bolted joints under static loads. However, in order to model joint failure accurately, it is required to calibrate the user-defined finite element using experimental data or a detailed 3D finite element model.

2 Experimental Procedures

Results from an experimental test series carried out on single-lap, single-bolt joints were compared to those obtained from the user-defined element model. This was to demonstrate the model's ability to represent the joint region for tapered and non-tapered specimens. In total, four joint configurations were compared, two tapered and two non-tapered. A summary of tests carried out as well as the composite layups used are given in Tables 1 and 2 respectively.

Test Name	Lay-up	Taper	t (mm)
SB_E	E	No	3.125
SB_C	C	No	2.125
SB_T_{TA-C}	A-C	A to C	1.625-2.125
SB_T_{C-E}	C-E	C to E	2.125-3.125

Table 1. Summary of validation experiments for user-defined element

Name	Lay-up	Plies	t (mm)
A	+45/90/-45/0/0/-45/90/+45/0/0/-45/90/+45	13	1.625
C	+45/90/-45/0/0/0/-45/0/90/0/+45/0/0/0/-45/90/+45	17	2.125
E	+45/90/-45/0/0/0/+45/-45/0/0/0/+45/90/-45/0/0/0/-45/+45/0/0/0/-45/90/+45	25	3.125

Table 2. Composite Layups Tested

The geometry of the specimens tested is illustrated in Figure 1. All joints were manufactured from a proprietary composite material and therefore the results presented in this paper are normalised. Joints were fastened using titanium Hi-Lite countersunk bolts and the test procedure followed the guidelines given in ASTM standard D5961/D5961M-08 [5]. For both of the tapered specimens tested, the taper angle obeys a ply drop-off ratio of 1:20 in the loading direction.

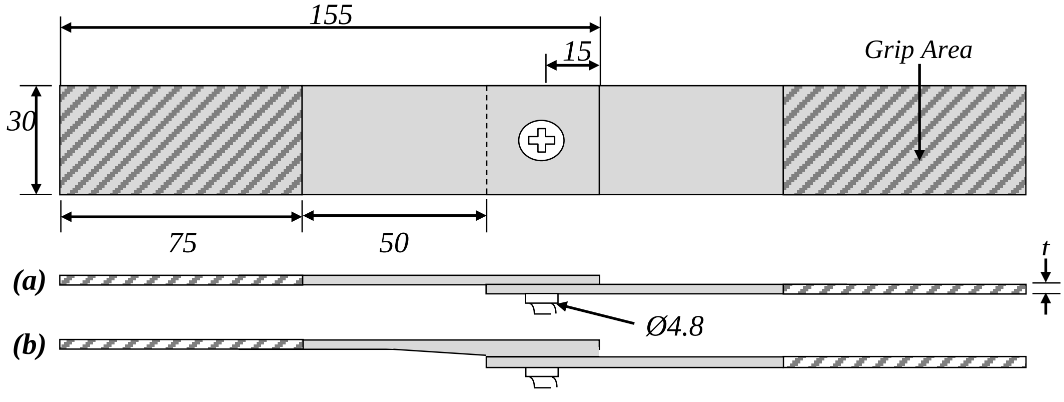


Figure 1. Single-lap, single-bolt specimen joint geometry with side-views: **(a)** laminate without taper; **(b)** laminate with taper

A Zwick 100kN universal hydraulic testing machine was used to conduct all tests. Each was carried out at a rate of 0.03mm/s and a minimum of three repeats were carried out for each joint layup. Load cell and machine stroke readings were taken for comparison with the user-defined element model.

2 Methodology

To improve the efficiency of the finite element analysis, the characteristic load-displacement curve of the single-bolt joint is predetermined using an analytical model. In the elastic range, the response of the joint is represented by a series of masses and springs where effects such as bolt-hole clearance and friction between laminates are taken into consideration. Figure 2 shows an illustration of the analytical model as well as a generalised load-displacement curve for single-lap single-bolt joints. It should be noted that the springs shown in Figure 2 have stiffness values in the *x* direction only. This spring-mass model is capable of accurately representing the joint response up to the onset of damage.

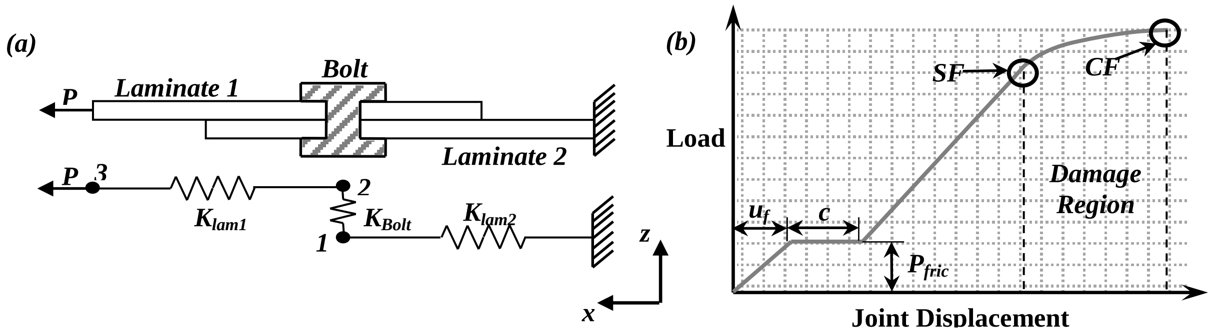


Figure 2. Single-lap single-bolt joint**:** **(a)** illustration of joint and equivalent mass-spring model; **(b)** generalised load displacement curve to failure

Upon analysing the free body diagrams of masses 1, 2 and 3 (shown in Figure 3) it can be seen that when dynamic effects are ignored the equations of motion for the system can be assembled as follows:

$$\begin{bmatrix} (K_{lam2}+K_{Bolt}) & -K_{Bolt} & 0 \\ K_{Bolt} & (K_{lam1}+K_{Bolt}) & -K_{lam1} \\ 0 & -K_{lam1} & K_{lam1} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} = \begin{Bmatrix} P_{fric}-K_{Bolt}(c+u_f) \\ -P_{fric}+K_{Bolt}(c+u_f) \\ P \end{Bmatrix} \qquad (1)$$

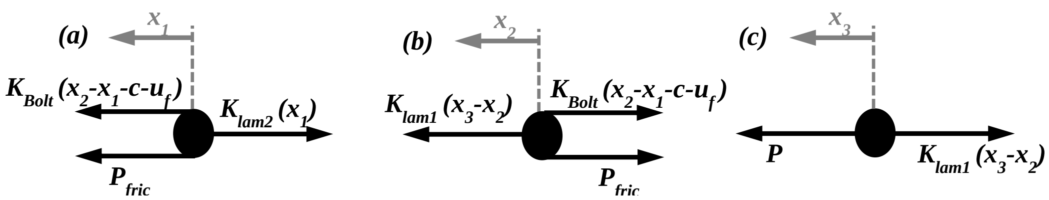


Figure 3. Free Body Diagrams of **(a)** Mass 1, **(b)** Mass 2 and **(c)** Mass, 3when dynamic effects are ignored

Where c is the bolt-hole clearance, P_{fric} and u_f are maximum load and associated displacement due to static friction and K_{lam1}, K_{lam2} and K_{Bolt} are the stiffness values of laminate 1, laminate 2 and the bolt region, respectively. The stiffness of laminate can be determined by equation 2 where *w* and *t* are the width and thickness of the laminate, *d* is the diameter of the bolt-hole and E_{xx} is the elastic modulus in the *x* direction.

$$K_{lam1}=\left(\frac{E_{xx}wt}{e\text{-}d}\right)_{lam1} \tag{2}$$

Nelson et al. [2] showed that the stiffness of the bolt can be determined by equation 3. The β term represents the fraction of the bending moment that is reacted by the bolt head. This is approximately 0.5 for countersunk fasteners.

$$\frac{1}{K_{Bolt}}=\frac{2(t_{lam2}+t_{lam1})}{3G_{Bolt}A_{Bolt}}+\left[\frac{2(t_{lam2}+t_{lam1})}{t_{lam2}t_{lam1}E_{Bolt}}+\frac{1}{t_{lam2}\left(\sqrt{E_{xx}E_{yy}}\right)_{lam2}}+\frac{1}{t_{lam1}\left(\sqrt{E_{xx}E_{yy}}\right)_{lam1}}\right][1+3\beta] \tag{3}$$

There is no need to take the change in stiffness of the laminate due to taper into consideration at the level of the analytical model. This is because the user-defined element is implemented only to represent the bolt region - the laminates are modelled separately as shell elements. Although it is possible to model shells with varying thickness and material properties, it was found to sufficient assume to that the properties of the taper section were the average of the adjacent composite layups.

Based on the spring model illustrated in Figure 2, a modification was made to account for the change in stiffness of the laminate due to taper in the analytical model. This is illustrated in Figure 4 (a). Two additional spring terms were added to the model representing the stiffness of the taper and the thinner layup region. The spring stiffness, K_{lam1}, in Figure 2 is now the equivalent spring taking K_{layup1}, K_{Taper}, and K_{layup2} as springs in series.

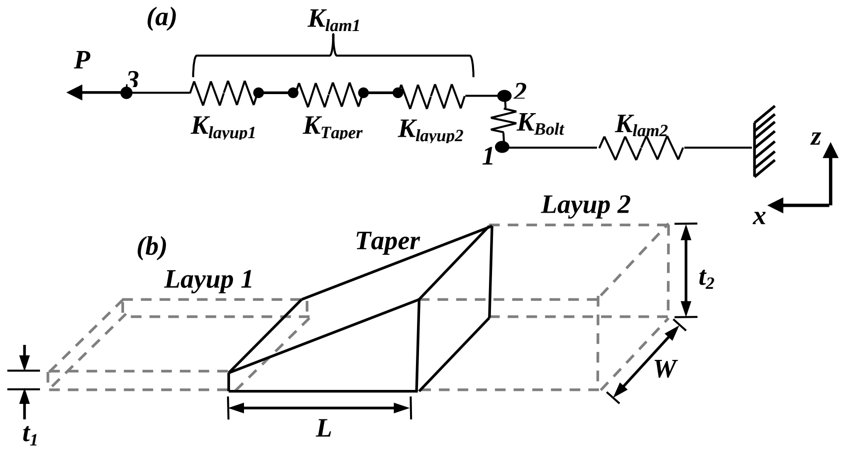


Figure 4. Single Lap, single-bolt joint with taper considerations**: (a)** equivalent mass-spring model; **(b)** illustration of tapered laminate

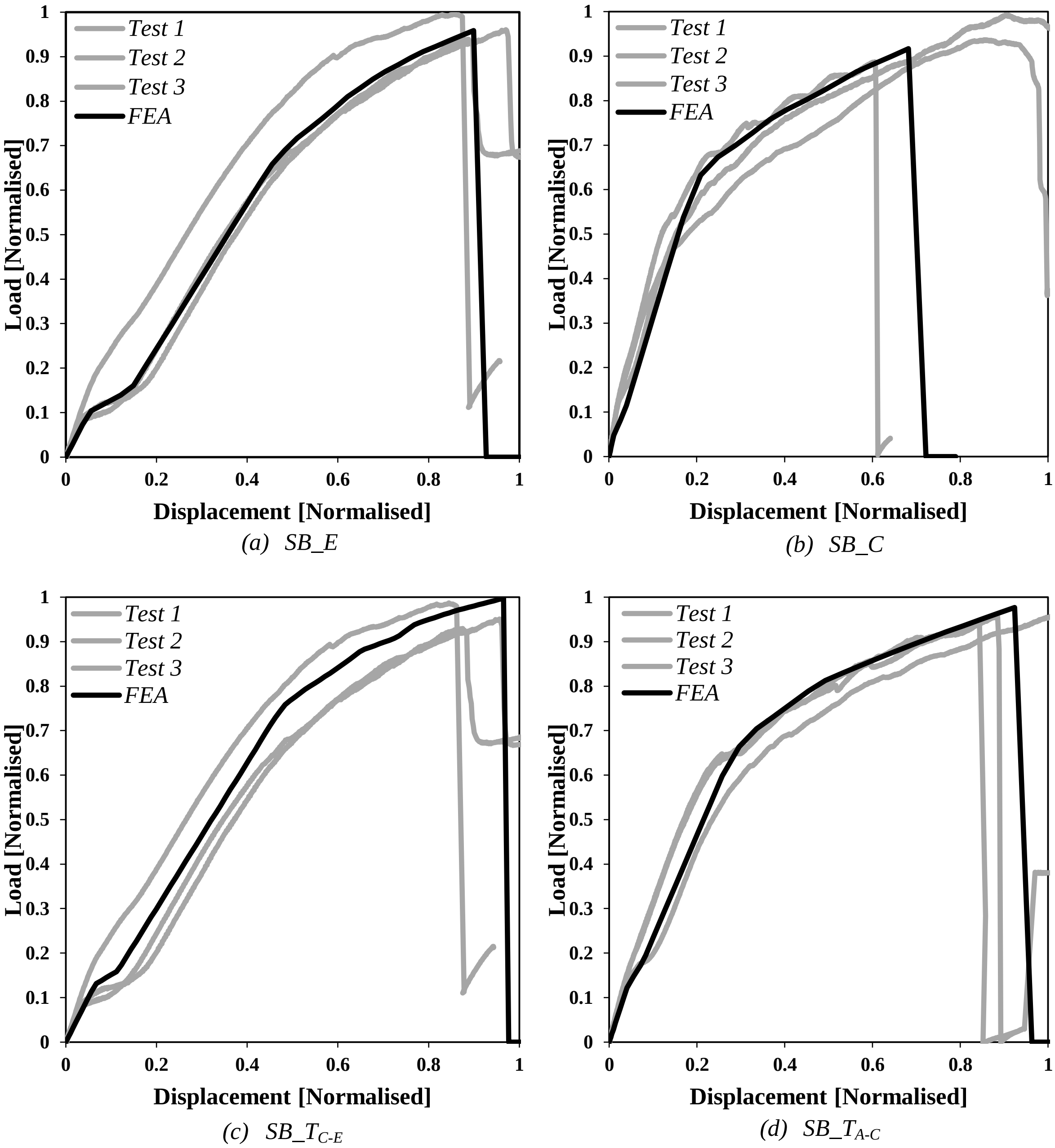
From strain energy considerations and assuming a rectangular cross-section for the tapered section it can be shown that:

$$K_{Taper}=\frac{EW(t_2\text{-}t_1)}{L\ln\left(\frac{t_1}{t_2}\right)} \tag{4}$$

To approximate the damage region of the load-displacement curve accurately a control case (either an experiment or a detailed finite element model) is required to evaluate the forces and displacements for the first significant (SF) and catastrophic failure (CF). A cubic spline method [6] is then used to determine the load-displacement curve for the damage region.

4. Results and Discussion

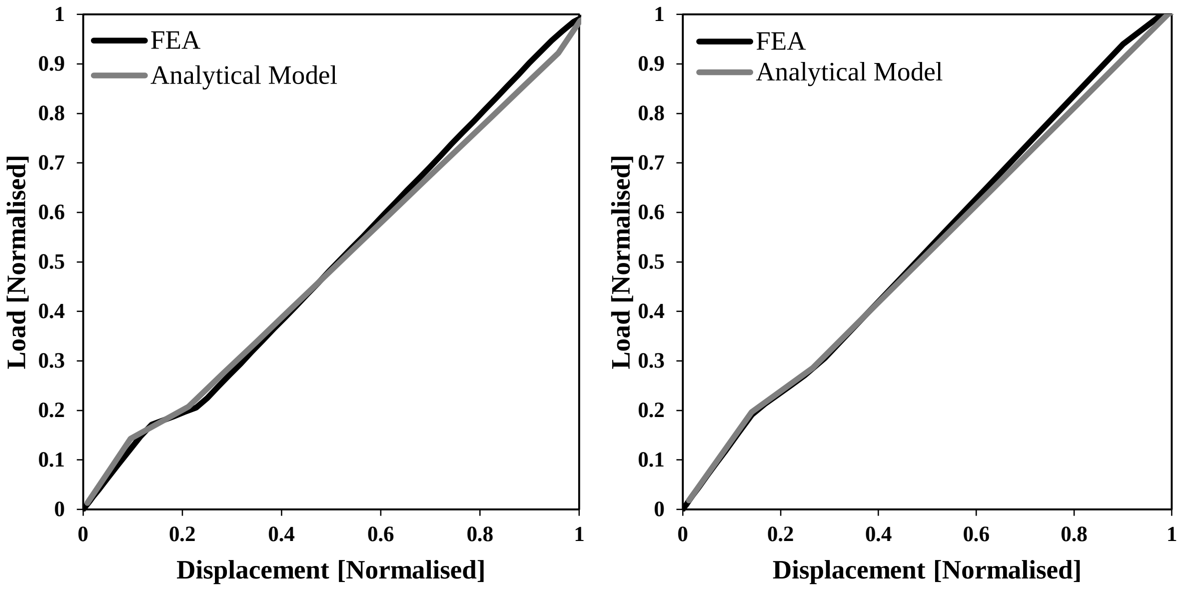
The following plots compare the results obtained from the finite element model using the user-defined element and those from the experiments carried out. The results were normalised with respect to the maximum load and displacement seen for the particular joint configuration. Plots (a) and (b) in Figure 5 compare the force-displacement curves for the non-tapered joints while plots (c) and (d) show the loading curves for the tapered joints. In both cases an extremely good correlation between the user-element and experimental data is observed, namely the force and displacement to failure and the stiffness of the joint in the elastic region.



(a) SB_E *(b) SB_C* *(c) SB_T_{C-E}* *(d) SB_T_{A-C}*

Figure 5. Characteristic loading curves for single lap, single-bolt tests

A further study was carried out to compare the modification that was made to the analytical model for tapered laminates. Only the elastic range of the joint was compared up to the onset of the first failure. It should be noted that in the finite element model, the change in stiffness of the laminate due to taper is accounted for not in the user-defined element but in the modelling of the laminates themselves (i.e. the shell elements). However in the modified analytical model the effect of taper is accounted for through additional spring elements defining the laminate stiffness. However, as can be seen in Figure 6 there is a very good correlation between the finite element and the analytical model for both tapered joint configurations.



(a) SB_T_{C-E} *(b) SB_T_{A-C}*

Figure 6. Comparison of user-element and analytical model in elastic region for tapered laminates

5. Conclusion

A user-defined element was developed to represent the bolt and joint foundation for the purpose of increased computational efficiency when analysing composite bolted lap joints. From the correlation observed between the finite element model and the experiments it is clear that the user-defined element is suitable for modelling single-bolt, single-lap joints with both tapered and non-tapered laminates.

Acknowledgements

This work was funded by the Irish Research Council for Science, Engineering and Technology.

References

[1] Tate M.B., Rosenfeld S.J. Preliminary investigation of the loads carried by individual bolts in bolted joints. *NACA* TN 1051, (1946).

[2] Nelson W.D., Bunin B.L., Hart-Smith L.J. Critical joints in large composite aircraft structures. *NASA CR-3710*, (1983).

[3] McCarthy M.A., McCarthy C.T., Padhi G.S. A simple method for determining the effects of bolt-hole clearance on load distribution in single-column multi-bolt composite joints. *Composite Structures*, **73(1)**, pp. 78-87 (2006).

[4] McCarthy C.T., Gray P.J. An analytical model for the prediction of load distribution in highly torqued multi-bolt composite joints. *Composite Structures*, **92(2)**, pp. 287-298 (2011).

[5] ASTM D5961/D5961M-08. *Standard test method for the bearing response of polymer matrix composite laminates* (2008).

[6] McCarthy C.T, O'Higgins, R.M. and Frizzell, R.M. A cubic spline implementation of non-linear shear behavior in three-dimensional progressive damage models for composite laminates. *Composite Structures*, **92(1)**, pp. 173-181 (2010).