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STRENGTH ANALYSIS OF HYBRID BOLTED/BONDED COMPOSITE JOINTS BASED ON FINITE ELEMENT METHOD

Blier, Raphael [1], Monajati, Leila [2], Mehrabian, Masoud [2], and Boukhili, Rachid [2]*
[1] Department of Mechanical Engineering, RMC, Kingston, ON, Canada, K7K 7B4
[2] Department of Mechanical Engineering, Polytechnique, Montreal, QC, Canada, H3T 1J4
* Corresponding author (rachid.boukhili@polymtl.ca)

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ABSTRACT

This research is conducted to provide further insights into the behavior of bolted/ bonded joints made of woven carbon fiber reinforced polymer (CFRP) laminates, which includes the critical design factors influencing the composite joint strength and failure conditions. A finite element analysis (FEA) has been conducted to examine the behavior of single-lap quasi-isotropic (QI) and cross-ply (CP) hybrid bolted/bonded (HBB) configurations subjected to tensile shear loading. The study of stress concentration around holes highlights the fact that HBB joints benefit from significantly lower stresses compared to only bolted joints, especially for CP configurations. It was determined that for longer overlap lengths, typically requiring more than two bolts, the bolts between the outer bolts would not contribute to increasing the HBB joint strength.

1 INTRODUCTION

The mechanism of damage initiation and bolt-adhesive interaction are important features characterizing the performance of hybrid bolted-bonded (HBB) joints. The bolt-adhesive interaction can take the form of load sharing or reduction of peel stresses at the overlap ends. According to the preliminary results, HBB joints offer superior performance compared to bolted joints but also to bonded joints due to the crack stopping featured by the bolts [1,2]. This indicates that the bolts must have a definite impact on the failure of the adhesive layer. Bodjona and Lessard [3] reported that only less than ten percent of the applied load was found to be transferred by the bolt in a single lap (SL) HBB joint when the adhesive was not fully plasticized. Moreover, controlling the adhesive thickness and minimizing bolt-hole clearance are efficient methods to limit the maximum plastic strain.

By doing finite element analysis (FEA), Kelly [4] investigated the effects of load sharing in SL HBB joints considering the effects of increasing adherend and adhesive thickness and decreasing overlap length, bolt pitch distance, and adhesive modulus on having higher load transferring. Li et al. [5] investigated various parameters in HBB joints and concluded that selecting a high strength with low modulus adhesive is preferable for improving bonding strength. It was also mentioned that HBB acts like a bonded joint before adhesive failure while it performs like a bonded joint after adhesive failure. In order to increase the load sharing before adhesive failure, Raju [6] designed an interference-fit HBB joint instead of a conventional neat-fit or clearance-fit bolt. The model reached ten percent higher load sharing considering equivalent load levels. Romanov et al. [7] signified the importance of joint overlap length on the joint strength rather than bolt positioning. It was concluded that shorter overlap lengths and smaller bolt-edge distances led to higher load sharing.

Digital image correlation (DIC) as one of the powerful tools for measuring strain field and recognizing the onset of failure around the fastener [8] has already been used to compare the experiments with FEA results. Through using the 3D-DIC technique, the experimental results using the current model were validated with FEA results in the previous article done by the same authors [9]. By using the same simulation modelling, a comparison of stress variation around holes in quasi-isotropic and cross-ply configurations considering only bolted and HBB joints along with the influence of the middle bolt in HBB joints will be investigated.

2 Numerical simulation procedure

A full description of the procedure followed for modeling the specimen considering its adhesive and composite material properties based on the classical plate theory, damage modelling, and mass scaling are well described in the previous article done by the same authors [9]. In the research mentioned, to ensure the FE results, they were compared with experimental procedures using the 3D digital image correlation method. It should be noted that a specific technique followed by Gordon et al. [10] has been followed to model plain weave fabric layers by substituting each fabric layer with 4 symmetric unidirectional plies. Washers and bolts were modelled considering temperature gradients for each joint configuration and special considerations regarding element types and contact definitions were completely explained.
In order to study laminates, three types of joint configurations including only bolted (OB), Only bounded and hybrid bolted-bonded (HBB) is considered. Two critical layups including Cross-ply (CP) and quasi-isotropic (QI) considering 12 plies are described in Table 1. The abbreviation CP12 signifies a 12-ply cross-ply layup, as an example.

Table 1. Layup configurations.

CP symmetric sequence-12 plies (CP12)	QI symmetric sequence-12 plies (QI12)
$[(0/90)/(0/90)/(0/90)/(0/90)/(0/90)/(0/90)]_S$	$[(0/90)/(\pm45)/(0/90)/(\pm45)/(0/90)/(\pm45)]_S$

The joint model considered in this study is shown in Figure 1 considering B3 as the nearest hole from the grip support and B1 as the furthest one. It should be noted that the results for the adhesive, such as shear or peal stress distributions are taken in the middle of the adhesive (where cohesive interaction is defined). For the following research, failure of the joint is defined as the onset of fiber or adhesive damage initiation. This was chosen as it reduced the length of the simulation while still being a good indicator of the relative strength of the different joint configurations.

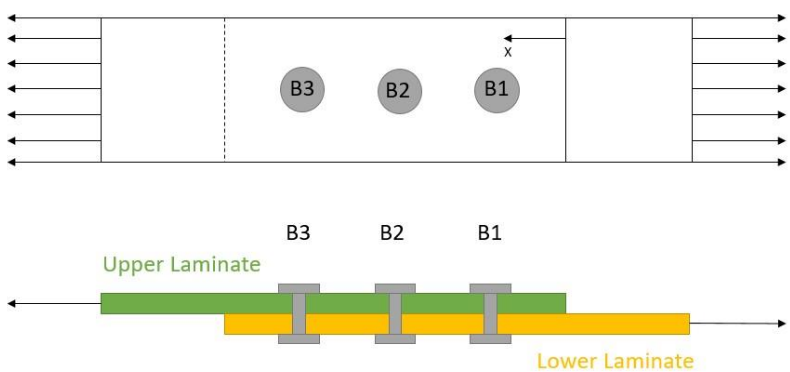

Figure 1. Joint Model.

3 Results

3.1 Stress Concentration in the Laminate in HBB and 3OB Joints

The critical state of stress at the hole that generates failure consists of the combination of σ_x and a shear component S_{xy}. A variation of the peak stress at all hole locations is of great interest to see how the joining method influences the development of those high stresses. The predicted variation of the normal stress with the imposed loading at the critical point of each hole of the top ply is depicted in Figure 2 and Figure 3 for 3OB and HBB joints consisting of CP and QI layups. Due to the bolt preload, negligible compressive stress (around 10 MPa) is observed at very low load levels as the laminate is compressed creating a compression zone in bending.

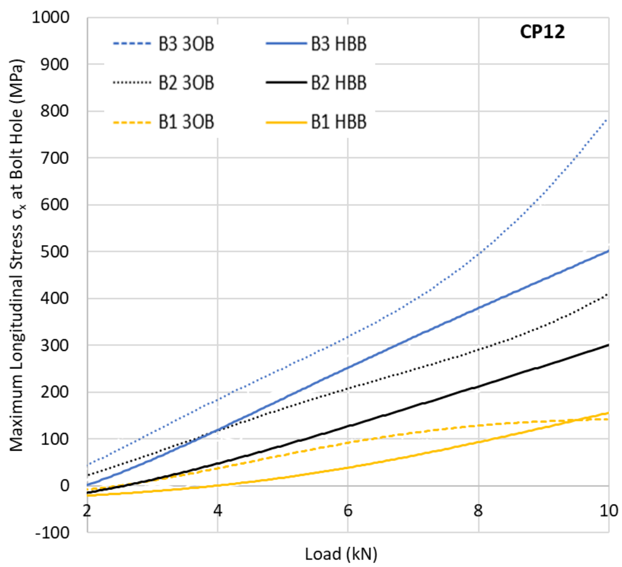

Figure 2. Maximum Longitudinal Stress σ_x at Different Holes in CP Layups.

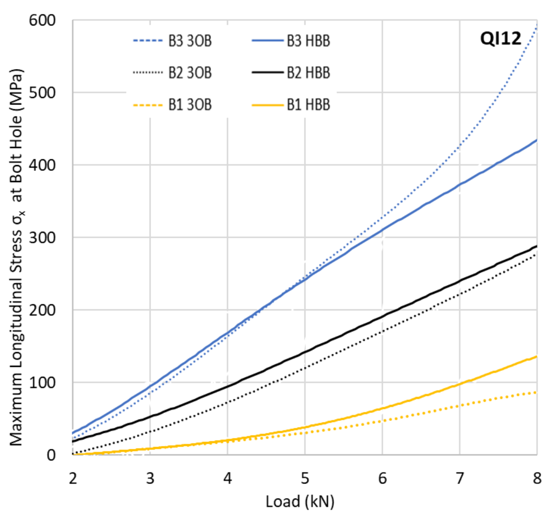

Figure 3. Maximum Longitudinal Stress σ_x at Different Holes in QI Layups.

For the QI layup, a slight reduction of the maximum longitudinal stress is observed for the HBB joints. However, this difference is much less apparent than in the case of the CP layup. The difference in behavior between the CP and QI layups can be explained by the fact that CP layups are more notch-sensitive, a phenomenon reduced by the adhesive layer. This notch sensitivity relates not only to longitudinal stresses σ_x, but also to shear stresses S_{xy}. CP layups suffer matrix damage at a lower load level compared to QI layups due to the development of higher shear stresses, reducing the local stiffness as shown in Figure 4 for the critical point (at hole B3). This data indicates a net gain in the reduction of the shear stress generated by the adhesive independently of the layup. This gain becomes even more substantial with increased loading. However, due to the notch sensitivity of CP layups, the effect is more significant, reducing matrix damage significantly. For the CP layups, the reduction of the maximum shear stress around the holes due to hybridization is almost double compared to a QI layup, showing the significant gains that can be achieved, especially for CP HBB joints.

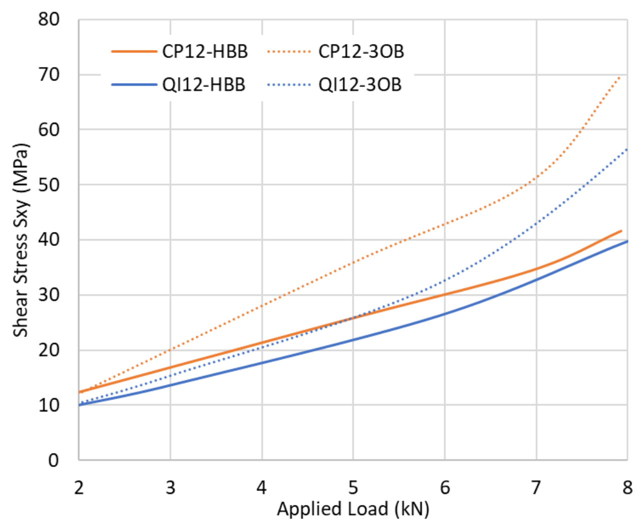

Figure 4. Maximum Shear Stress S_{xy} in 0° Plies at hole B3 for CP12 and QI12 Joints.

3.2 Role of Middle Bolt in 3-Bolts HBB Joints

Improvements in HBB joint design may take the form of an increase in the joint load-carrying capability, but also a joint weight reduction for the same load-carrying capability. The latter will be investigated first as Gamdani et al. [2] indicated a potential redundancy of the middle bolt in 3-bolt HBB joints. For that reason, models were developed with the same overlap length, but one had three bolts and the other had two bolts. Simulations were run for CP and QI layups, and it was found that the removal of the middle bolt did not influence the failure load of the joint, as shown in Table 2.

Table 2. Failure Load for Different HBB Joint with and without Middle Bolts.

Model	Failure mode	Load at failure (KN)
3-Bolts e/d=3 (CP12)	Fiber Failure	15.41
2-Bolts e/d=3 (CP12)	Fiber Failure	15.30
3-Bolts e/d=3 (QI12)	Adhesive Failure	13.78
2-Bolts e/d=3 (QI12)	Adhesive Failure	13.94

It was shown previously that at B3, located on the grip side, the longitudinal tensile stresses were much higher than at the hole on the free side, making this location the focus for the stress levels comparison. To understand the reason for the similar joint strength upon the removal of the middle bolt stresses around the critical hole were monitored for the HBB joint using CP laminate as shown in Figure 5. It is found that the presence of the middle bolt does not alleviate the stresses at the critical hole. This is due to the load being transferred uniquely by the adhesive, a common phenomenon when using a stiff adhesive in HBB joints, which means that the stress levels are independent of the presence of the middle bolts.

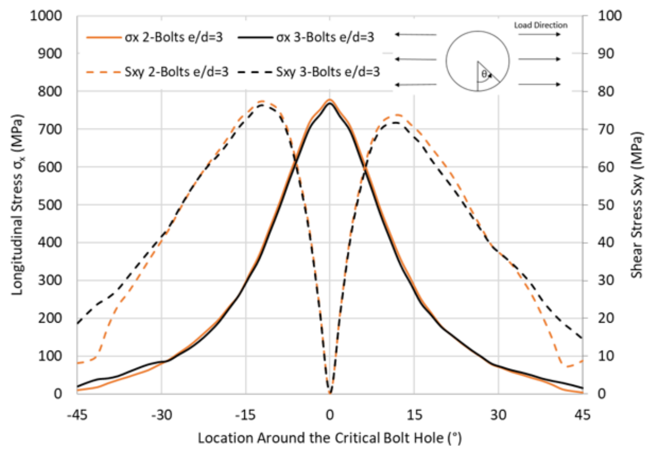

Figure 5. Effect of Middle Bolt in Tensile σ_x and Shear Stress S_{xy} Distribution around the Critical Hole in CP12-HBB Joints at 14 kN.

Similarly, the stresses were monitored in the adhesive at the overlap end. As was the case for stresses at the critical hole, there is no significant difference between the two configurations. The stress distribution shown in Figure 6, for the CP case taken as a basis for this comparison, highlights that although slight discrepancies are observed, the removal of the middle bolt did not affect the stresses in the adhesive layer. As such, for an overlap length requiring more than one bolt to maintain e/d=3, it is recommended that only two bolts are used. The bolts between the outer bolts are considered redundant and will only add weight to the joint.

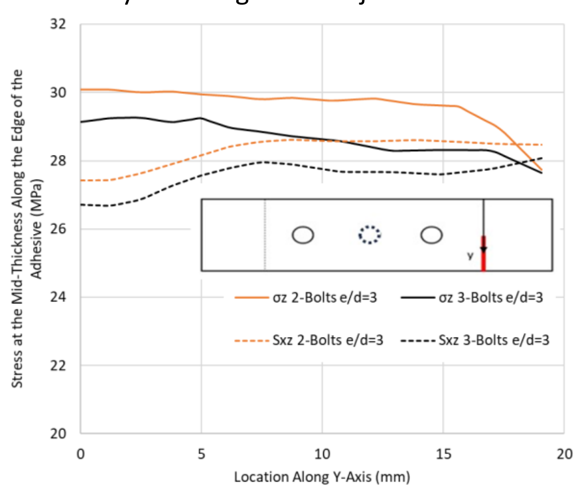

Figure 6. Effect of Middle Bolt in Peel σ_z and Shear Stress S_{xz} at the Overlap Ends in CP12-HBB Joints at 14 kN

4 Conclusion

An examination of the mechanics of hybrid bolted/bonded joints with three bolts based on finite element analysis was performed considering both cross-ply (CP) and Quasi-isotropic (QI) configurations. It was identified that the stresses were concentrated at the hole closer to the grip side in the laminates. HBB joints have considerably lower stresses compared with only bolted joints while CP layups benefit more from hybridization than QI layups due to their higher notch sensitivity. For longer overlap lengths typically requiring more than two bolts, it was identified that the middle bolts did not contribute to increasing the strength of the HBB joints since the critical regions are at the overlap ends.

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