QUASI-STATIC STRENGTH OF HYBRID BONDED-BOLTED SINGLE-LAP JOINTS

Kobyé Bodjona[1] and Larry B. Lessard[2]

[1]Department of Mechanical Engineering, McGill University, Montreal, Canada
Email: kobye.bodjona@mail.mcgill.ca, Web Page: http://composite.mcgill.ca
[2] Department of Mechanical Engineering, McGill University, Montreal, Canada
Email: larry.lessard@mcgill.ca, Web Page: http://composite.mcgill.ca

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Abstract
In this work the quasi-static strength of bonded and hybrid bonded-bolted single-lap joints with different types of adhesive is investigated experimentally. It is found that when a bonded joint has a thick, flexible and ductile adhesive layer, the load at which the first fracture occurs can be increased substantially through addition of a bolt to the joint ("hybridization"). Conversely, when the adhesive layer is thin and stiff, the addition of a bolt does nothing to increase the fracture onset load. Furthermore, the stiffness of and energy dissipated by a hybrid bonded-bolted joint relative to its constituents are also shown to be strongly dependent on the adhesive system.

1. Introduction

Over the course of the past few decades, the combination of bonding and bolting has intrigued many researchers and designers of composite structures, e.g., [1-4]. The fundamental question occupying these investigators has been whether such a "hybrid" joint can offer any advantages compared to using either type of joint by itself. The findings have been mixed. Some investigators claim that hybrid bonded-bolted joints are fundamentally flawed [2, 5]. Their argument is that since the bonded joint is typically considerably stiffer than the bolted joint, the bolt does not actively partake in load transfer until failure of the adhesive. It is only following adhesive failure that the bolt becomes active, after which the joint behaves essentially like a bolted joint until ultimate failure of the bolt or adherends. Consequently, the joint limit strength (defined as the onset of fracture) is no greater than that of the underlying bonded joint by itself and the ultimate strength is no greater than that of the strongest constituent joint by itself. This explanation is supported by a growing body of experimental results [1, 4, 6-8]. However, the studies in question only truly pertain to a particular configuration. The literature shows that the joints in these studies invariably use stiff and thin bondlines, mimicking the way in which bonded joints are traditionally designed.

Other investigators have shown experimentally and convincingly that there are in fact hybrid joint configurations for which the fracture onset load is increased compared to that of the underlying bonded joint by itself [3, 9]. In addition, the joint ultimate strength can also sometimes be improved, such that the hybrid outperforms *both* of its constituents joints [3, 10]. It is remarked that all of these studies use rather unorthodox bondline designs, featuring flexible adhesives and thick bondlines.

Based on these observations, the aim of the present work is to test the hypothesis that the adhesive system (type and thickness) has a major influence on hybrid bonded-bolted joint performance—including the fracture onset load—relative to its constituent joints. This is achieved by means of quasi-static testing of various (bonded, bolted and hybrid bonded-bolted) single-lap, single-bolt joints in uniaxial tension.

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2. Hypothesis

If the quasi-static performance (i.e., stiffness, strength and energy dissipation) of a Hybrid Bonded-Bolted (HBB) joint relative to the underlying joints is related to the adhesive type/thickness, then varying the adhesive type/thickness will cause a change in the relative joint performance.

3. Test Matrix

To test the hypothesis, the test matrix presented in Table 1 was developed. Each cell corresponds to a particular configuration and contains the number of tested specimens in parentheses. For each joint type, the adhesive type/thickness was varied while the composite laminates and joint geometry were kept constant.

Table 1. Test matrix.

<table>
<tr><th>Adhesive Type / Joint Type</th><th>Cytec FM300-2M Film Adhesive, 0.25 mm Nominal Thickness</th><th>Hysol EA9361 Paste Adhesive, 0.5 mm Nominal Thickness</th></tr>
<tr><td>Bonded</td><td>(5)</td><td>(3)</td></tr>
<tr><td>Bolted</td><td colspan="2">(4)</td></tr>
<tr><td>Hybrid Bonded-Bolted</td><td>(4)</td><td>(3)</td></tr>
</table>

As shown, between 3 and 5 specimens were tested per configuration. Originally, it was intended to test 5 specimens per configuration. However, a manufacturing error (faulty layup) led to the scrapping of a number of specimens. Nevertheless, it is considered that even 3 repeats should result in acceptable statistical precision.

4. Specimen geometry and manufacture

The specimen geometry that was tested is shown in Figure 1. As illustrated, the grip ends of the adherends were fitted with tabs.

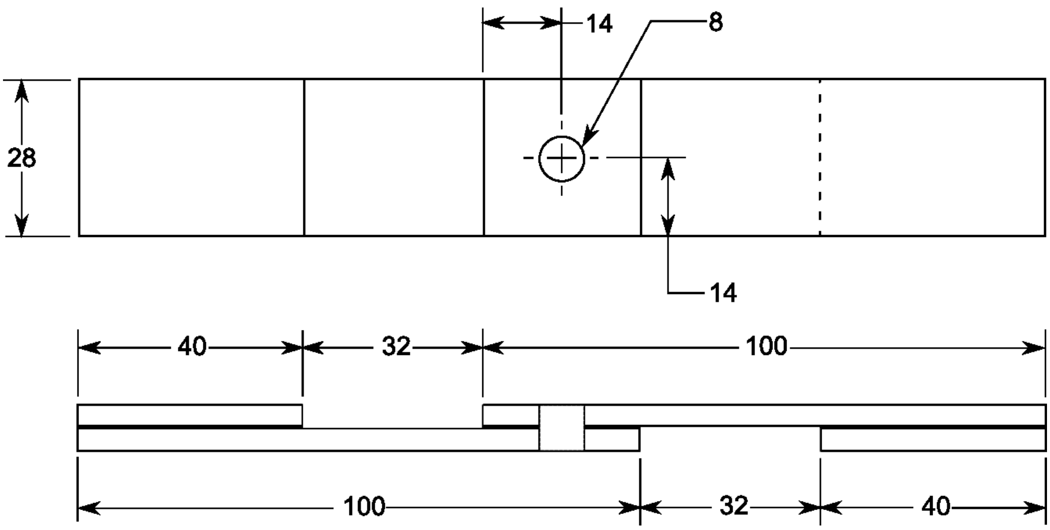

Figure 1. Specimen geometry.

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Both the adherends and the tabs were made from a laminated composite plate with a layup of [45/0/-45/90]$_{4s}$. This laminate was manufactured from Cycom T650/5320 unidirectional pre-impregnated CFRP tape. The manufacturer's recommended out-of-autoclave cure process was used, resulting in a measured post-cure laminate thickness of 4.42 ± 0.07 mm. A diamond-tipped saw was used to cut the adherends and tabs from the plate, following which the laminate quality was verified using microscopic void analysis of a number of samples obtained during the cutting process. Subsequently, the joints were manufactured.

To manufacture the bonded joints, a special mold was used to enable precise control of the adherend alignment, overlap length and bondline thickness (for the paste adhesive). The latter two variables were controlled using a set of specially manufactured shims/spacers placed inside the mold. The bonding surfaces of the adherends and tabs were first de-greased with acetone and subsequently abraded using a sand blaster. Any dust generated was removed using compressed air. The adherends were hence bonded/assembled in the mold. Hysol EA9361, being a two-part paste adhesive, required mixing prior to application. This mixing was performed using a Thinky ARE-310 centrifugal mixer in order to achieve good uniformity and avoid entrapped air bubbles. The EA9361 joints were cured at 80°C for 60 minutes, while the FM300-2M joints were cured at 121°C for 90 minutes, following the manufacturers' specifications. Excess adhesive that spilled from the joints during cure was carefully removed using a hack saw and sanded down with fine grit sandpaper to appear flush with the joint. The average EA9361 bondline thickness was measured post-cure to be 0.460 ± 0.028 mm. This value was obtained by measuring the adherend thickness in the overlap region prior to bonding, and then measuring the bonded sandwich post-cure. The adhesive thickness was taken to be the difference between these two measurements. The closeness of the measured value to the desired nominal adhesive thickness of 0.5 mm and low scatter confirms the ability of the developed manufacturing system to produce controlled, consistent thickness bonds for the EA9361 adhesive. The FM300-2M bondline thickness was accurately controlled without the use of shims since this adhesive contains an embedded scrim cloth. It was thus simply assumed to be equal to the manufacturer's stated nominal thickness of 0.25 mm.

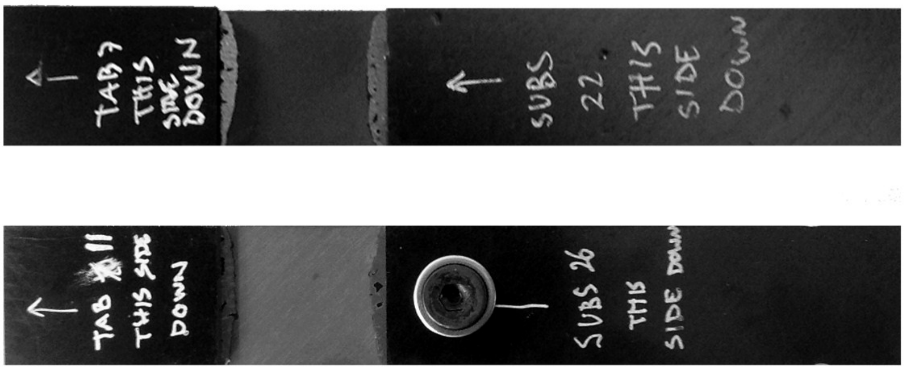

Figure 2. Example bonded joint and hybrid joint specimens.

The HBB joints were created by first manufacturing the underlying bonded joint, followed by drilling an 8 mm hole at the center of the joint overlap using a CNC drill. A CoroDrill 854 composite-specific drill bit was used for optimal hole quality. The diametric tolerance of the hole was confirmed to be within 25.4 microns using a set of go/no-go gauges. The bolted joints were manufactured using the same process as the HBB joints, except that the overlap region was evidently not bonded. For both the bolted and hybrid joints, the bolts that were used were Misumi GDMSB8-13-F10-M8 steel bolts. DIN-125 flat washers were placed on either side of the joint between the bolthead and metric M8 heavy hex nut, as is visible in Figure 2. The nut was finger tightened prior to installation of the joint in the testing machine.

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5. Test procedure

The joints were tested under quasi-static tensile conditions at a displacement rate of 0.006 mm/min, consistent with the displacement rate at which the EA9361 adhesive was characterized. A 100 kN MTS tensile testing machine was used for this purpose. During testing, the load and crosshead displacement were recorded. All tests were performed under Room Temperature Dry (RTD) conditions. To minimize the effect of external influences, tests for either type of adhesive were always performed within the same day.

6. Results and discussion

6.1 Stiffness

Figure 3 shows the load-displacement curves for the EA9361 bonded and hybrid joints and the bolted joints. It is evident that the stiffness of the bonded and hybrid joints is initially similar. At a load of around 5 kN, the stiffness of the bonded joint significantly decreases. This is explained by plasticity spreading throughout the bonded area [11]. When this happens, the adhesive loses much of its resistance to additional deformation, resulting in the observed stiffness decrease. The HBB joint stiffness also decreases at the same load; however, it remains greater than those of both the bonded joint and the bolted joint. This is explained as follows. Once the adhesive has plasticized, the HBB joint compliance—like the bonded joint—starts to significantly increase. However, the bolt-hole clearance soon becomes taken up and most of the additional load begins to be transferred through the bolt. The hybrid joint stiffness hence becomes equal to that of the bolted joint in addition to the residual bonded joint stiffness.

The bolted joint stiffness is initially lower than that of both the unyielded bonded and hybrid EA9361 joints and is quasi-linear up to a load of around 16 kN. At this point, the composite begins to sustain damage. The damage increases with increasing load, causing the bolted joint stiffness to gradually decrease.

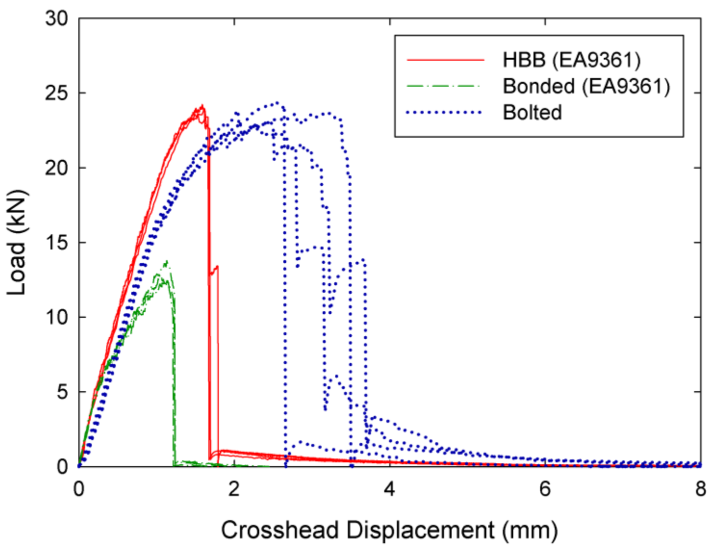

Figure 3. EA9361 load-displacement curve.

The FM300-2M bonded and hybrid joints load-displacement curves are shown in Figure 4. Between 0 and 12 kN of applied load, the HBB joint and bonded joint exhibit quasi-identical stiffness (which is significantly greater than that of the bolted joint) and the load displacement curves are virtually linear.

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The distinct bilinear load-displacement behavior of the EA9361 joints is not observed. At a load of approximately 12 kN, the adhesive fractures, leading to sudden failure of the bonded joint and a drastic reduction in the load and stiffness of the HBB joint. The latter is able to continue sustaining load following the adhesive fracture with identical stiffness to that of the bolted joint.

The initial joint stiffness, calculated as the average slope of the load-displacement curves between 0 and 5 kN, is compared in detail in Figure 5 for both the FM300-2M and EA9361 bonded and hybrid joints. It is clear that the choice of adhesive system (type/thickness) has an important effect on both the hybrid and bonded joint stiffness, with the FM300-2M joints being significantly stiffer than the EA9361 joints. However, for a given type of adhesive, the hybrid and bonded joints initially have very similar stiffness. This indicates that the adhesive is the dominant load transfer mechanism in this initial region. The HBB stiffness is in each case slightly lower than the bonded stiffness, which is explained by the smaller bonded region due to the hole in these joints, although the difference is not statistically significant.

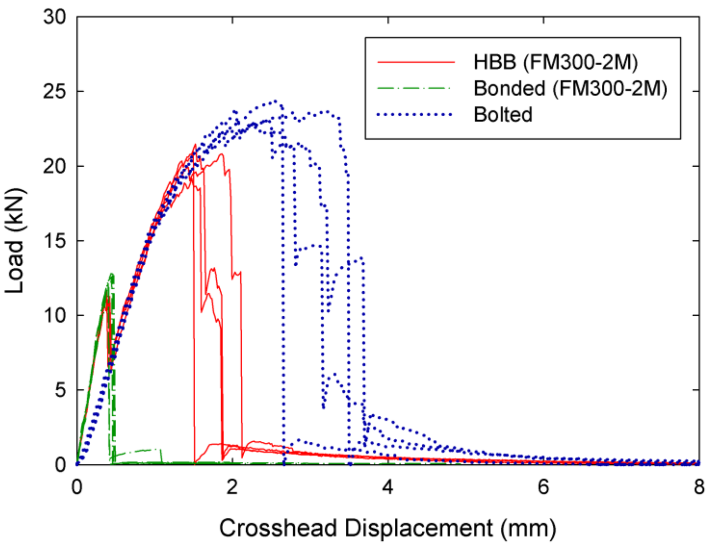

Figure 4. FM300-2M load-displacement curve.

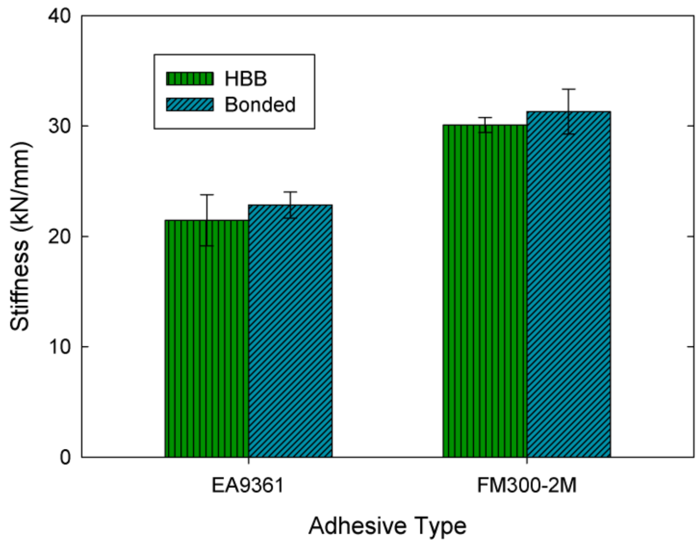

Figure 5. Comparison of joint stiffness in the 0-5 kN range.

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6.2 Strength

The ultimate strengths of the various joint configurations are compared in Figure 6. In addition, the 2% yield strengths for the HBB and bolted joints are also shown. For both the EA9361 and FM300-2M adhesives, it is evident that the bonded joint is the weakest type of joint (it should of course be kept in mind that this statement is not generally true). For EA9361, the HBB joint and bolted joints have statistically similar ultimate strengths. Meanwhile, for FM300-2M the HBB joint actually has a significantly lower ultimate strength than the bolted joint. The yield strengths also exhibit an interesting trend. For the EA9361 joints, the HBB 2% offset yield strength (corresponding to onset of damage in the composite) is 18% greater than that of the bolted joint. On the other hand, for the FM300-2M joints it is seen that the damage onset in the HBB joint is not affected compared to that of the bolted joint.

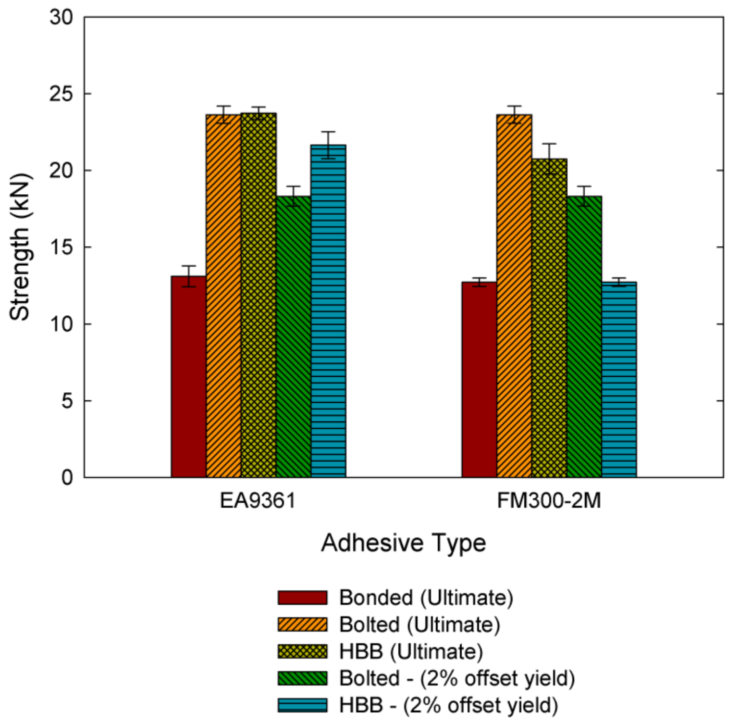

Figure 6: Comparison of joint strengths

6.3 Energy dissipation

One suggested advantage of hybrid bonded-bolted joints is that they could increase the amount of energy that the joint is able to dissipate during fracture, which could potentially be important for, for example, crashworthiness. The energy dissipated by the joint is simply the area underneath the load-displacement curves shown in Figures 3-4. Importantly, no studies on hybrid bonded-bolted joints have so far explicitly addressed this important aspect, despite having had access to the data to do so. The results of this analysis are shown in Figure 7 below.

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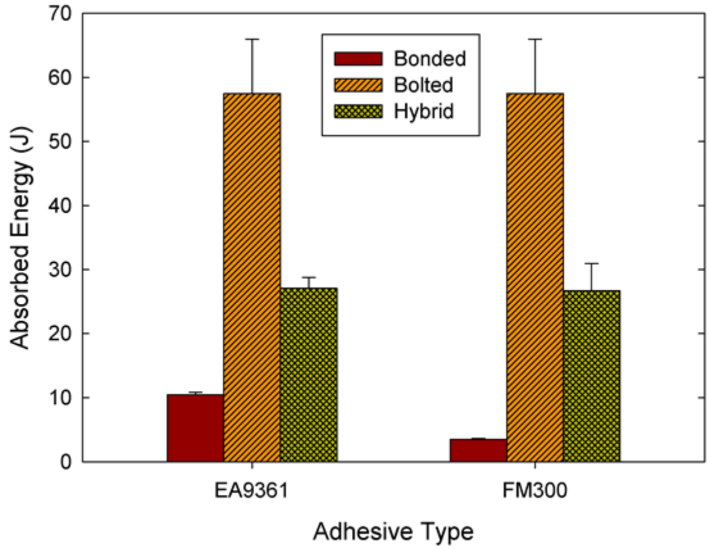

Figure 7: Comparison of energy dissipation for different joint types

Some important observations can be made from Figure 7. First, the brittle (FM300-2M) bonded joint dissipates the least energy by a considerable margin. The ductile (EA9361) bonded joint dissipates 2.99 times as much energy as the brittle joint, despite the strengths of these joints being almost identical (see section 6.2). The bolted and hybrid joints both dissipate substantially more energy during fracture than either of the bonded joints.

Examination of the bolted and hybrid joint fracture energies reveals a somewhat surprising result: the hybrid joint dissipates significantly less energy during fracture than the bolted joint for both EA9361 and FM300 adhesives. This is an important experimental observation, because it proves beyond a doubt that hybrid bonding-bolting is not necessarily the optimal solution with regards to energy absorption. While it is better than just bonding, it can be significantly worse than plain bolting.

A proposed explanation for this requires examination of Figures 3 and 4. First, for the EA9361 hybrid joint, the adhesive failure is delayed to a much higher load than in the EA9361 bonded joint. In fact, adhesive failure occurs at a load slightly above the ultimate strength of the plain bolted joint. Thus, once the adhesive fractures, the underlying bolted joint cannot sustain the load that is suddenly transferred to it by itself and fractures catastrophically and suddenly. The gradual, progressive failure that is experienced by the bolted joint does not occur and thus less energy is dissipated.

For the FM300 hybrid joint, the mechanism is slightly different. In this joint, the adhesive fails at a load level that the bolted joint by itself is able to sustain. However, during the abrupt adhesive failure, it is hypothesized that significant dynamic loads are exerted on the composite as the compliance of the joint suddenly drastically changes, leading to sudden acceleration of the components. This may lead to damage in the composite, leading to the reduced residual strength of these joints as evidenced in Figure 10.6. Thus, there is again reduced scope for progressive failure, leading to decreased energy dissipation.

7. Conclusions

Based on the experiment presented in this chapter, the following conclusions can be drawn:

1) The adhesive system (type/thickness) has a major effect on both the absolute and relative stiffness of bonded and hybrid joints

2) The adhesive system (type/thickness) has a major effect on the relative strength of bonded and

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hybrid joints

3) Contrary to expectation, the energy dissipated by a hybrid joint is not necessarily greater than that which would be dissipated by the underlying bolted joint by itself, and may in fact be significantly less. However, the dissipated energy may generally be expected to be greater than that of the underlying bonded joint by itself.

4) The joints with the ductile (EA9361) adhesive dissipated significantly more energy compared to the joints with the brittle (FM300-2M) adhesive

The hypothesis that the adhesive system has an important effect on the hybrid joint performance is strongly supported by conclusions 1-4 of the experimental results.

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