# Experimental study of the hybridization effect on bolt-hole elongation of multi-bolted single-lap composite joints using DIC

Masoud Mehrabian[1]*, Rachid Boukhili[1]

[1]Department of Mechanical Engineering, Polytechnique Montreal, Quebec, H3C 3A7, Canada

*Corresponding author (masoud.mehrabian@polymtl.ca, 4389277028)

**Keywords:** Bolt-hole elongation, Composites, Bolting, Hybrid joints, DIC

## Abstract

There are different types of joining methods which are being used in aeronautical structures in order to fasten the composite components. One of the high frequent techniques, which has been widely used, is single-lap joints. The common methods for joining thermoset composites are only-bolted (OB), adhesive bonding or combination of both methods, called hybrid bolted/bonded (HBB). An experimental investigation was conducted to determine the effect of hybridization (applying an adhesive between the two parts of a single-lap bolted joint) on bolt-hole elongation (BHE) of multi-bolted single-lap composite joints. To do so, the non-contact optical-based technique, which is called DIC (digital image correlation), is used. The laminated composite material under investigation in this study is a carbon fiber reinforced epoxy (CFRE) composite manufactured by the vacuum-assisted resin infusion process. The changes in bolt-hole elongation are tracked in the case of cross-ply (CP) and quasi-isotropic (QI) stacking sequences which are tested in two laminated thicknesses; eight plies and twelve plies.

The bolt-hole elongation (also known as hole wear) is of great concern in fatigue and also quasi-static loading, but its experimental measurements is very challenging. In the literature, it has been mostly done by displacement records of the mounted extensometers on the tested specimen, which is always associated with some errors and inaccuracies due to the movement of the fixture of the tensile test machine. In this study, the non-contact DIC technology contributed significantly to highlight BHE in detail. This in situ and robust measurement tool tracks the digital images of the specimen surface and compares the un-deformed with the deformed ones while a joint coupon is under tensile loading. DIC results showed the influence of the strain concentration relief around the holes caused by hybridization, on bolt-hole elongation. DIC technique is found to be an efficient and highly practical method in this respect.

## 1. Introduction

Carbon fiber reinforced polymer (CFRP) composites are being widely used in primary structures of aircrafts, ships, and other applications where high reliability must be maintained during either short-term or long-term operations due to their excellent specific properties such as good mechanical properties like light weight, high strength, low thermal and electrical conductivity and corrosion resistance [1, 2]. Three types of joints are commonly used to connect composite components which are mechanically fastened joints, adhesively bonded joints, and hybrid of the both techniques [3]. Various parts of a composite structure should be connected to each other using the mentioned joining techniques. The presence of the joints increase the flexibility of the whole structure. The added flexibility not only includes the elongation of the hole as well as the stress concentration around these holes, but also the deformation/rotation of the bolt [4]. Here in this work, the first aspect, i.e. hole elongation, is investigated in the case of both only-bolted (OB) and hybrid bolted/bonded (HBB) joints. While the hole elongation is of significant concern in cyclic loading and researchers put too much focus on it so far, according to [5], hole elongation of fatigue tested composite joints was remarkably smaller than that of tensile tested ones. Therefore, it is necessary to explore the hole elongation response and corresponding bearing behavior and their accumulated effects on mechanical behavior of multi bolted bonded single lap composite joints. In this work, the aim is to investigate experimentally the hole elongation of only-bolted (OB) single-lap composite joints and evaluate the effects of hybridization on it.

Chen [6] found that in fatigue testing, bearing failure generally occurs due to joint stiffness reduction and/or significant elongation of the joint hole, and high clamp-up torque results in small hole elongations. Moreover, it was found that the elongation of the bolt-holes is by far the most important structural phenomenon controlling stiffness [7]. Girard et. al. [8] showed that composite lay-up can affect the hole elongation in a way that the angle-ply and the quasi-isotropic lay-ups present similar hole elongations which are larger than the cross-ply hole elongation. Under the fatigue testing, long fiber reinforced leaf spring joint experienced lower hole elongation than unreinforced or short fiber reinforced for all the stress levels [9]. It is evident that the bolt-hole elongation increases as the number of fatigue cycles increase, while it decreases gradually with the increase in interference-fit sizes. Moreover, hole elongation shows a linear variation trend under lower tensile stress, and an exponential variation trend under higher tensile stress [10]. Results of the influence of bolt hole to edge eccentricity for double shear composite bolted joints showed that increasing of edge distance results in growing the bolt hole elongation [11]. The combined effects of seawater ageing and fatigue loading on the bearing performance and failure mechanism of single-lap composite bolted joints was investigated by Zhang et al [5], and it was found that the hole elongation, under quasi-static loading, for fatigue tested specimens is considerably smaller than that of non-fatigue tested. Sajid et al. [12] investigated the role of washer size on bolt hole elongation of a single lap basalt composite joint and a significant hole elongation was observed for larger washer configuration, but there was no apparent hole elongation for small washer configuration.

This investigation was done in order to provide more precise results regarding hole elongation of single lap composite joint using digital image correlation technology. The obtained results can assist to understand more profoundly the behavior of only bolted (OB) and hybrid bolted/bonded (HBB) joints. The experimental DIC results are expected to highlight more details to contribute in composite joining design for different types of aeronautic structures.

## 2. Experimental procedure

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 and 8 plies of 3K plain wave carbon fabric with a 135.11 g/m2 surface weight [13]. The mean thickness value of the panels is about 2.6 mm and 1.6 mm for 12 and 8 layers respectively. The woven plies are oriented to obtain the quasi-isotropic (Q) and cross-ply (CP) laminate configurations which their lay-up are given in Table 1.

Table 1: Stacking sequences of the manufactured laminates.

| Code | Lay-up | Plies | Average thickness (t, mm) |
|---|---|---|---|
| CP8 | $[(0/90)/(0/90)/(0/90)/(0/90)]_s$ | 8 | 1.65 |
| QI8 | $[(0/90)/(\pm45)/(0/90)/(\pm45)]_s$ | 8 | |
| CP12 | $[(0/90)/(0/90)/(0/90)/(0/90)/(0/90)/(0/90)]_s$ | 12 | 2.63 |
| QI12 | $[(0/90)/(\pm45)/(0/90)/(\pm45)/(0/90)/(\pm45)]_s$ | 12 | |

Single-shear multi-bolted joints were designed and manufactured according to the ASTM-D5961 [14]. In order to fasten the two parts in single lap (SL) only bolted (OB) joints, steel hex head shear bolts (NAS6204-4) with a diameter of 6.35 mm, nuts (MS21042-4) and cadmium-plated steel washers (NAS1149F0463P), with an internal diameter of 6.73 mm and external diameter of 12.70 mm on both head and nuts sides, were utilized. A tightening torque of 5 Nm applied to each of the bolts by means of a Tohnichi Dial Torque Wrench DB25N-S. A specialized carbide drill with a diameter of 6.35 mm, obtained from YG-1 America, Inc. was used to drill in the CFRP specimens [3]. The only difference between only bolted joints and hybrid-bolted-bonded (HBB) joints is applying an adhesive between the faying surfaces. The adhesive used is the same epoxy resin utilized for manufacturing of the composite laminate [13]. The prefix of OB and HBB is added to the laminate code, e.g. HBB-QI8, to specify the class of configuration to be either only bolted or hybrid-bolted-bonded joint respectively. The geometrical configuration of single lap OB and HBB composite joints is shown in Figure 1.

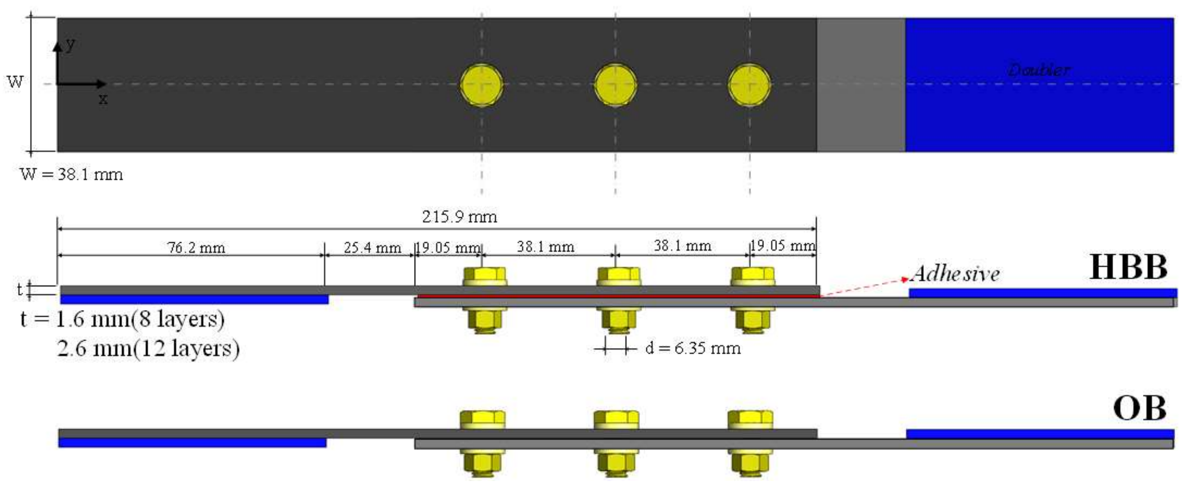


Figure 1: Specimen geometry and dimensions used for OB and HBB single lap joints.

In this study, digital image correlation technology was used to measure the full-field displacement and deformation of the surface of interest. The basic principle of this optical non-contact measurement technique is based on tracking (or calculating) the random pattern on the specimen surface which is carried out by matching the local distribution of pixel concentration, i.e. subsets, between the un-deformed image and the deformed images during the specific time interval [3]. The surface deformation is computationally reached by optimizing a cross-correlation or least-squares function to evaluate the degree of similarity between undeformed and deformed specimen in terms of the grayscale intensity values [15]. The 3D DIC system and software used is a Vic-3D v 7.2.4 model from Correlated Solutions Inc. (CSI), USA.

# 3. Results and discussion

## 3.1. Bolt-hole elongation (BHE)

The bolt-hole elongation (AKA hole wear) is of great concern in fatigue and also quasi-static loading, but its experimental characterization is very challenging. In this study, the non-contact DIC technology contributed significantly to highlight it in detail. To do so, three virtual extensometers (VE) were placed diametrically in the axial direction at the bolt positions (inset photo in Figure 3) and they are labeled as E3, E2 and E1. The following first section studies the case of only bolted joints (Figure 3-4), the second section deals with hybrid bolted bonded joints (Figure 5-6), and finally, the third section compares the two in a bar chart diagram at 15kN and 25kN for 8 and 12 layers laminate respectively (Figure 7). For the sake of better visualization and perform comparison, a curve is fitted to the scattered data points. The test results analyzed are based on the DIC data recorded for eight different single-lap joint tests (see Table 1), and the corresponding failure loads and load–displacement responses are shown in Figure 2.

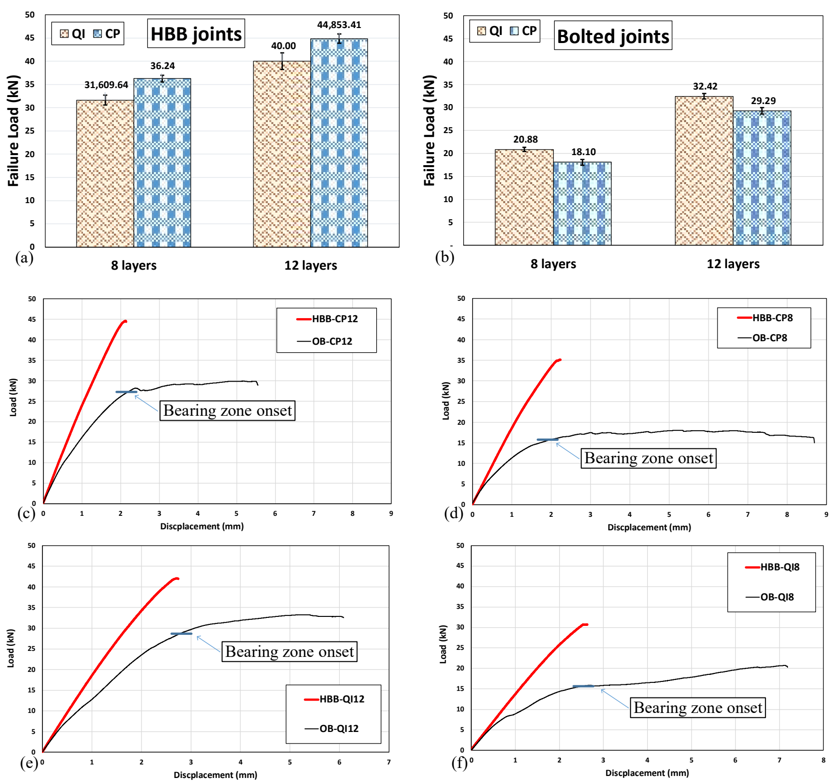


Figure 2: Failure load of CP and QI (a) HBB and (b) OB, as well as load-displacement behavior of OB vs HBB joints, (c) CP12, (d) CP8, (e) QI12 and (f) QI8.

### 3.1.1. BHE of only bolted (OB) joints

Bolt-hole elongation is generally defined as the term used to describe the deformation of the bolt-hole caused by both bearing of the bolt-shank against the bolt-hole [7] and the by-pass load which flows around hole. Figure 3 illustrates BHE throughout the applied tensile load and upon the onset of the bearing zone in the OB joints (Figure 2), where the joint entered the rather plateau phase. At first sight, it can be observed intuitively that BHE decreases gradually as advancing from hole 3 (grip side) towards hole 1 (free side). This can be justified due to the stepwise reduction of the by-pass/bearing load ratio in the mentioned direction [3]. At the equal load level, the thinner joints experienced more BHE than the thicker ones (more pronounced at the critical region, B3). This might be attributed to the higher induced bending stress in thicker joints due to greater geometrical eccentricity [16]. Consequently, outer surface of the thicker laminate (at the fastener location) may confront more compression than the thinner ones which could reduce overall BHE. Furthermore, it could be inferred that in the thinner joints, more portion of the applied load is transmitted through the plate. Figure 3 shows obviously that there is a non-linear relationship between BHE and tensile loading. A parametric factor can be assigned calling BHE stiffness ($k_e$) which represents the slope of load-elongation curves. The curves of CP lay-up exhibits two different values for $k_e$. The first portion of the curves is mostly linear and has a higher value of $k_e$. However, it is followed by lower BHE stiffness as the curve slope suddenly reduced. The curve of this section become nonlinear which is associated with considerable local damage in vicinity of the bolt-hole (it is more explained in the following paragraph). This is unlike QI lay-up showing a rather single curve slope which results in minor changes in BHE stiffness. It is suggested that the less notch sensitivity of QI than CP could be the reason [17]. At the lower load level, i.e. first portion, CP lay-up presents slightly higher stiffness than that of QI because the former laminate possess proportionally more fibers oriented along the load direction [8].

As stated before, BHE is associated with the combination of bearing and by-pass loads, in which the stress concentration of the former is more severe than the later [18] and may alter the magnitude of local elongation, i.e. BHE. For both thin and thick configurations and at the lower load levels, QI experienced more BHE than CP. However, as the load increases, BHE curves of CP surpassed that of QI, which ended up CP having more elongation. As a result of that, more bearing damage is formed around the bolt-hole of CP. Figure 4 compares the consequence of more BHE of OB-CP12 than OB-QI12 under the critical bolt, i.e. B3, where failure occurred. Less BHE of QI, which is accompanied by better bearing performance, results in higher strength retention in QI than CP for bolted joints (Figure 2) [3]. In 8-layer joints, the curves of CP associated with holes 3, 2 and 1, surpassed that of QI at approximately 7.5 kN, 10 kN and 11 kN respectively. The corresponding values for 12 layers are about 12 kN, 17.5 kN and 20 kN. It can be said that with an acceptable estimation, the CP curves of E3, E2 and E1 overtook that of QI at roughly 40%, 55% and 60% FL respectively. So, it can be seen that for the critical bolt, i.e. B3, this happened much sooner and at about the moment of transition of the load transfer mechanism from friction between faying surfaces to bolt load bearing [16]. According to the mentioned percentages, it might be suggested that bolt shank of B2 and B3 get into contact with the bolt-hole perimeter (at the surface of interest) with a small delay compared to the case of B1.

The observation of CP surpassing QI could be elucidated by the fact that the stress concentration is intensified when the number of $0^o$ plies increases, and lessened when the portion of $\pm 45^0$ plies rises. While the applied load increases, the stress concentration becomes a dominated factor in generating delamination and macro cracking within the laminate and specifically around the holes. Therefore, during the increase of the applied load, CP suffers more from severe stress concentration than QI, which eventually led to experiencing higher BHE. Overall, it can be concluded that in single-lap bolted composite joints, the rate of increase in the level of BHE is highly dependent on the laminate lay-up, e.g. portion of $0^o$ plies, and a laminate with lower $0^o$ plies content finally undergoes less hole wear and restored higher strength.

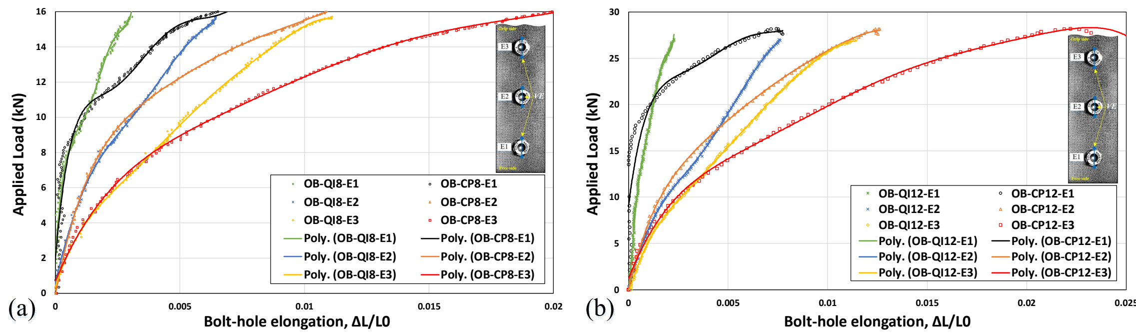


Figure 3: Bolt hole elongation of OB-CP and OB-QI (a) 8-layer and (b) 12-layer.

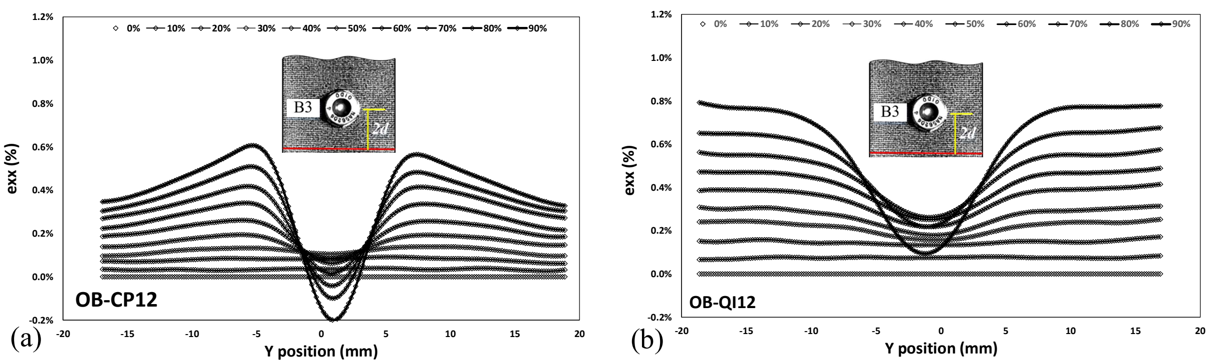


Figure 4: Deformation below B3 between 0% and 90% of the applied load: (a) OB-CP12 and (b) OB-QI12.

### 3.1.2. BHE of hybrid bolted bonded (HBB) joints

Figure 5 shows BHE for the case of HBB joints and up to the complete failure. Like the bolted joints, it is observed that the values of BHE decreases from hole 3 to hole 1. Moreover, at the equal amount of the applied load, the thinner joints experienced more BHE than the thicker ones. It can be deduced that there is more by-pass load within the laminate in thinner configurations than the thicker ones, despite the fact that the main mechanism of the load transmission between the plates takes place via the adhesive. It is interesting to observe that in a given thickness, the BHE values of each individual holes of QI and CP are almost equal, which clearly indicates the independency of BHE from laminate stacking sequence and bolt movement in hybrid bolted-bonded single-lap composite joints.

Moreover, there is not any fair share of bearing act in forming the hole elongation (curve trend), probably because of the added adhesive. Thus, it proves again that in multi bolted hybrid composite joints, the dominant mechanism of load transmission is adhesive itself to a significant extent. Similar to Figure 4, the surface deformation under the B3 for HBB-CP12 and HBB-QI12 is shown in Figure 6. It can be seen that the curves do not cross each other, and the concavity (depression) shape is formed merely by the bypass load, which flowed around the hole and has its own maximum tensional effect on bilateral sides of the hole [3].

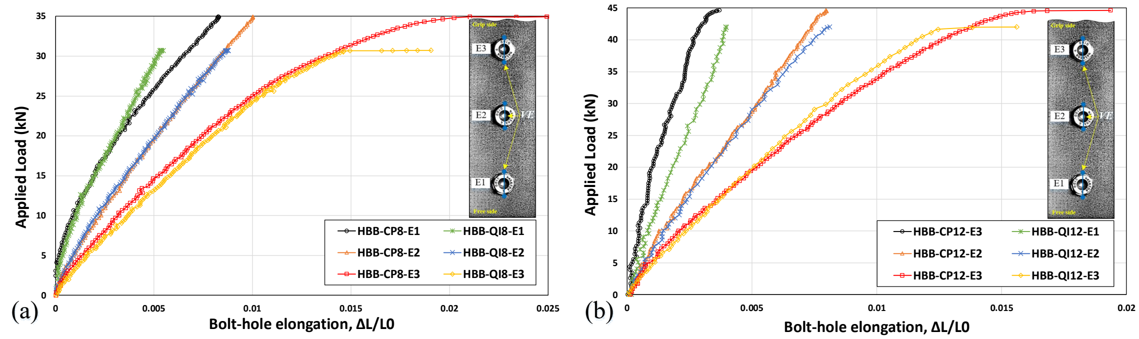


Figure 5: Bolt hole elongation of HBB-CP and HBB-QI (a) 8-layer and (b) 12-layer.

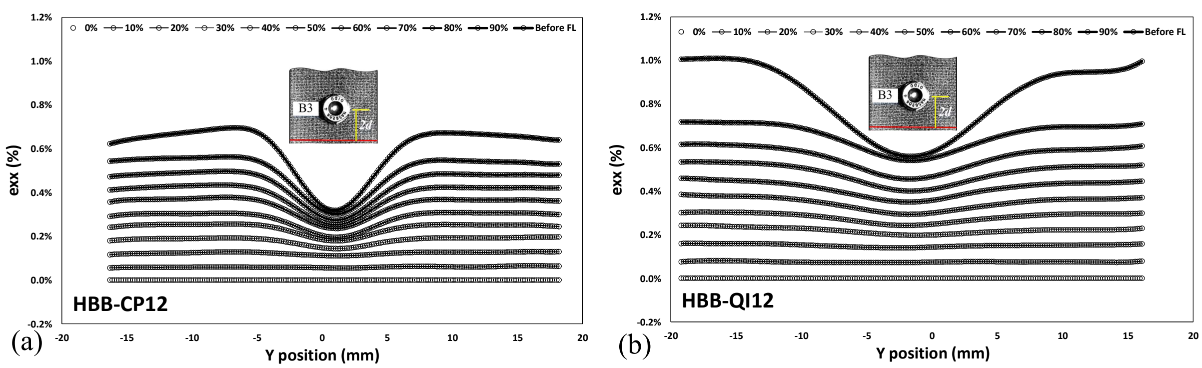


Figure 6: Deformation below B3 from 0% up to before final failure: (a) HBB-CP12 and (b) HBB-QI12.

### 3.1.3. Bolt hole 3 elongation in OB versus HBB – CP and QI

As mentioned before, the aim of this section is to compare BHE of bolted versus hybrid bolted-bonded joints to see the effect of hybridization on hole elongation changes. Figure 7 shows the comparison for all the bolt-hole, and at two points of interest (15 kN and 25kN for 8-layer and 12-layer, respectively) which corresponded to non-linear section of the load-displacement diagram (Figure 2). As mentioned before, the elongation values of BH1, BH 2 and BH3 of only-bolted cross-ply joints are greater than that of the quasi-isotropic for both thin and thick laminates at the higher load level. In a given thickness, BHE of HBB is almost the same, but it remarkably varies in OB case. It is clearly evident that hybridization diminished hole elongation in which the reduction of about 36% and 65% in B3 were experienced by QI and CP configurations respectively. It is interesting to see that hybridization contributes better for CP, compared to QI, since the CP suffers from severe stress concentration around the holes and adhesive reliefs it. This statement is proved here, since results exhibit more elongation reduction of CP than QI after applying adhesive between the adherends. Better performance of the adhesive in reducing dramatically the BHE of CP, assisted this configuration in sustaining its strength (as was shown in Figure 2).

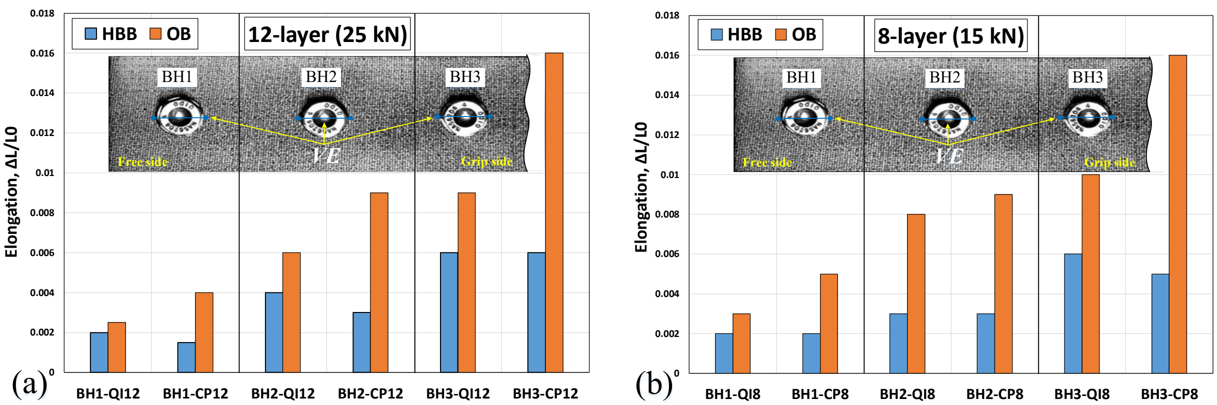


Figure 7: Comparison of BHE in OB versus HBB of each CP and QI joints at a certain load level (a) 25 kN 12-layer, (b) 15kN 8-layer.

## 4. Conclusion

In this work, digital image correlation (DIC) technology was used to measure precisely the hole elongation of multi bolted single lap carbon fiber composite joint and assess the effect of adding adhesive between the joint parts (hybridization) on bolt-hole elongation (BHE). The consequent bearing response of the investigated lay-ups, namely cross-ply (CP) and quasi-isotropic (QI), were also examined. The following remarks are drawn from this study:

- Due to higher sensitiveness of CP to the stress concentration, at higher load level, BHE magnitude of CP becomes greater than that of QI.
- Better bearing performance in QI leads to higher strength retention in QI than CP for bolted joints.
- Hybridization reduces BHE substantially which was more pronounced in CP than QI due to the stress concentration relief around the bolt-hole provided by the adhesive. This aids CP to sustain its strength.
- Bolt-hole elongation in HBB is independent from laminate stacking sequence.
- It was found that the laminate lay-up is an important factor in influencing hole elongation (hole wear) which aids for better design of a bolted composite joint.
- Digital image correlation technique is found to be an efficient and highly practical method in measuring the hole elongation.

## References

[1] Mehrabian M, Golmakani M. Nonlinear bending analysis of radial-stiffened annular laminated sector plates with dynamic relaxation method. Computers & Mathematics with Applications. 2015;69(10):1272-302.
[2] Davies P, Rajapakse YD. Durability of composites in a marine environment: Springer; 2014.
[3] Mehrabian M, Boukhili R. 3D-DIC strain field measurements in bolted and hybrid bolted-bonded joints of woven carbon-epoxy composites. Composites Part B: Engineering. 2021:108875.

[4] Vangrimde B, Boukhili R. Analysis of the bearing response test for polymer matrix composite laminates: bearing stiffness measurement and simulation. Composite structures. 2002;56(4):359-74.
[5] Zhang K, Li H, Cheng H, Luo B, Liu P. Combined effects of seawater ageing and fatigue loading on the bearing performance and failure mechanism of CFRP/CFRP single-lap bolted joints. Composite Structures. 2020;234:111677.
[6] Chen H-S. The static and fatigue strength of bolted joints in composites with hygrothermal cycling. Composite structures. 2001;52(3-4):295-306.
[7] Lim JB, Nethercot D. Stiffness prediction for bolted moment-connections between cold-formed steel members. Journal of constructional steel research. 2004;60(1):85-107.
[8] Girard C, Dano M-L, Picard A, Gendron G. Bearing behavior of mechanically fastened joints in composite laminates--Part I: strength and local strains. Mechanics of Advanced Materials and Structures. 2003;10(1):1-21.
[9] Subramanian C, Senthilvelan S. Effect of reinforced fiber length on the joint performance of thermoplastic leaf spring. Materials & Design. 2010;31(8):3733-41.
[10] Li J, Zhang K, Li Y, Liu P, Xia J. Influence of interference-fit size on bearing fatigue response of single-lap carbon fiber reinforced polymer/Ti alloy bolted joints. Tribology International. 2016;93:151-62.
[11] Croxford AM, Davidson P, Waas AM. Influence of hole eccentricity on failure progression in a double shear bolted joint (DSBJ). Composites Science and Technology. 2018;168:179-87.
[12] Sajid Z, Karuppanan S, Sallih N, Kee K, Shah S. Role of washer size in mitigating adverse effects of bolt-hole clearance in a single-lap, single-bolt basalt composite joint. Composite Structures. 2021;266:113802.
[13] Gamdani F, Boukhili R, Vadean A. Tensile behavior of hybrid multi-bolted/bonded joints in composite laminates. International Journal of Adhesion and Adhesives. 2019;95:102426.
[14] 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.
[15] Daly SH. Digital image correlation in experimental mechanics for aerospace materials and structures. Encyclopedia of Aerospace Engineering. 2010.
[16] Mehrabian M, Boukhili R. Quantifying of secondary bending effect in multi-bolt single-lap carbon-epoxy composite joints via 3D-DIC. Composites Science and Technology. 2020:108453.
[17] Gamdani F, Boukhili R, Vadean A. Tensile strength of open-hole, pin-loaded and multi-bolted single-lap joints in woven composite plates. Materials & Design. 2015;88:702-12.
[18] Skorupa A, Skorupa M. Riveted lap joints in aircraft fuselage: design, analysis and properties: Springer Science & Business Media; 2012.