FAILURE MODELLING OF WOVEN GFRP BOLTED JOINTS UNDER QUASI-STATIC LOADING

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Abstract

A 2-D finite element model has been developed to simulate crack growth (net-tension and shear-out failures) in composite bolted joints. Results from the model have been compared with a similar approach from the literature and experimental data for a woven fabric system. Agreement is reasonable in each case.

1 Introduction

In comparison with composite materials based on unidirectional pre-preg, composite materials based on woven fabric reinforcement exhibit reduced mechanical properties (in particular stiffness and strength, although impact behaviour is relatively good), while offering some advantages in terms of manufacturing (in particular drape-ability) and economics. For these reasons woven composites have found application in a number of sectors. A difficulty with woven fabric composites (as with other composites) are the complexities involved in designing structurally efficient joints, whether through adhesive bonding or mechanical fastening; it is mechanical fastening (bolted joints) that is considered in the current work.

Mechanically fastened (double-lap) composite joints exhibit three main types of failure mode, namely net-tension, shear-out or bearing mode, see e.g. [1]. The failure mode and strength depend upon many factors including joint geometry (i.e. hole size, joint thickness, width and end distance) [2, 3], fastener and washer parameters (including bolt clamp-up) [4, 5] and material properties [2]. Net-tension failures (associated with low ratios of joint width to hole diameter, w/d) and shear-out failures (associated with low values of joint end distance to hole diameter, e/d) can be catastrophic in nature, while bearing failure is more progressive. For this reason bearing failure is preferred, although joints which fail in the net-tension mode can be more efficient structurally in terms of the failure load per unit width of joint. The width of joint at which the failure mode transition from net-tension to bearing occurs is material dependent, with the transition occurring at lower values of w/d for more fibre dominated lay-ups [3].

Bolt clamp-up is a particularly important variable for composite laminates, with clamped joints showing a higher strength than pinned joints [4-7]. Clamp-up leads to load transfer by friction and additionally may constrain premature splitting and failure of the joint. Ideally modelling approaches should consider these effects, which are intrinsically three-dimensional in nature.

With regard to modelling, while there are two-dimensional analytical models for the stresses around a loaded hole [8], the complexity of the bolted joint problem is such that it is usually approached using finite element models, of varying degrees of complexity. A relatively early study by Crews *et al*. [6] provides a comprehensive two-dimensional finite element analysis (FEA) of the pin-loaded hole in CFRP laminates. Over the years there have been many two-dimensional analyses, e.g. [9-18], and some three-dimensional analyses, e.g. [19, 20], which have developed further understanding of the effect of key parameters on the stress distribution in composite bolted joints and proposed strategies for predicting joint strengths in the various failure modes. To predict joint strength, a number of studies, e.g. [9, 10], use the peak local stresses in conventional composites failure criteria, such as Tsai-Hill or Hoffman, while others, e.g. [11, 12], invoke the point/average stress criteria [21] characteristic distance argument and apply the chosen failure criterion at some distance from the hole edge. Other studies [16, 17] use fracture-mechanics-based failure criteria. Of particular interest to the present work is the approach of Hollman [17] who used a cohesive zone model (CZM), based on earlier work by Aronsson and Backlund on open holes [22], to predict net-tension and shear-out failures. Many of the studies mentioned here obtain good agreement between the predicted strength and experiment, but there is generally an element of model calibration required and the effect of clamp-up does not often appear to be considered explicitly.

The current study is concerned with developing finite element-based models for failure of composite bolted joints, in particular for a quasi-isotropic GFRP woven fabric laminate. In previous experimental work on this composite system, damage and fracture in open hole geometries was investigated [23]. It was shown that tensile failure involved the development of a damage zone at the edge of the hole. The damage was modelled as an effective crack, which propagated catastrophically at the peak load. Subsequently the behaviour of double-lap bolted joints from the same woven fabric system was investigated experimentally [24] and it was shown that the net-tension failure mode involved similar damage phenomena to those seen in the open notch experiments. This suggests that it should be possible to apply a similar modelling approach to the two problems. Recent modelling work has covered the open notch problem and demonstrated that a finite element framework, using either a cohesive zone model (CZM) or XFEM to simulate the crack growth gives strength predictions in good agreement with experiment [25].

A similar approach is adopted here in the context of composite bolted joints. The next section describes the two dimensional finite element model used, which simulates the full contact between the bolt and the laminate. The failure criterion is implemented in two ways, first through the use of CZMs to simulate net-tension and shear-out failures in a joint and then through the use of XFEM to represent net-tension failure. The approach based on CZMs is validated against the work of Hollmann [17] to provide confidence in the model and then the XFEM results are compared with the experimental results from Kontolatis [24].

2 Finite Element Analysis

2.1 Joint geometries, material properties and contact modelling

The first model analysed the geometry reported by Hollmann [17]. The plate width, *w*, was 36.5 mm, the end distance, *e*, was 10 mm and the hole diameter, *d*, was 5.95 mm. Three CFRP laminate lay-ups were investigated. Table 1 gives details of the lay-ups and the elastic properties, as well as the unnotched laminate strengths and fracture energies: The laminates consisted of a 0^0 dominated lay-up (Laminate A), a 90^0 dominated lay-up (Laminate B) and a quasi-isotropic lay-up (Laminate C). The average ply thickness was given as 0.127 and this gives a plate thickness of 2.54 mm for laminates A and B and 4.064 for laminate C. Figure 1 shows the idealised joint geometry – symmetry means that only half the model needs to be analysed and this was carried out using commercial software ABAQUS CAE Version 6.10.1 [26]. A full contact model was used to capture the bolt-hole interaction. In general at any load level, the bolt/hole contact surface for close-fit bolts lies in the range $80^\circ \leq \theta \leq 85^\circ$. This full contact model is in contrast to the approaches used by Hollmann, who does not model the bolt. Instead he investigated three boundary conditions corresponding to no friction, sticking friction and a mixed condition. To load the model, tensile load was applied on the right edge while the left edge remained free and the steel pin was fixed. The interaction between bolt and the inner surface of the hole are assigned as a “master-slave” interaction. In this approach, contact between the master surface (steel bolt) and the slave surface (notch edge) leads to relative displacements. Interaction between the two surfaces of bearing contact is assumed to be frictionless.

The second model is based on the experimental work conducted by Kontolatis [28] on double-lap bolted joint configuration. The 1.25 mm thick GFRP woven fabric composite plate (for properties see Table 2) and the steel pin (bolt) of 5 mm diameter are explicitly modelled in 2-D (see Figure 1). Four geometries of GFRP woven composite plate, with *w*/*d* ratios in the range *w*/*d* = 2 to *w*/*d* = 5, were analyzed. All plates had *e*/*d* = 4, which was sufficiently large to eliminate the shear-out mode.

2.2 Failure Models

Two similar approaches were implemented in the present study. The first method, implemented in the models of the CFRP laminates, used CZMs to represent shear-out and net-tension failures. Each CZM requires a strength property (at which damage initiates) and the fracture energy – see figure 2. For the material and joint geometry combinations investigated, it was found that failure occurred in shear-out. It is important to note that using the CZM approach means that the crack path is pre-defined.

In order to predict failure in the net tension mode in the woven GFRP laminates an XFEM approach, applied previously to open hole geometries [25], was used. The XFEM approach within ABAQUS allows the crack to propagate along an arbitrary path within a specified region, rather than making a prior assumption regarding the crack growth direction. The constitutive law parameters are show in Table 2. It is important to note that while the CZM parameters used in Hollmann [17] are based on calibration of joint models with experiment (and so ties in the uncertainties associated with bolt clamp-up effects), the property values from Belmonte *et al.* [23] are measured independently from tests on unnotched laminates and a single edge notched fracture mechanics specimen.

3 Results and Discussion

3.1 Strength of CFRP bolted joints

The comparison of the predicted strengths with the experimental strengths and the prediction of Hollmann [17] are shown in Table 3. For each laminate, the model predicted failure by shear-out (see Figure 3), which is consistent with the experimental observations and is associated with the low *e*/*d* ratio. The agreement between theory and experiment is very good, in all cases better than 10%.

As indicated in the previous section, a full contact model was used in the current work to describe the interaction between the bolt and the laminate and this gives a more realistic representation than the pre-defined boundary condition used in Hollman [17]. In spite of this, the difference between the predictions of the two approaches is minor.

3.2 Stress distributions in the vicinity of the bolt in pin-loaded quasi-isotropic GFRP woven fabric laminates

Figure 4 and 5 show stress distributions along the net-tension plane (Figure 4) and around the hole boundary (Figure 5) for different values of *w*/*d*.

From Figure 4 it can be seen that the stresses in the radial direction are negligible, as expected given that there is no contact between the bolt and the hole at the point on the boundary corresponding to the net-tension plane. The stresses on the net tension plane are influenced strongly by the joint geometry, with larger stresses at the lower values of *w*/*d*.

Figure 5 shows the extent of the contact region for each value of *w*/*d*, with the pin and the hole separating when the radial stress is equal to zero. Within the contact region, the radial stress distribution shows the expected trend with the maximum value immediately below the pin. Interestingly the location of the maximum tangential stress, which is associated with the initiation of net-tension failure, varies slightly with joint geometry. For larger values of *w*/*d* the maximum tangential stress occurs at about 85°, which for the joint with the smallest *w/d* the maximum tangential shear stress occurs at just over 90°. Larger width size shows trend increment in tensile stresses, corresponds to the capability of the laminate plate sustains higher load.

3.3 Strength prediction of GFRP woven fabric bolted joints

The predicted results for the bearing strength in the net-tension failure mode as a function of normalised joint width are shown in Table 4. Typical predicted crack paths are shown in Figure 6. The predicted strengths from the XFEM model (second column) are much lower than the experimental results shown in the first column.

The approach here is based on a 2-D model and so ignores frictional load transfer arising from bolt clamp-up – in the experiments the bolt torque used was 5 N m. The load-displacement curves shown in Kontolatis [24] were analysed in order to detect the applied load at which friction is overcome and the bolt starts to bear on the inside of the hole. This is usually characterised by a load drop, although this feature was more apparent in some curves than others. The results are shown in Figure 7 and from this the sliding force associated with the friction due to clamping applied was taken as 1250 N, which is equivalent to a bearing stress of 200 N/mm^2. This stress needs to be added to the FEM results before they can be compared with experimental data. Table 4 shows that agreement is improved somewhat, especially at smaller *w*/*d*, although the predictions are still low. While this initial agreement is encouraging, the frictional correction used here is somewhat simplistic; improved strength predictions may result from using a 3-D model. It is also noted that the relatively low thickness of the GFRP laminates means that the proportion of the load transfer associated with friction is very high. It would be useful to validate the method presented here for laminates with a range of thicknesses.

4 Concluding Remarks

CZMs and XFEM have been implemented within two-dimensional finite element analyses of composite bolted joints. The CZM approach gives good agreement with experimental data and the strength predictions reported by Hollmann for three lay-ups of CFRP. The XFEM approach has been implemented within a model for a woven quasi-isotropic GFRP laminate. Predictions for failure strength in net-tension show reasonable agreement with experiment, provided that an allowance is made for the load transfer associated with friction as a result of bolt clamp-up. Further work needs to consider the effect of clamp-up in more detail and to examine the transition from net-tension failure to bearing failure.

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Table 1: Moduli and CZM properties of CFRP laminates analyzed by Hollmann [17]

	Stacking sequence	**E_x *GPa***	**E_y *GPa***	**G_{xy} *GPa***	**τ_o *MPa***	**G_{IIC} kJ/m^2**
A	$[\pm45/0_2/90/0_2/90/0_2]_s$	91.8	41.4	9.96	1000	340
B	$[\pm45/90_2/0/90_2/0/90_2]_s$	41.4	91.8	9.96	400	31
C	$[(\pm45/0/90)_2/0/90/\pm45]_s$	52.2	52.2	19.6	500	46

Table 2: Moduli and CZM properties assigned to the woven GFRP laminates tested in ref. [24] (data taken from Belmonte *et* al. [23]

Mate-rial	**E_x *GPa***	**E_y *GPa***	**ν_{xy}**	**G_{xy} *GPa***	**σ_o *MPa***	**G_c *kJ/m^2***
GFRP	16	16	0.3	4.42	291	20.26
Steel	210	-	0.3	-	-	-

Table 3: Comparison of experimental and predicted bolted joint strengths for CFRP laminates investigated by Hollmann [17] (for definition of lay-ups, see Table 1)

	Experimental Strength, P_{ult}^{Exp} (kN) [21]	Predicted Strength, $P_{ult}^{Prediction}$ (kN)		
		FEM	**% error**	**% error (by Hollmann)**
A	5.68	5.49	3.33	4.6
B	5.93	6.00	1.18	3.3
C	17.28	15.92	-7.9	-3.8

Table 4: Comparison of experimental [24] and predicted joint strengths for woven GFRP laminates

w/d	**Exp. bearing stress (MPa)**	**XFEM bearing stress (MPa) [A]**	**Sliding stress (MPa) [B]**	**Prediction bearing stress (MPa) [A]+[B]**	**Error (%)**
2	357.5	116.66	200	317	11.3
3	580.83	191.63	200	392	32.5
4	655.2	237.10	200	437	33.3
5	724	270.55	200	471	34.9

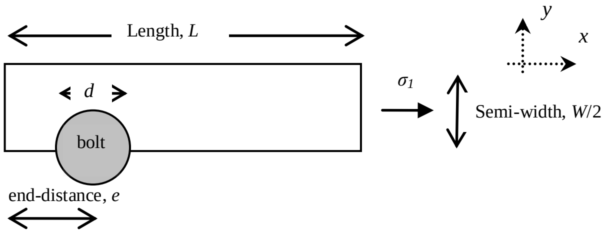

Figure 1: Dimensions of bolted joint geometry

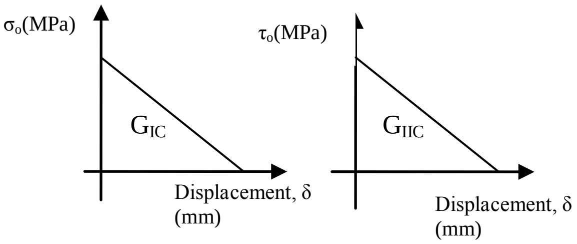

Figure 2: Physically-based constitutive model used in the current study following work of Hollmann [17]

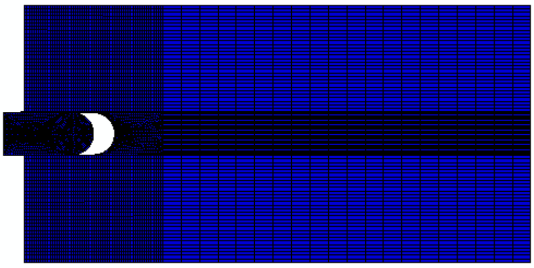

Figure 3: Shear-out failure simulated using cohesive zone model (CZM) approach

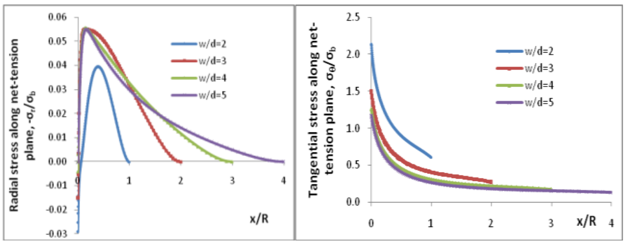

Figure 4: Stress distribution along net-tension plane for woven GFRP bolted joints at various *w*/*d*

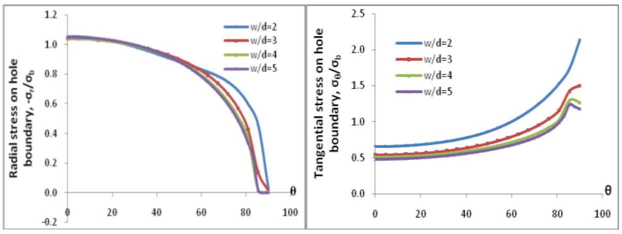

Figure 5: Stress distribution around the hole boundary for woven GFRP bolted joints at various *w*/*d*.

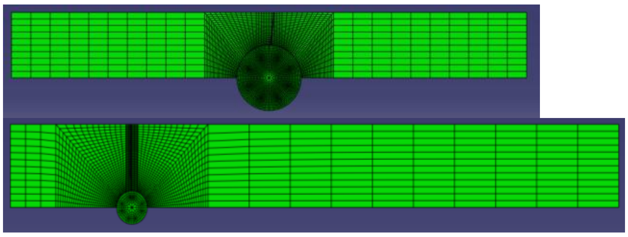

Figure 6: Simulated net-tension failure in woven quasi-isotropic GFRP using XFEM for w/d=2 (top) and w/d=5 (bottom).

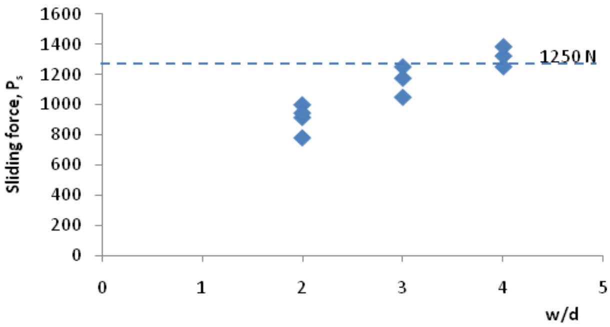

Figure 7: Sliding force in woven quasi-isotropic GFRP bolted joints (data taken from load-displacement curves in [24])