Strength Prediction of Double-Lap Woven CFRP Bolted Joint Incorporating Material Softening

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Abstract. Strength prediction is discussed using a traction-separation damage model incorporating material softening for bolted joint that fails in bearing mode. The modelling approach in the bolted double-lap joint of current work is a simplistic approach to predict the strength of bearing failures. This is clearly shown in bearing failure which occurred experimentally at higher W/d ratios. A simple method for degrading material properties in the region of bearing failure was investigated and, from a preliminary study, was found to be promising. This approach is easily-implemented, and has been shown to be applicable to woven fabric composite materials in double-lap bolted joint.

Introduction

Composite materials offer a flexibility in processing, which often leads to a reduction in part count compared to conventional materials. Even so, many structures require joining, either though mechanical fastening or adhesive bonding. Mechanically fastened joints are preferred and widely used due to their effectiveness in transferring high loads, the simplicity of preparation, the ease of disassembly for routine inspection and their insensitivity to environmental conditions. The major challenge with mechanically fastened joints is that the introduction of a hole to a composite plate leads to a stress concentration, which cannot be relieved by plastic flow in the way that is possible in a metallic material. Hence there is a significant reduction in strength as a result of the stress concentration introduced by any hole or cut-out. Moreover the way in which damage develops in the composite in the presence of a stress-raiser is complex and currently there is a lack of design tools to enable engineers to predict reliably the strength of open-hole or mechanically fastened composites.

Three distinct failure modes can occur in composite bolted joints as shown in Fig. 1. Net-tension failures are given by sudden crack propagations to failure due to relatively small area of sample cross-section. Shear-out failure occurs in small end-distance to hole centre or in highly orthotropic laminates such as cross-ply lay-up. Bearing failure is given as compressive failure close to contact region at the hole edge, exhibiting more ductile failure behaviour. Failures may also exist due to secondary failure modes, such as mixed net-tension and shear-out failure known as cleavage failure.
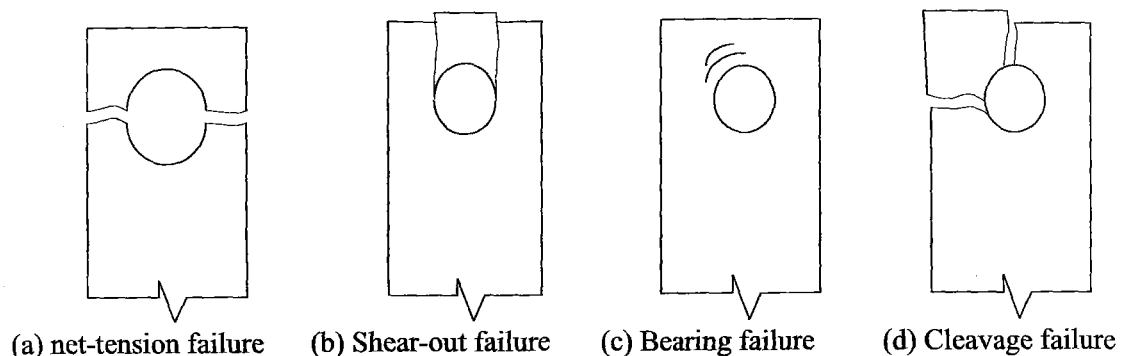

(a) net-tension failure   (b) Shear-out failure   (c) Bearing failure   (d) Cleavage failure

Fig. 1: Failure modes in mechanically fastened composite joints

Early experimental work with woven system such as Okutan *et. al.* [1], Aktas and Dirikolu [2] and Karakuzu *et. al.* [3] has considered pin joint (not clamped) looking at how strength and failure modes relate with geometrical parameters such as hole diameter, d, laminate thickness, t, width, W, and edge distance, e. Due to low bearing compressive strength of woven system compared to non-woven counterparts, critical W/d is increased and dependent on woven system investigated. The effect of stacking sequence on bearing strengths in woven fabric systems has been investigated by Ujjin *et. al.* [4] and Aktas *et. al.* [5]. The geometry of the bolted joint problem, which is used in further discussion, is given in Fig. 2.
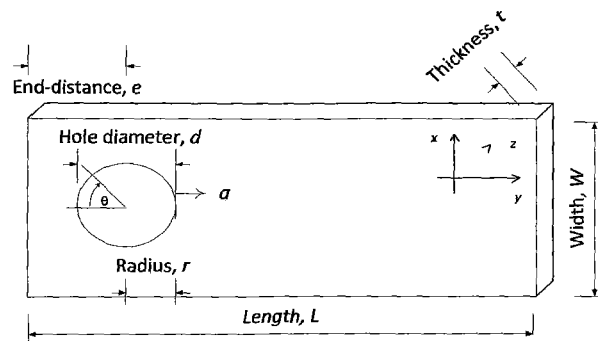

Fig. 2: Geometry dimension used in bolted joint problems

Eriksson [6] used a two-dimensional finite element model to apply the point stress criterion to predict tension failure. It was assumed that failure initiation occurred at points on the hole boundary where fibres are either tangential or normal to the boundary. . The concept of a characteristic curve together with the Yamada-Sun [7] failure criterion was used to predict bearing failure which was strongly dependent on lay-up. As the tension failure generally occurred in one defined plane, the points where the characteristic distances were determined could have been limited. No comparison with experimental results was made.

Hollmann [8] works with an improved damage zone model (DZM) that was initially used for notched strength prediction by Arronsson and Backlund [9], to model the failure of graphite/epoxy bolted joint composite. The PDM models predict the lamina strength and material degradation without considering the lamina interaction effects and dissipated fracture energy. However, Hollmann [8] determined the fracture energy by calibration of data from previous researchers associated with extreme temperature normalised to room temperature. Since the work of Hollmann [8], there does not appear to have been any further studies simulating crack growth in bolted joints using the Cohesive Zone Model (CZM) approach.

More recent work by Campilho *et. al.* [10] studied the fracture characterization of adhesive joints in opening mode using XFEM. He used a traction-separation relationship which is commonly used in CZM in his XFEM model. However, due to mixed mode propagation in adhesive joints, XFEM fracture prediction is unfeasible as current ABAQUS limitation only allows a single value of maximum strength for damage initiation. The developments of XFEM give new possibilities in using traction-separation relationship which is already widely used in CZM.

Finite Element Modelling

The joint is modelled within a three–dimensional FE framework using ABAQUS CAE Version 6.10 [11]. The composite plate is sandwiched between two steel plates and fastened with a single steel bolt as shown in Fig. 3. The hole diameter was 5 mm and the plate thickness was 2.08 mm. A typical mesh of the joint model is shown schematically in Fig. 4. Symmetry in the y-direction was used in all cases for computational efficiency. The meshes are refined in the vicinity of hole edge, while away from the hole the mesh can be made coarser [mesh sensitivity studies were carried out to ensure that the strength predictions reported later were not mesh-dependent]. 8-node linear brick elements [C3D8 in

ABAQUS CAE] were used because these elements are compatible with the XFEM-based failure model that was used. A perfect fit between the bolt and the hole is assumed. Master-slave interactions are applied between regions in contact. In double-lap bolted joint model, a total of eleven master-slave interactions are assigned between corresponding contact faces. Friction was incorporated between regions in contact, assuming a co-efficient of friction of 0.1 for steel-steel (plate-fastener) and 0.3 between steel plate and composite plate; these values are similar to those used by other researchers, e.g. [12]. Implementation of XFEM approach is similar to open hole problem [13] and double-lap bolted joint failed in net-tension [14].
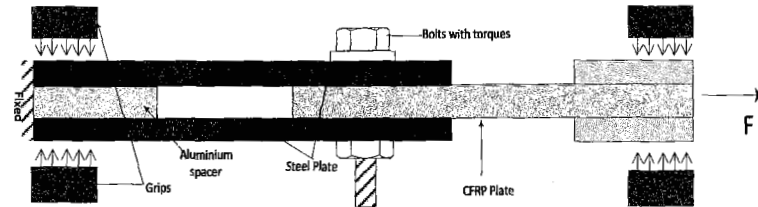

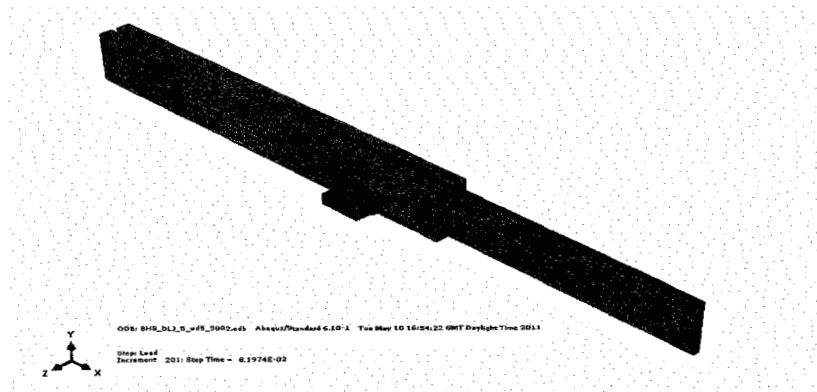**Fig. 3: Double-lap bolted joint configurations**

Fig. 4: FEA model of double-lap bolted joint implemented in ABAQUS CAE.

The CFRP plain weave (PQ8) had been characterised previously by Ahmad *et al.* [13]. The fiber was Toray T300 high strength carbon fibres and were manufactured from Primco Prepregs with a layer thickness of about 0.2 mm. while the matrix was an epoxy resin system, Vantico MY750. CFRP woven fabric systems were fabricated by St. Bernard Composites Ltd. The volume fraction was 45%, determined using the burn-off technique and average thickness of 2.03 mm. Experimentally determined strength and toughness properties (specifically the unnotched strength, σ_0 and fracture energy, G_c) required for the XFEM are also shown in Table 1. The fracture energy was determined using a single-edge notch test geometry, following ASTM Standard E 399-90, while the unnotched strength was measured using rectangular test coupons, 20 mm wide.

Table 1: Elastic properties of joint members (after Ahmad [13])

Material	E_x/E_y [GPa]	E_z [GPa]	v_{xy}	v_{zy}/v_{zx}	G_{xy} [GPa]	G_{zy}/G_{zx} [GPa]	σ_0 [MPa]	G_c [kJ/m^2]
CFRP	36.8	12	0.33	0.3	13.86	4.04	428	17.9
Steel	210	-	0.3	-	-	-	-	-

The implementation of traction-separation constitutive model as shown in Fig. 5 used in the previous 3-D modelling [13,14] is in order to predict the strength of composite plate that failed in opening crack mode, i.e., net-tension failure. Current work in this paper attempts to incorporate bearing failure that occurred behind the bolt to capture the bearing-net-tension mode. Bearing failure involves different damage mechanism events such as matrix cracking, delamination and fibre instability that reduce the load carrying capability behind the bearing bolt as failure initiation and its propagation occur. A similar bolted double lap joint model was used, but a small region behind the bolt was assigned a material with degraded stiffness as shown in Fig. 6.
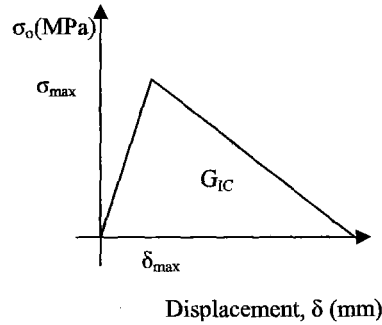

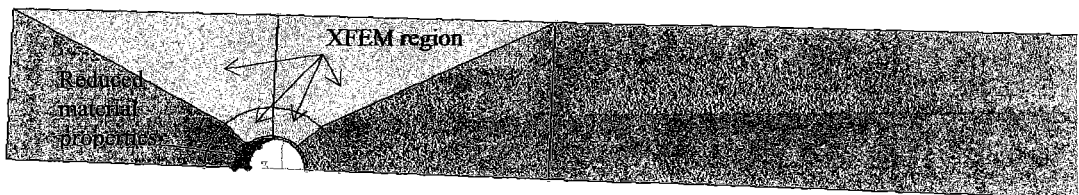**Fig. 5: Physically-based constitutive model used in the current analysis**

Fig. 6: Reduced modulus behind bolt to capture significant initial bearing prior to ultimate net-tension

Results and Discussions

Bearing failure exhibits progressive failure. However, only limited bearing damage can be modelled using the approach developed here. It is not possible to model pure bearing mode failure with large bearing. It is expected that the higher material stiffness of CFRP produces an increase in radial stress, therefore softening the material behind bolt will reduce the radial stress to resemble initiation of bearing failures at the hole edge prior to net-tension failures. Table 2 shows results from a parametric study with different degrees of material softening. Slightly increased failure strength is obtained as the percentage of softening increases from 40% to 100%. The increase is, however, insignificant. So the conclusion is that softening in bearing will not affect the predicted net-tension strength to a great extent.

Table 2: Parametric study with variation in the degree of material softening

Materials	Configuration	W/d	Exp. Bearing (N/mm^2)	% of material degradation	FEA bearing (N/mm^2)	% difference
PQ8	d=5 mm, FT	5	782	100	757	-3.2
				80	764	-2.3
				60	765	-2.2
				40	766	-2.0

Conclusions

A three dimensional model has been developed to predict bolted joint strength in the bearing failure mode. Strength prediction is discussed using a traction-separation damage model. The modelling approach in the bolted double-lap joint is similar to that used in the open-hole problem and net-tension bolted joint. A simple method for degrading material properties in the region of bearing failure was investigated and, from a preliminary study, was found to be promising.

References

[1]   Okutan, B., Aslan, Z., Karakuzu, R., "A Study of the Effects of Various Geometric Parameters on the Failure Strength of Pin-loaded Woven-Glass-Fibre Reinforced Epoxy Laminate." *Composites Science and Technology*, 2001: 61:1491-1497.

[2]   Aktas, A., Dirikolu, M.H. "An Experimental and Numerical Investigation of Strength Characteristics of Carbon-Epoxy Pinned-joint Plates." *Composites Science and Technology*, 2004: 64:1605-1611.

[3]   Karakuzu, R., Gulem, T., İcten, B.M.,. "Failure Analysis of Woven Laminated Glass-Vinylester Composites with Pin-loaded Hole." *Composite Structures*, 2006: 72:27-32.

[4]   Ujjin, R., Crosky, A., Schmidt, L., Kelly, D., Li, R., Carr, D.,. "Damage Developement during Pin Loading of a Hole in a Quasi-isotropic Carbon Fibre Reinforced Epoxy Composite." *Structural Integrity and Fracture International Conference (SIF'04)*. Brisbane, 2004. 359-365.

[5]   Aktas, A., Imrek H, Cunedioğlu, Y.,. "Experimantal and Numerical Failure Analysis of Pinned-joints in Composite Materials." *Composite Structures*, 2009: 89:459-466.

[6]   Eriksson, I.,. "An Analysis Method for Bolted Joints in Primary Composite." *AGARD Conference Proceedings 427*. Madrid, Spain, 1987. 6.1-6.19.

[7]   Yamada, S.E. and Sun, C.T.,. "Analysis of Laminate Strength and its Distribution." *Journal Composite Material*, 1978: 12:275-284.

[8]   Hollmann, K.,. "Failure Analysis of Bolted Composite Joints In-plane Failure Modes." *Journal of Composite Materials*, 1996: 30(3):358-383.

[9]   Aronsson CG, Backlund JA. "Sensitivity Analysis of the Damage Zone Model." *Computers and Structures*, 1986: 22:669-676.

[10]   Campilho, R.D.S.G., Banea, M.D.,Chaves, F.J.P., Da Silva, L.F.M.,. "Extended Finite Element for Fracture Characterization of Adhesive Joints in Pure Mode I." *Computational Materials Science*, 2011: 50:1543-1549.

[11]   6.9.1, ABAQUS®V. *User's Manual and Theory Manual*. Hibbit, Karlson and Sorensen, Inc

[12]   McCarthy, C.T., McCarthy, M.A., Stanley, W.F., Lawlor, V.P.,. "Experinces with Modelling Friction in Composite Bolted Joint." *Journal of Composite Materials*, Vol. 39, pp 1881-1908, 2005.

[13]   Ahmad, H., Crocombe, A.D., Smith, P.A., "Physically Based Finite Element Strength Prediction in Notched Woven Laminates under Quasi-static Loading." *Plastics, Rubber and Composites*, 2013:42(3):93-100.

[14]   Ahmad, H., Crocombe, A.D., Smith, P.A., "Strength Prediction in CFRP Woven Laminate Bolted Double-Lap Joints under Quasi-static Loading by using XFEM." *Composite Part A*, 2014:56:192-202.