# Bearing Stresses in Bolted Composite Joints with Different Contact Interactions.

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***Abstract*— In a bolted joint, it has been shown to be better to model the real contact between bolt and hole than to fix the boundary of the hole edge, a practice used by most previous researchers. Master-slave interaction was implemented in ABAQUS to simulate full contact conditions. Stress distributions were plotted along net-tension plane and hole boundary. Due to geometric non-linearity, the clearance and friction coefficients used substantially effected the maximum stress on hole boundary as shown using the benchmarking work of Eriksson. A physically-based constitutive model used is based on state-of-the art fracture mechanics was used for bolted joint strength prediction. Idealized models from Hollmann were remodelled both by fixing the hole boundary (following the original author) and by implementing full contact condition using CZM and XFEM. The physically-based constitutive law used independently measured of unnotched strength and fracture energy parameter for crack opening, which is calibrated from available literatures (known as apparent fracture energy). Good correlation with experimental results was found when using the real contact condition.**

***Keywords*—**finite element modelling; bolted joints; CFRP; stress distribution; XFEM

## I. Introduction

A bolted joint problem exhibits more complex behaviour than an open-hole plate problem as the load transfer among joint components and associated failure mechanisms with composite laminate plate requires good physical understanding. It is more complicated as clamping loads and existence of clearance and friction promote geometry non-linearity. Hence, most of the strength predictions in the bolted joint problem are based on finite element analysis approach.

Different application of composite materials appears different tolerances of clearance level that may apply through its joint. The aerospace application enforced most stringent clearance level compared to other structural applications. The amount of contact between the bolt-hole reduced significantly as clearance increased. McCarthy *et. al*. [1] carried out extensive experimental investigations and observed that there is a lagging prior to initial contact which relies on the clearance size. McCarthy *et. al.* [1] also found that the ultimate bearing strain $\varepsilon_u^b$ increases significantly with increasing clearance as a result of extensive damage in the bearing plane due to shear cracks propagated from the edge of the bolt-hole due to a smaller contact area leads to higher compressive contact area. Interference fit pins can relieve high stress concentration factors; however, there is an optimum level of interference and this also depends on the degree of anisotropy.

Complex function method was developed by Muskhelishvili and adapted to anisotropic materials by Lekhnitksii [3]) for stress distributions with stress raisers. In pin-loaded holes problem in orthotropic plates were shown by classical approximation solution method of Waszczak and Cruz [4] and superposition method by deJong extended to effects of frictions, pin elasticity, clearance and laminate properties within FEA by Eriksson *et. al* [5] and Hyer and Klang [6]. deJong superposition [7] was primarily formulated for isotropic material with pin joint; this, however, may implemented on quasi-isotropic composite materials.

Since early researchers were working with 2-D finite element models and plane stress state, CLPT theory applies. The simplication of 2D in-plane models neglected out-of-plane parameters contributed by the bolt. Simplification of FEA 2-D model can be used to predict the behaviour of pin joint precisely by implementing iterative or inverse methods. Iterative methods allow the geometric non-linearity relation between the areas of contact with load that can trigger friction. Inverse methods require only linear finite element analysis, resulting in simpler models. It should be noted that this method is only applicable when geometric and loading symmetries exist.

Early research (e.g. Hollmann, [2]) virtualizes the existence of the bolt by fixing the contact angle of the bolt-hole with a predefined angle rather than calculating them. The simplified 2D models ignore the effect from the bolt load. Crews, Hong and Raju [8] completed a parametric study on stress distributions around the hole boundary for a variation of *W/d* values to include bolt properties and contact between bolt and the laminate. Stress distributions are strongly dependent on the anisotropy for both magnitude and location of peak hoop stress on the hole boundary.

The 0º lay-up gave largest stress concentration (about 4.5), followed by cross-ply lay-up (about 3.75) and the lowest stress concentration is with the quasi-isotropic lay-up (about 1.7). This is consistent with the open-hole problem. These parameters change the location and value of ultimate hoop stress. Rowlands *et. al*. [9] compared strain obtained from finite element model to experimental strains using strain gauges on the bearing plane. They found that increased friction was able to redistribute the load and correspondingly the position of the main load-carrying fibres away from the bearing plane towards the net-tension plane. This paper is started with benchmarking the work of stress distribution from Eriksson's work [5] with some changes to the boundary conditions. This latter predictive study was undertaken in 2-D using a similar approach to that used in the notched strength prediction [10].

## II. FINITE ELEMENT MODELLING

### *A. Stress Distribution in bolted Joint from Eriksson's work*

Stress analysis in bolted joints is necessary to make early prediction of crack initiation and propagation based on maximum stress at the vicinity of the notch edge in quasi-static loading. As shown by several authors (Errikson [5] and Hyer and Klang [6]), the maximum radial stress occurs at 0° and tangential stress at about 85° (see Fig. 1 for origin of θ). The numerical prediction using ABAQUS is compared with an analytical equation for isotropic material proposed by de Jong [7] based on perfect-fit pin-loading, without clearance, interference, clamping force, friction etc. Including friction and clearance involves geometric non-linearity due to load transfer between notch surface and bolt edge. On the other hand, linear elastic response can be assumed in FEM framework with frictionless and perfect-fit case.

This benchmarking work is done using the work of Eriksson *et. al.* [5]. Some modifications in laminate plate geometry were made to actual experimental geometry by Eriksson to idealise the experimental conditions. The length of the coupon was made larger to relieve any end effects. Specifically the static analysis is 2-dimensional, and the composite is idealized as elastic orthotropic material. Radial stress, $\sigma_{rr}$ tangential stress, $\sigma_{\theta\theta}$ and shear stress, $\tau_{r\theta}$ are substantially affected by the laminate elastic properties. The other two variables being studied were clearance and friction. The stress distributions shown are tabulated along the notch boundary and net-tension plane and also compared to de Jong's [7] superposition formulation for isotropic materials.

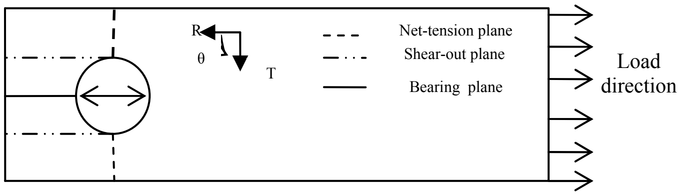



Fig. 1: Direction of notch boundary considered

A schematic of the composite laminate is shown in Fig. 1. The material properties of three laminate plates with different stacking sequences that were investigated are shown in Table 1. The laminate width and bolt diameter was idealized as 36 mm and 6 mm respectively to produce the *W/d* ratio of 6. The left edge of composite plate is a free edge and pressure of 125 N/mm$^2$ is applied at the right edge of the plate. The bolt is modelled as a rigid body and is fixed, enabling contact with the hole to be modelled. Only half of the joint was modelled utilizing the symmetry about the centre line of the plate. The interaction between the hole and bolt edge need to be modelled using contact behaviour, assuming rigid-deformable contact using master-slave interaction. This idealization is based on high modulus of steel bolt (assigned as master region) compared to composite plate (as slave region). This type of contact allows the bolt component to penetrate into composite laminate region on left side of the notch edge. Slave regions are meshed with finer elements than master region as suggested by ABAQUS 6.9.1 documentation [11].

Table 1: Homogeneous elastic properties of laminate understudied.

| Percentage of plies in directions 0/90/±45 | $E_x$ (GPa) | $E_y$ (GPa) | $G_{xy}$ (GPa) | $v_{xy}$ |
|---|---|---|---|---|
| Laminate A 25/25/50: Quasi-Isotropic | 51.4 | 51.4 | 19.3 | 0.33 |
| Laminate B 69/6/25 | 102 | 24.2 | 111 | 0.44 |
| Laminate C 6/69/25 | 24.2 | 102 | 112 | 0.10 |

Parametric studies were conducted to investigate changes in the stress distribution with different laminate elastic properties and were then extended to include bolt friction and clearance.

*B. Strength Prediction from Hollmann's work.*

Hollmann [2] conducted a bolted joint strength prediction study of composite laminate with geometric parameters and effective elastic properties as shown in Fig. 2 and Table 3 respectively. The effective elastic properties were derived from Classical Laminate Plate Theory (CLPT). Three types of laminate were considered; 0° dominated (Laminate A), 90° dominate (Laminate B) and quasi-isotropic (Laminate C). The current work studied three cases of contact between plate and the bolt; the first two cases model the interaction by partially constraining the surface of the hole and are based on the original work by Hollmann [2]. The third case is full contact interaction between both laminate and pin as shown in Table 4. Generally at any load level, bolt/hole contact surface for perfect-fit bolts lies between $\theta \leq 80°$ and $\theta \leq 85°$. Hollmann considered three load cases and the extreme two (which set the contact surface to $\theta \leq 80°$) are taken for current analysis. Hollmann does not model the bolt, but he fixed the contact boundary on notch surface to simulate bolt penetration on composite plate to reduce computational effort. In this current study, full contact is included as one case to simulate real contact simulation. Hollmann [2] used zero tangential displacement to represent the friction interaction boundary condition as shown in Table 4.

Numerical modelling approach using XFEM frameworks requires material properties data of un-notched laminate strength and fracture energy which Hollmann [2] obtained from the available literature. Different materials use different testing techniques in obtaining fracture toughness [13, 14]. These are shown in Table 3. The original work of Hollmann [2] used Mode I along net-tension plane and Mode II along shear-out plane. However, the current study only considers Mode I failure based on net-tension plane. The geometry and material orientations of the composite plates are shown in Fig. 3. The numerical modelling results are listed and compared with experimental work. No pre-defined crack is required in XFEM approach but it is better to restrict the XFEM response to a small region to reduce computational effort.

Table 2: Elastic properties of uni-directional T300/914C graphite/epoxy composite.

| $E_{11}$(GPa) | $E_{22}$(GPa) | $G_{12}$ (GPa) | $v_{21}$ |
|---|---|---|---|
| 138 | 10.0 | 3.57 | 0.35 |

Table 3: Effective elastic properties of the laminate idealized

| Laminate | Stacking sequence | $E_x$ (GPa) | $E_y$ (GPa) | $G_{xy}$ (GPa) | $\sigma_o$ (MPa) | $G^*_{1C}$ ($kJ/m^2$) |
|---|---|---|---|---|---|---|
| A | $[\pm45/0_2/90/0_2/90/0_2]_s$ | 91.8 | 41.4 | 9.96 | 1000 | 340 |
| B | $[\pm45/0/90_2/0/90_2/0]_s$ | 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 |

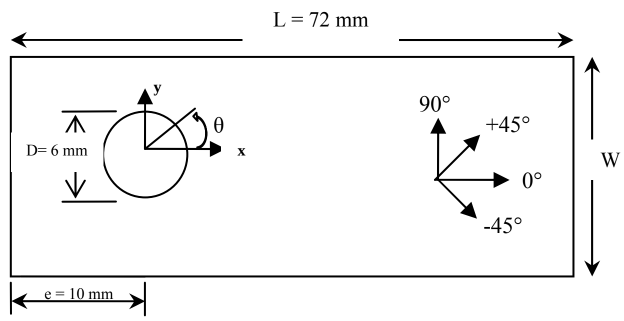



Fig. 2: Geometry of the composite laminate specimens

Table 4: Contact surfaces between bolt-hole boundary condition

| Boundary Condition | Zero Radial Displacement | Zero Tangential Displacement | "Equivalent Friction" |
|---|---|---|---|
| BC1 | $\theta_r \leq 80°$ | $\theta_t \leq 80°$ | 100% |
| BC2 | $\theta_r \leq 80°$ | $\theta_t \leq 0°$ | None |
| BC3 | Full contact simulation | | |

## III. Results and Discussions

### *A. Stress Distribution in bolted Joint from Eriksson's work*

Fig. 3 and 4 shows the stress distribution for the different laminate elastic properties along net-tension plane and on notch boundary respectively. Fig. 6 shows the effect of friction coefficients on perfect-fit hole-laminate interaction by considering Laminate A with coefficient of friction, $\mu$ of 0, 0.2 and 0.5. Three clearance sizes ($\lambda$) for laminate C were analyzed next; namely, zero clearance (perfect-fit), $\lambda$=0.01 and $\lambda$=-0.0066 and shown in Figure 7.

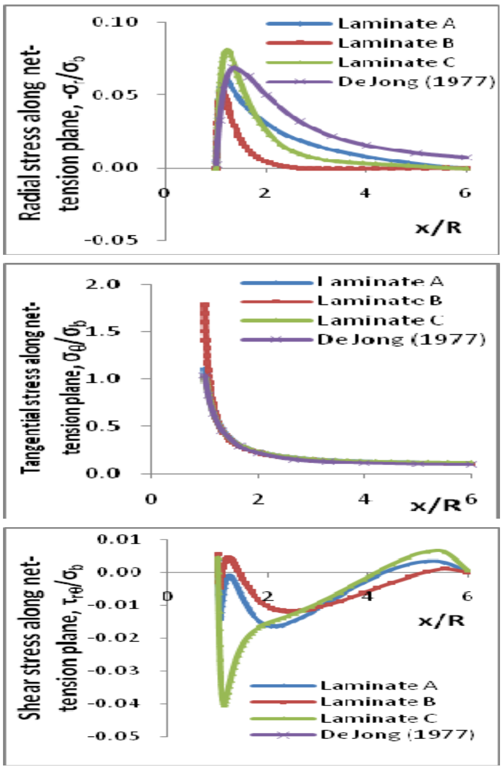



Fig. 3: Effect of laminate properties upon stress distribution along net-tension plane.

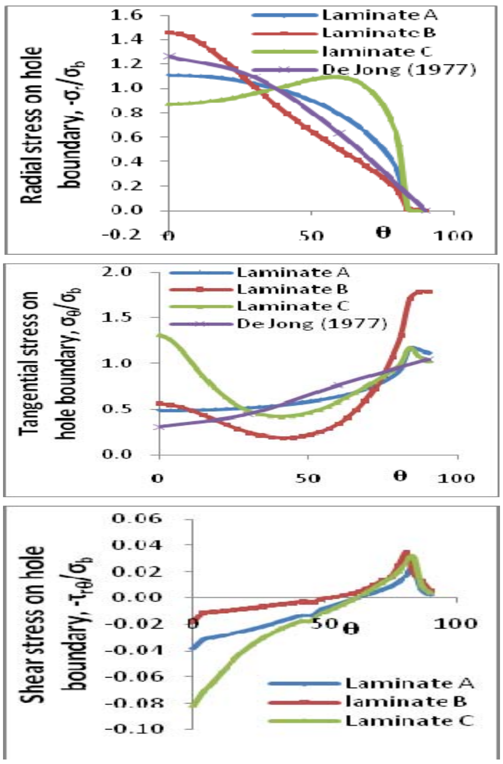



Fig. 4: Effect of laminate properties upon stress distribution on hole boundary.

The stress distribution along the hole boundary was strongly dependent on the laminate properties. From Fig. 3, Laminate A which shows isotropic lay-up shows similar trend to that given by De Jong [7]. Zero-plies dominated Laminate B which is stiffest in x-direction giving higher radial stress at $0^{o}$ and Laminate C is 90° dominated, which is stiffest in y-direction giving highest radial stress at about $90^{o}$ as shown in Fig. 4. Laminate C gave highest tangential stress at $0^{o}$ but small effect with other laminates at $90^{o}$.

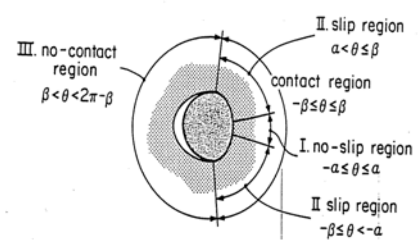



Fig. 5: Contact interaction at pin/hole boundary (after Hyer and Klang, 1987)

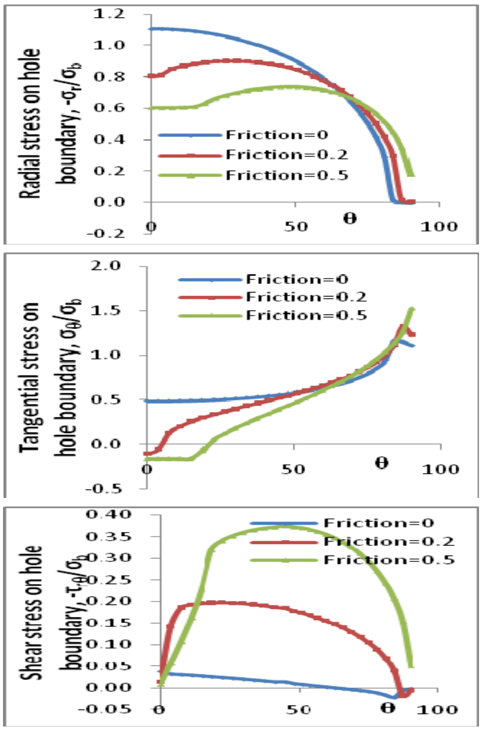
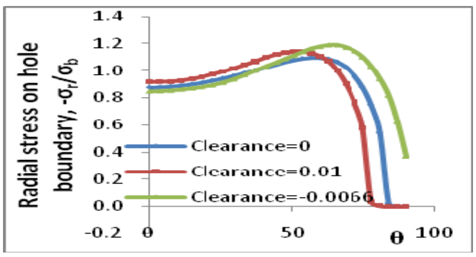



Fig. 6: Effect of friction upon stress distribution of Laminate A on hole boundary

From Fig. 5, it can be observed that three regions exist at the hole boundary; namely non-slipping region, slipping region and no contact region. In the frictionless case, the no-slip region exists only at the origin point; the slip region is larger than the friction case and the no contact region smaller than with friction. With friction, the slip region is smaller and contact interaction changes depending on the friction's coefficient. Therefore, less radial stress is found as friction increased compared to higher radial stress of frictionless case as shown in Fig. 6. Further, by increasing friction, the tangential stresses were decreased at $0^{o}$, but increased for θ about $80^{o}$.



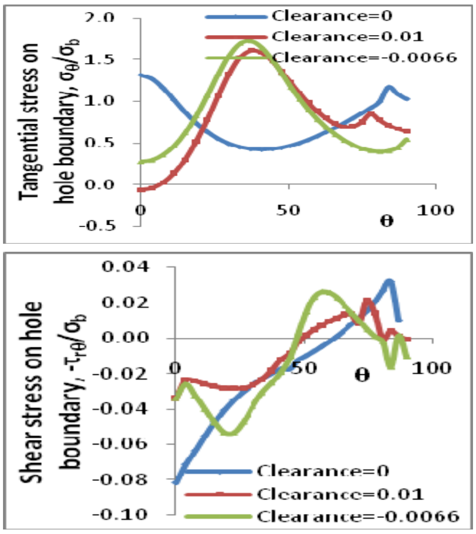



Fig. 7: Effect of clearance upon stress distribution of Laminate C on hole boundary

As shown in Naik and Crews [12] work, increasing clearance tends to increase contact radial stresses and a smaller contact region leads to higher tangential stresses. This can be shown in Fig. 7, where a clearance of -0.0066 (interference of 0.0066) gave highest values of tangential stress compared to laminate with clearance of +0.01. The peak values of radial stresses are almost the same magnitude but are located at different positions. This study gave a good understanding of stress distribution within a composite laminate and identified variables that substantially change the interaction between the respective components.

*B. Strength Prediction from Hollmann's work.*

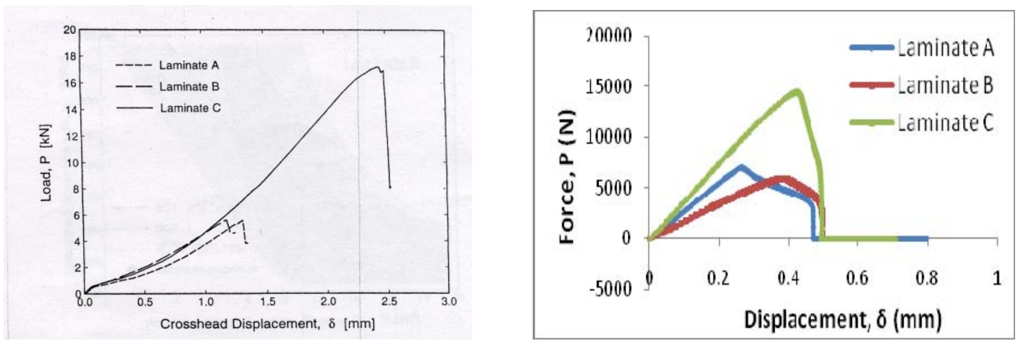



Fig. 8: Comparison of experimental work (left, Hollmann (1986)) and full contact CZM model (right).

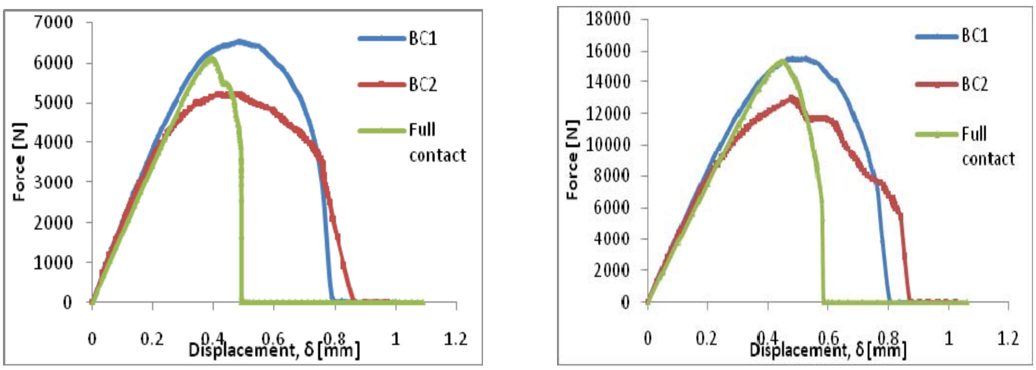



Fig. 9: Comparison of boundary conditions Laminate B (left) and Laminate C (right)

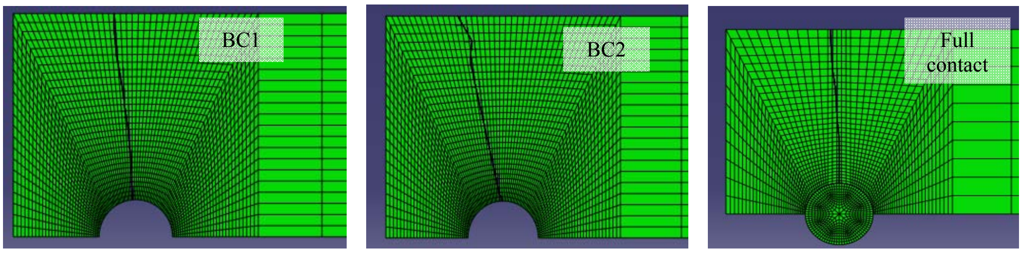



Fig. 10: Crack propagation of XFEM results with effects of boundary conditions.

As full contact is idealized to represent real interaction between the bolt and laminate, this type of boundary condition gave a more realistic representation compared to using a pre-defined fixed boundary condition on hole boundary. Load-displacement curve of CZM model gave similar curve trend to experimental work which shown in Fig. 8. This produces the best prediction for Laminate B, but significant discrepancy for laminate A and C.

Table 5: Prediction of numerical bolted joint strength with experimental works.

| Laminate | Experimental Strength, (kN) | Predicted Strength (kN) | | | |
|---|---|---|---|---|---|
| | | CZM | XFEM | | |
| | | | BC1 | BC2 | BC3 |
| A | 5.68 | 7.02 | 9.04 | 6.91 | 7.41 |
| B | 5.93 | 5.93 | 6.53 | 5.22 | 6.12 |
| C | 17.28 | 14.48 | 15.53 | 12.96 | 15.34 |

## IV. Conclusions

In current work, 2-D model had been compared with experimental work and closed form solution taken from literatures by several authors. More contact pair were involved and several parameters, among others; friction, lay-up, thickness and hole size were incorporated in the model leading to more complex behaviour and difficulty in obtaining convergence. The respond of bolt pre-load upon the laminate configuration need to be looked into more detail as the variations in torque intensity will initiate different mechanism of failure onset will remarkably changing the ultimate failure.

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