Tensile behavior of hybrid multi-bolted/bonded joints with carbon/epoxy composites

Farid Gamdani, Rachid Boukhili *, Aurelian Vadean
Department of Mechanical Engineering, Polytechnique Montreal,
Montreal, QC, H3C 3A7, Canada

ABSTRACT

Hybrid-bolted/bonded (HBB) joints and only-bolted (OB) joints according to ASTM D5961 geometry were tested in single shear, two-piece test specimen with one, two and three bolts. Quasi-isotropic and cross-ply carbon epoxy composite panels were manufactured from plain wave carbon fabrics using the infusion process. For HBB joints with one and two bolts, the load-displacement curves display two distinct regions: an adhesive failure corresponding to a sudden load-drop followed by a progressive bearing failure due to the delayed action of the bolts. Conversely, for the three-bolts HBB joints, the two steps discontinuity disappears and the behavior is continuous denoting a possible synergy between the adhesive and the bolt. The same tests were repeated using a smaller width to hole diameter (W/d) ratio. The general pattern behavior remains the same for the single bolt. Nevertheless, the two steps behavior disappear for the two-bolts HBB. It was also noticed that once the adhesive fails, the load supported by the HBB joint is high that that of the only bolted (OB) joints. However, this positive effect is only observed for quasi isotropic laminates. As it might be expected, the joint stiffness and ultimate load for OB joints increases with increasing the number of bolts. However, the initial stiffness of HBB joints is not affected by the overlap distance, although the ultimate load increases with increasing the overlap distance. The combination of these features led to the conclusion that the optimal multi-bolted HBB joints is a joint with only the external bolts. Such a joint combine the safety provided by the bolts and the efficient load transfer provided by the adhesive and such a combination is expected to be even more effective for the case of cyclic loading.

Keywords:
Composites. Bolted joints. Bonded joints. Hybrid joints. Bearing failure. Tensile failure.

Corresponding author. Tel.: 1-514-340 4711. E-mail address: rachid.boukhili@polymtl.ca

1 Introduction

Most of mechanical structures are constituted of many parts connected together by a variety of joints (fastened, bolted, bonded, welded, etc.). Joints are usually regarded as the weakest link of the structure because they constitute the sites of potential damage initiations and failure and as such they require close monitoring. Joining also means a loss of continuity which in terms of mechanical performance, means a loss of efficiency. For composite structures, the most efficient bolted joint does not exceed the standard OHT (open-hole-tension) or FHT (filled-hole-tension) strength of the material, which in other terms does not exceed 50% of the tensile strength of the un-notched material [1].

A relatively large amount of studies has been devoted to improve bolted joint efficiency, among them the idea to combine adhesive bonding and mechanical fastening [2 - 9]. While mechanically fastened joints (bolted or riveted) remain the most trustworthy joining methods for composite structures particularly for aeronautic applications, adhesive bonding has been always considered as an alternative method with the highest potential. Indeed, theoretically, adhesive bonding has the potential to achieve full efficiency, particularly for simple joint configurations involving thin composite structures. However, in practice adhesive bonds suffer many drawbacks as the lack of efficient inspection methods of the joints, surface preparation of the adherents prior joining, environmental concerns, sensitivity to peel stresses, etc. [10].

To the author's knowledge, the first publicly available comprehensive investigation for joints combining mechanical fastening and adhesive bonding can be attributed to Hart-Smith [3,4]. Investigation [3], cautioned that individual joint strengths (bolt & bond) cannot be summed because the individual stiffnesses of each load path differ and acknowledged that bonding and bolting together do not achieve any significant advantage over adhesive bonding alone in well-designed intact structures. Fu and Mallick [5], investigated HBB joints under static and fatigue loading for E-glass mat reinforced Polyurethane composites intended for automotive composites. They concluded that the hybrid joints have a higher static failure load and longer fatigue life than the adhesive joints. Kelly [6] investigated the load transfer by the bolt as function of adhesive thickness and modulus, adherent thickness, overlap length and pitch distance. He concluded that the benefit of adding bolts to a bonded joint is greater if the joint is flexible either as a result of the adhesive material or joint design. In a subsequent paper, Kelly [7] showed that hybrid joining (bonded/bolted) offer potential improvement in strength and fatigue life in comparison to adhesive bonded joints.

This investigation with multi-bolt HHB joints is undertaken to provide more experimental data and understand more profoundly the behavior of HBB joints beyond the case of single HBB joints. The experimental results are expected to highlight more details to redirect future analytical modelling and finite element simulation.

1 EXPERIMENTAL PROCEDURES

Carbon-fibers reinforced epoxy (CFRE) composites were manufactured by the vacuum assisted resin infusion (VARI) process using a commercial Araldite epoxy resin system. The CFRE composite laminates are composed of 12 plies of 3K plain wave carbon fabric with a 135.11 g/m^2 surface weight. The mean thickness value of the panels is about 2.7 mm, and the average fiber volume fraction (V_f) is about 52%. The measured void content does not exceed 1%. The woven plies are oriented to obtain the quasi-isotropic (Q) and cross-ply (CP) laminate configurations as shown below:

Quasi-isotropic (Q) symmetric sequence:	$[(0/90)/(\pm45)/(0/90)/(\pm45)/(0/90)/(\pm45)]_S$
Cross-ply (CP) symmetric sequence:	$[(0/90)/(0/90)/(0/90)/(0/90)/(0/90)/(0/90)]_S$

In the stacking sequence shown above, (0/90) or (±45) indicate a single woven ply. For all laminates, the warp side is oriented toward the zero direction. To construct the quasi-isotropic laminates, a (0/90) woven ply is simply rotated to obtain a (±45) ply.

The single-shear bolted joints with one and two bolts were performed according to ASTM-D5961[11]. For the case of three bolts, the same geometry with two bolts (ASTM-D5961) is used, except that the joint members are extended to house the third bolt with the same inter-bolt distance (IBD) and end-distance. All the mechanical tests were performed on a servo-hydraulic MTS machine model 810 as illustrated in Figure 1 for the case a three bolts single-shear-lap joint.

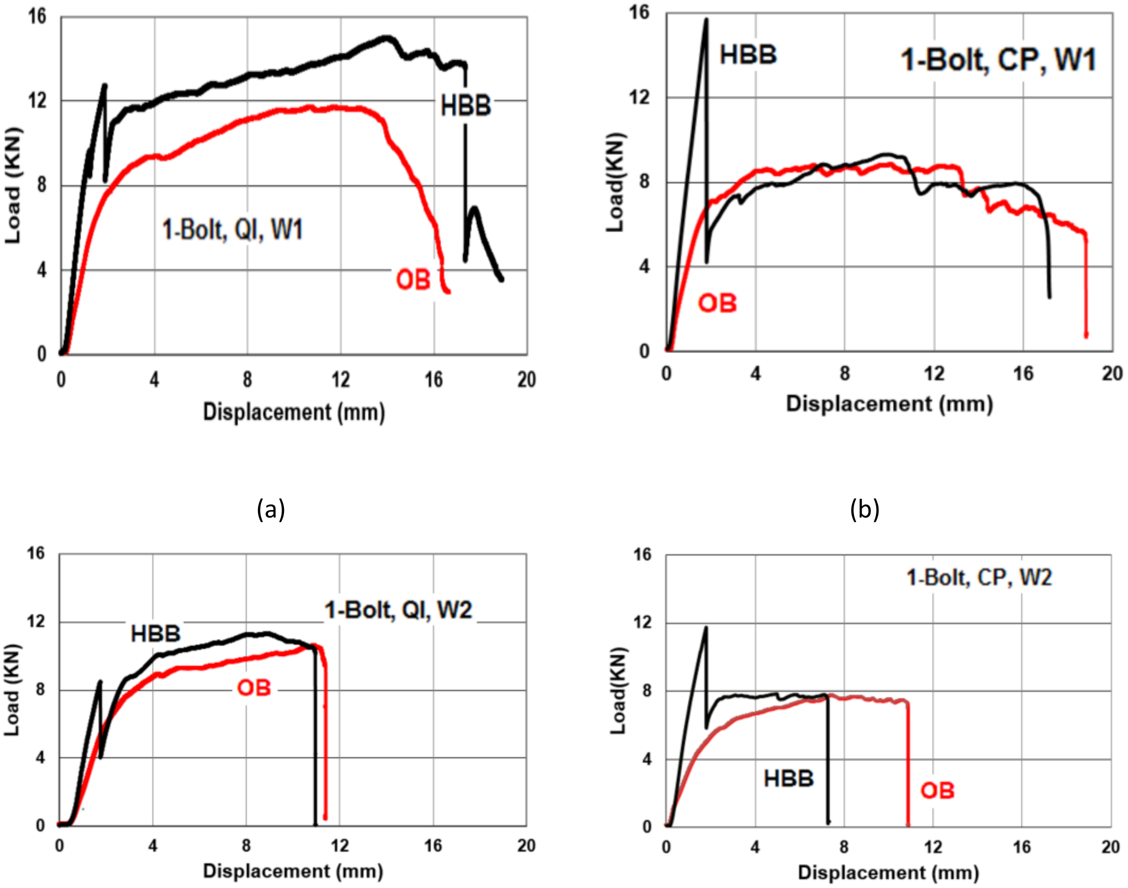
All the bolts used in this investigation are steel hex head shear bolts Model NAS6204-4 with a diameter of 6.35 mm. The washers used are cadmium-plated steel washer Model NAS1149F0463P with internal diameter of 6.73 mm and external diameter of 12.70mm. For all the bolted joints, a bolt tightening torque of 5N.m is applied with a Tohnichi Dial Torque Wrench DB25N-S. It should be noted that the use of a 6.35 mm hole instead of a 6 mm hole is a deviation from ASTM D5961 that results in a width (W) to diameter (d) ratio of W/d = 5.7 instead of the ASTM recommended W/d = 6. The 5% difference in the W/d ratio has no perceptible effect on the discussed subjects. The second deviation is that the ASTM D5961 recommended fastener torque in the range of 2.2-3.4 N·m while in this investigation a torque of 5 N.m is used. It is difficult to achieve the ASTM recommended low level torque with accuracy and the ASTM 5961 justifies this relatively low level of fastener installation torque to give conservative bearing stress results. In addition, this investigation addresses joints with multiple bolts and in such case the use of a higher fastener torque can help achieve a more even load distribution as reported in [12].

Figure 1 Front and back faces of a 3-Bolts specimen mounted on MTS 810 Machine

1 RESULTS AND DISCUSSION

3.1 Hybrid bonded/bolted joint behavior with one bolt

Figure 2 shows a typical and representative load-displacement behaviour of only-bolted (OB) and hybrid-bolted-bonded (HBB) joints with one bolt. Diagrams (a) and (b) are for quasi-isotropic and cross-ply laminates using the standard width W1=36mm. Diagrams (c) and (d) use narrow specimens with width W2=22mm. For all the displayed cases the failure of HBB proceeds in two steps. In the first step, the load increases linearly with the displacement and then decreases sharply denoting the instable fracture of the adhesive. The load starts to increase again but the load-displacement behaviour becomes clearly non-linear and resembles the response of the OB specimen which proceed by progressive damage build–up under the action of the bolt (bearing failure). The described two-steps general pattern behavior is independent from the stacking sequence (CP versus Q) and also independent from the width (W1=36mm versus W2=22mm). However, there is a major difference between the HBB behaviour of CP and Q laminates in terms of the maximum load reached during the test. In the case of CP, the maximum load is controlled by the adhesive while in the case of quasi isotropic the maximum load is controlled by the bolted joint. The other important feature from Figure 2 is related to the post-adhesive-failure behavior. For the case of CP laminates, the magnitude of the plateau reached by the load is sensitively the same as with the OB joints. For the case of Q laminates, the magnitude of the plateau reached by the load is clearly higher than for the only bolted joints.



(a) (b)

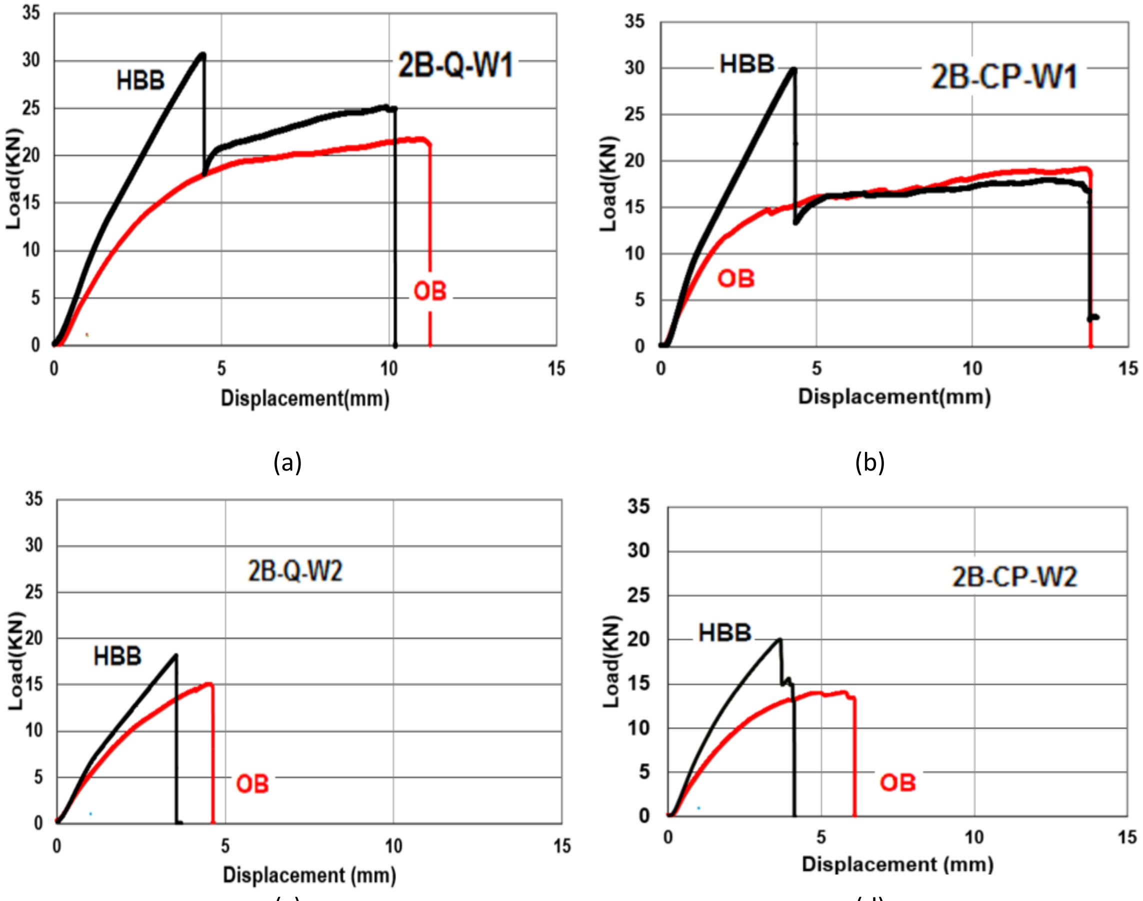
(c) (d)

Figure 2 Load-displacement behaviour of only bolted (OB) and hybrid bolted bonded (HBB) joints with one bolt. Diagrams (a) and (b) are for quasi-isotropic and cross-ply laminates using the standard width W1=36mm. Diagrams (c) and (d) use narrow specimens with width W2=22mm.

3.2 Hybrid bonded/bolted joint behavior with two bolts

Figure 3 shows typical and representative load-displacement behaviour of only bolted and HBB joints with two bolts. Diagrams (a) and (b) are for quasi-isotropic and cross-ply laminates using the standard width W1. Diagrams (c) and (d) use narrow specimens with width W2. As opposed to the preceding case of one bolt, the failure load of HBB joint with two bolts is always higher that that of OB joints. The post-adhesive-failure behavior displayed in the preceding case of one bolt is again displayed in Figure 3 for the case of two bolts. Indeed, as shown in Figure 3a and 3b, for the quasi-isotropic laminates, the magnitude of the plateau reached by the load for HBB joints is clearly higher than for the OB joints. However, for the case of CP laminates, the magnitude of the plateau reached by the load is sensitively the same as with the OB joints. Accordingly, if we combine the observations on Figure 2 and Figure 3, it can be asserted that the hybridization has a clear positive effect on the post-adhesive-failure behavior for quasi-isotropic laminates and this positive effect in not observed for cross-ply laminates. This stacking sequence effect (quasi-isotropic versus cross-ply) on the post-adhesive-failure behavior of HBB joints with one and two bolts may be explained in terms of different damage accumulation mechanisms. In a previous a study dedicated to only-bolted specimens with same laminates, it was shown that the CP configuration are more notch sensitive than the Q configuration [1]. Consequently, during the loading phase preceding the adhesive failure, the damage growth around the bolt-hole is probably more severe in the case of the CP laminate. Once the adhesive fails, the load is transferred to the bolts which in turn compresses the hole surface in contact. For the quasi-isotropic configuration, the damage is delayed and will start only after the adhesive has failed. At this stage it requires more energy to reach the damage level that otherwise would have been reached in OB joints. This situation translates in higher resistance and higher load bearing. For the case of CP specimens which are more notch sensitive, damage may have already been accumulated and the mechanism assumed for the quasi-isotropic configuration is not operative.

It can be noticed that the failure proceeds in two-steps only for large width (W1). However, narrow specimen shows a one-step failure behaviour. It should be noted that some narrow CP specimens (Figure 3d) show some reminiscence of the two step behavior. It was also observed that the specimens which fail in one step failure fail by net-tension along the bolt hole and display limited hole crushing under the bolt. An explanation of the one-step-failure behaviour is given for the next case treating the three bolts HBB joints.



(a) (b)

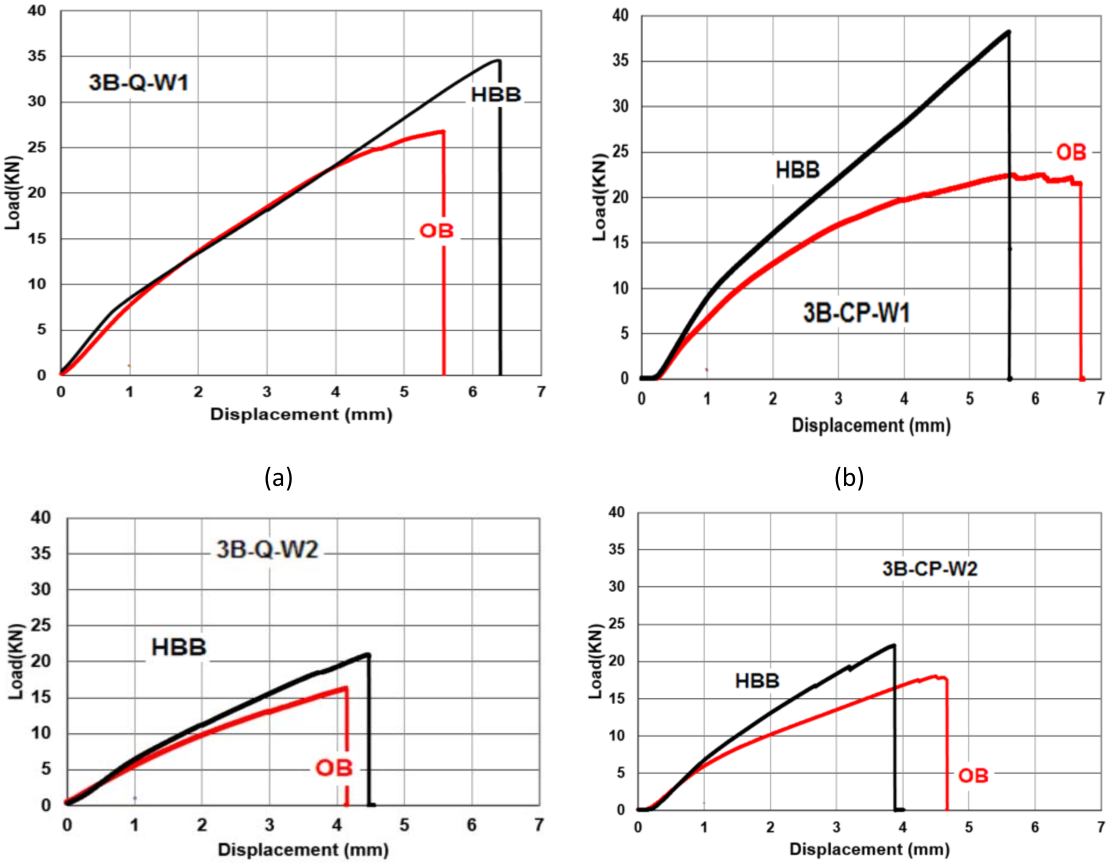
(c) (d)

Figure 3 Load-displacement behaviour of only bolted (OB) and hybrid bolted bonded (HBB) joints with two bolts. Diagrams (a) and (b) are for quasi-isotropic and cross-ply laminates using the standard width W1=36mm. Diagrams (c) and (d) use narrow specimens with width W2=22mm.

3.3 Hybrid bonded/bolted joint behavior with three bolts

Figure 4 shows typical and representative load-displacement behaviour of HBB and OB oints with three bolts. Diagrams (a) and (b) are for quasi-isotropic and cross-ply laminates using the standard width W1. Diagrams (c) and (d) use narrow specimens with width W2. As opposed to the preceding case of one and two bolts, the 2-step behaviour disappear completely for all the configuration tested (CP versus Quasi and W1 versus W2) and the failure load of HBB with three bolts is always higher that that of only bolted specimens.

In the early stage of loading (before the adhesive yield or fail), the load is transferred between the joint members via the adhesive. During this stage, the bolt does not transfer any noticeable load and does not crush the extremity of the hole as in an only-bolted joint. Once the adhesive fail abruptly, the load is suddenly transferred to the bolt. If the transferred load exceeds the maximum load that can be carried out by the effective cross section, the material will necessarily fail by net tension as a specimen containing a central hole. Actually, the behavior of a specimen containing a central hole is well described by the Open-Hole-Tension (OHT) test and Filled-Hole-Tension test (FHT).



(a)

(b)

(c)

(d)

Figure 4 Load-displacement behaviour of only bolted (OB) and hybrid bolted bonded (HBB) joints with three bolts. Diagrams (a) and (b) are for quasi-isotropic and cross-ply laminates using the standard width W1=36mm. Diagrams (c) and (d) use narrow specimens with width W2=22mm.

A remarkable feature observed on the fracture of the 3-bolts HBB joints is that up to the final fracture, the damage initiation and propagation appears to be located almost exclusively in the external bolt-holes area as sketched on Figure 5. The final fracture ultimately proceeds from one these two locations in a net tensile fracture mode as observed for the OHT or FHT tests [1].

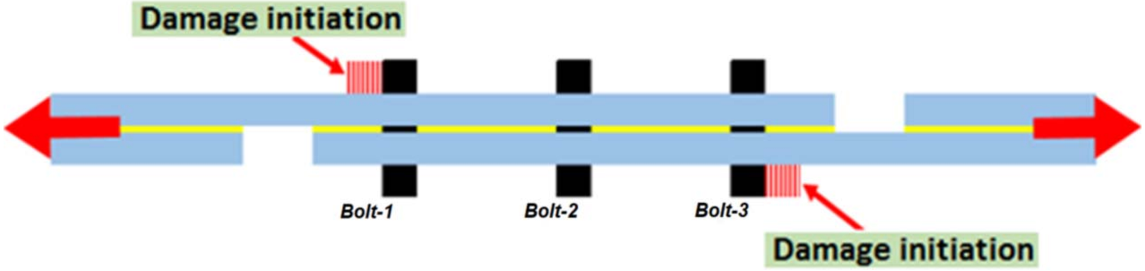


Figure 5 Illustration showing the localisation of the failure initiation and propagation in a three bolts HBB.

3.4 Explanation of the net-tension fracture behaviour with three bolts HBB joints

The behaviour of HBB specimens with three bolts discussed previously and displayed in Figures 4 and 5, can very easily explained if we consider the following two assumptions:

- The maximum strength that can be achieved by a multi-bolted specimen is the OHT or FHT strength as reported in the parent preceding investigation [1].
- The strength achieved by a bonded joint with sufficiently large overlap inherently exceeds the OHT or FHT strength.

Bearing the preceding assumption in mind, if the HBB joint reaches a load that is higher that the OHT or FHT strength, once the adhesive fails or yields, the operating load is quite higher than that can be supported by the multi bolted joint regardless of the number of bolts.

In order to verify the preceding statement, we have recalled the OHT and FHT strength of the same carbon/epoxy laminates from reference [1]. These results are shown in Table 1 and Table 2.

Table 1. Data from [1]. In [1] the strength is given in MPa. To convert the MPa in N, we multiplied by the nominal cross-section (2.65mm X 36mm)

Width = 36 mm	Quasi-isotropic laminates	Cross-ply laminates
OHT strength, N	30 146	29 669
FHT strength, N	31 196	31 577

Table 2. Data from [1]. In [1] the strength is given in MPa. To convert the MPa in N, we multiplied by the nominal cross-section (2.65mm X 22mm)

Width = 22 mm	Quasi-isotropic laminates	Cross-ply laminates
OHT strength, N	18 423	18 131
FHT strength, N	19 064	19 297

As it can be seen when comparing the ultimate load on Figure 3 on one hand and the maximum loads from Table 1 and Table 2, the assumption made above (i.e. once the adhesive fails or yields, the operating load is quite higher than that can be supported by the multi bolted joint regardless of the number of bolts) is verified and hence the behaviour of the multi-bolted HBB joints is explained. Indeed, for the standard joint with a quasi-isotropic configuration, the HBB joint reaches 35kN before the adhesive fails. In the meantime, the FHT of the material is 32kN. For the standard joint with a cross-ply configuration, the HBB joint reaches 38kN before the adhesive fails. In the meantime, the FHT of the material is 32kN. The same remarks are true for the case of the narrow HBB joints.

3.5 3-bolts HBB versus 2-bolts HBB with the equal overlap distance

In order to isolate the contribution of the central bolt in the 3-bolts HBB joints, tests were performed on the same 3-bolts HBB joint but without the center hole and bolt. That means there are only two bolts but the inter-bolt distance (IBD) is 72mm, which is equivalent to the distance between the two external bolt of the regular 3-bolts HBB joint as sketched in Figure 6. As shown by the typical load-displacement curves on Figure 6, the 2-bolts HBB specimen with an IBD=72mm achieves the same strength as the regular 3-bolts HBB. On the same diagram, the behavior of the regular 2-bolts HBB (IBD=36mm) as well as another 2-bolts HBB with a IBD=54mm are added. So, the diagram of Figure 6 offers the opportunity to display the effect IBD on the behaviour of 2-bolts HBB joints. It can be seen that when the IBD increases, the strength of the joint increases. Ultimately, when using the same overlap as for a regular 3-bolts HBB, the joints achieves the same strength as the 3-bolts HBB. These results show that for multi-bolted HBB joints the strength is governed by the adhesive and the internal bolts are unnecessary. Of course we can argue that the bonded joint is inherently stronger that the bolted joints. While this is being true for static loading, it will not be the case for cyclic loading. Under cyclic loading, the contribution of the bolts will be positive. Indeed, the external bolts may be required to stop the crack propagation that will necessarily start from the edges of bonded joint. Such a study dealing the cyclic loading of multi-bolted HBB joints is under completion by the authors.

4. CONCLUSIONS

A close look of the load-displacement response of only bolted (OB) and hybrid bolted bonded (HBB) joints shows that once the adhesive has failed, the residual load bearing becomes equivalent to that of OB specimen for the cross-ply configuration (CP) while it is higher for the quasi-isotropic configuration (Q). This feature is also verified for the case of narrow specimens as well as for the joints with two bolts.

A remarkable feature observed on the fracture of the 3-bolts HBB joints is that up to the final fracture, the damage initiation and propagation appears to be located almost exclusively in the external bolt-holes area as sketched on Figure 5.

The OHT or FHT strength is of the material determines if the multi-bolted HBB joint will fail in one or in two steps. If the HBB reaches a load higher that the equivalent OHT strength, the HBB will fail in one step, since the load transferred after the adhesive failure exceeds the OHT strength which is a limiting load fro multi-bolted OB joints.

Finally, the results show that for multi-bolted HBB joints the strength is governed by the adhesive and the internal bolts are unnecessary. While this is being true for static loading, it will not be the case for cyclic loading. Under cyclic loading, the contribution of the bolts will be positive. Indeed, the external bolts may be required to stop the crack propagation that will necessarily start from the edges of bonded joint. Such a study dealing the cyclic loading of multi-bolted HBB joints is under completion by the authors.

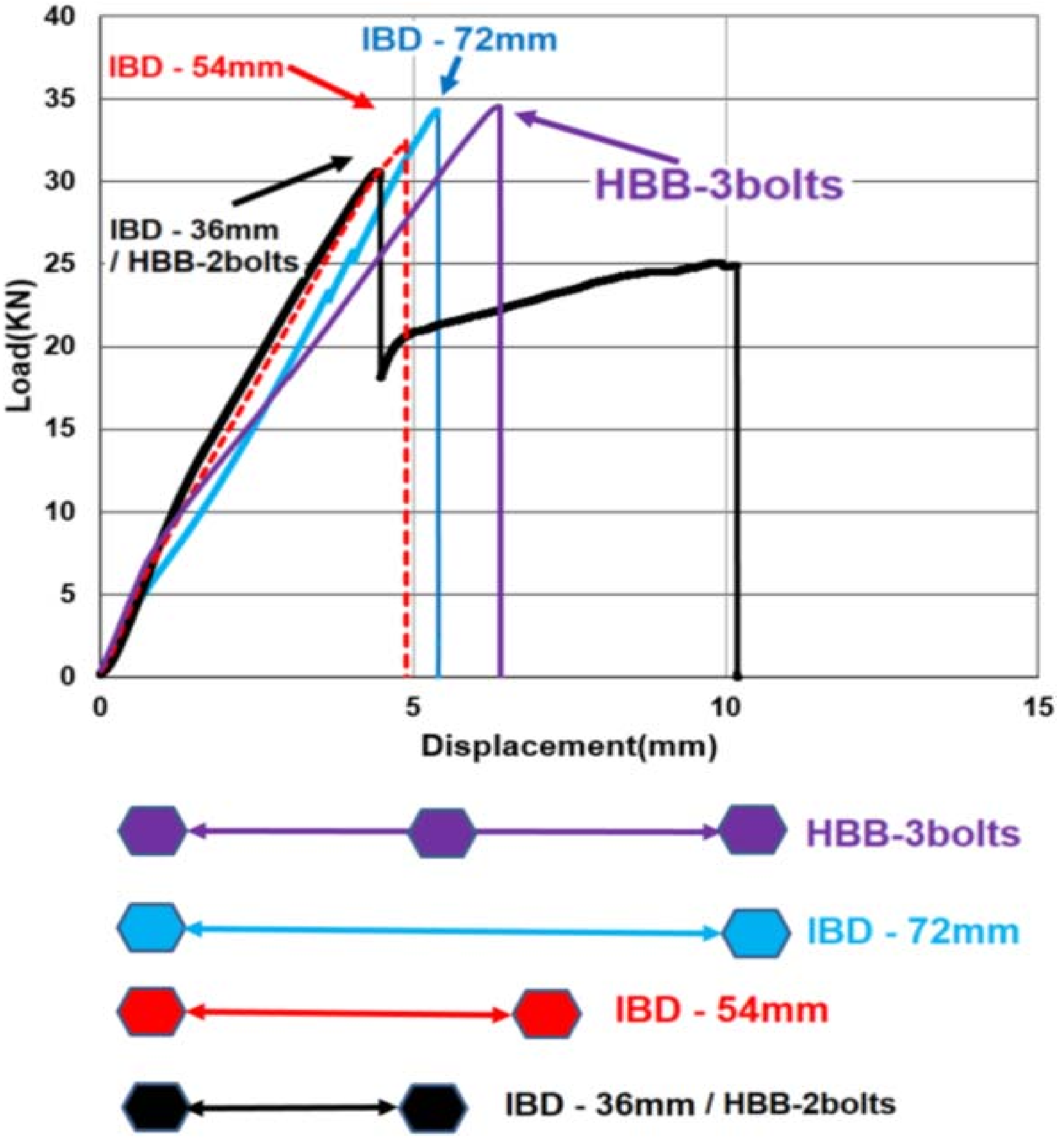


Figure 6 Effect of the inter-bolt distance (IBD) on the strength of HBB joints. The a 2-bolt HBB joint can achieve the same strength as a 3-bolt HBB with the same overlap as shown by comparing the HBB-3bolts curve with the IBD-72mm curve.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ). We also thank Bombardier Aerospace, L-3 Communications and Delastek Aeronautique Inc. for their valuable support.

REFERENCES

[1] F Gamdani, R Boukhili, A Vadean. Tensile strength of open-hole, pin-loaded and multi-bolted single-lap joints in woven composite plates. Materials & Design 88, 702-712 (2015)

[2] Mosallam, Ayman S. "Design guide for FRP composite connection". American Society of Civil Engineers, ASCE manuals and reports on engineering practice; no 102, 2011.

[3] Hart-Smith LJ., Design methodology for bonded-bolted composite joints. Vol.1 Analysis Derivations and Illustrative Solutions. Technical Report AFWAL-TR-81-3154, Douglas Aircraft Company, February 1982.

[4] Hart-Smith LJ. Bonded-bolted composite joints. J Aircraft 1985;22(11):993–1000.

[5] Fu M and Mallick PK. Fatigue of hybrid (adhesive/bolted) joints in SRIM composites. International Journal of Adhesion & Adhesives 21 (2001) 145-159.

[6] Kelly G. Load transfer in hybrid (bonded/bolted) composite singlelap joints. Composite Structures, 2005;69:35–43.

[7] Kelly G. Quasi-static strength and fatigue life of hybrid (bonded/ bolted) composite single-lap joints. Composite Structures, 2006;72: 119–29.

[8] S. Gomez, J. Onoro and J. Pecharroman, "A simple mechanical model of a structural hybrid adhesive/riveted single lap joint", International Journal of Adhesion & Adhesives 27 (2007) 263–267

[9] F. Moroni, A.Pirondi and F.Kleiner, "Experimental analysis and comparison of the strength of simple and hybrid structural joints", International Journal of Adhesion & Adhesives 30 (2010) 367–379.

[10] AA Taib, R Boukhili, S Achiou, S Gordon, H Boukehili. Bonded joints with composite adherends. Part I. Effect of specimen configuration, adhesive thickness, spew fillet and adherend stiffness on fracture. International Journal of Adhesion and Adhesives 26 (4), 226-236 (2006)

[11] ASTM-D5961/D5961M – 13, Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. United States; 2013

[12] McCarthy CT, Gray PJ, An analytical model for the prediction of load distribution in highly torqued multi-bolt composite joints, Composite Structures 2011; 93: 287–298