Experimental Investigation of Multi-Material Aluminum-to-Steel and GFRP-to-Steel Bonded and Bolted/Bonded Connections

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ABSTRACT

Through an experimental study, this paper describes the behavior of single-lap bonded, bolted and bolted/bonded connections for configurations with minimum geometric parameters proposed in design references. Two types of multi-material connections are considered: Glass Fiber Reinforced Polymer (GFRP)-to-steel and aluminum-to-steel. At first, the behavior of multi-material bonded connection using methacrylate and epoxy adhesives is evaluated. Then experimental results of bolted connections are presented. Finally, the contribution of adhesive in GFRP-to-steel and aluminum-to-steel bolted connections is investigated. Test results show that on single-lap simply bonded joints, failures mostly occur at the substrate to adhesive interface. Sanding the GFRP plate was found to improve the connection strength. Despite their lower elastic modulus, methacrylate adhesives with larger elongation provides better strength due to their high resistance in peeling. For bolted/bonded joints, the adhesive was found to improve the elastic behavior and the strength of GFRP-steel joints while its effect for aluminum-steel joints was not apparent due to reduce bonded surface and the high strength performance of the bolted plates.

Keywords: Connection, bolt, pultruded GFRP, aluminum, single-lap, adhesive, multi-material.

INTRODUCTION

This study was initiated in the context of developing a high strength and low weight portable emergency bridge for railways. The use of aluminum or Glass Fibre-Reinforced Polymer (GFRP) elements is a promising option for secondary elements in such bridges due to their light weight, corrosion resistance, and low maintenance cost. For this type of application, bolted connections appear to be the most practical choice. However, connection strength could be critical and it was anticipated that a combination of bonded and bolted connections could provide advantages over simply bolted ones. For instance, since bolts introduce stress concentrations, which in turn generate capacity reduction or even fracture in the plate, the contribution of an adhesive may to increase significantly the efficiency of the connection. This type of connection is called hybrid joint.

When connecting two metal plates together with adhesive, the basic failure modes observed are: adhesive (Figure 1a), cohesive (Figure 1b) or thin-layer cohesive (Figure 1c). The same modes are observed when connecting FRP plates. Additional failure modes observed for FRP materials are fibres tear (Figure 1d), light-fibres-tear (Figure 1e), stock-break (Figure 1f) (ASTM D5573-99 2005). For adhesive failure, also called interfacial failure, the separation appears at the adhesive-adherent interface (Figure 1a). Cohesive failure is marked by the rupture of the adhesively bonded joint, such that the separation is within the adhesive (Figure 1b). Thin-layer cohesive failure is similar to cohesive failure, except that the failure is very close to the adhesive-substrate interface, characterized by a light dusting of adhesive on one substrate and a thick layer of the adhesive left on the other (Figure 1c). For fibres tear failure (Figure 1d), failure appears exclusively within the FRP matrix, characterized by the appearance of the reinforcing fibers on both rupture surfaces. Light-fibres-tear failure

occurs within the FRP substrate, near the surface, characterised by the FRP resin matrix visible on the adhesive, with a few glass fibers transferred from the substrate to the adhesive (Figure 1e). Stock-break failure mode (Figure 1f) is characterized by a break of the FRP substrate outside the adhesively bonded joint region, often near it. Any combination of two or more of the six classes of failure mode cited above is called mixed failure (ASTM D5573-99 2005). It is however to be noted that there is no such classification when multi-material plates are bonded together. When adhesive is combined with bolts in a connection loaded in tension, bearing, net-section, cleavage or shear failures (Figure 2) occur after the failure of adhesive.

In civil engineering related works, extensive studies have been carried out on the use of strengthening concrete or steel structure with adhesively bonded Carbon FRP (CFRP) strips and sheets. However, most experimental studies on joining FRP composite plates or aluminum plates with bolt and adhesive focused on aerospace and automotive applications. For instance, Hart-Smith (1985) considered various aspects of the combination of adhesive bonding and mechanical fastening of fibrous composite structures for aerospace industry. The author found that using hybrid connection do not necessary provides better strength than well design simply bonded joint. However, the combination of bonding and bolting was found to be particularly useful for repair and to prevent damage from spreading. Imanaka and al. (1995) performed a fatigue tests on rivet, adhesive and adhesive/rivet on high-strength steel joints with different lap widths, adhesive and rivet strengths. They found that the fatigue strength of the adhesive joints can be improved through combination with rivet of nearly equal or slightly higher fatigue strength than adhesive joint. Also, fatigue crack was found to propagate more gradually in combined joints than in adhesive joints after crack initiation. Fu and Mallick (2001) studied the static and

98 fatigue performance of adhesive/bolted joints in structural reaction injection molded
99 composite. They found that although the hybrid joint has a higher performance
100 compared to the simply bonded joint, the structural performance of the hybrid joint
101 can be further improve if the washers that provide full clamping pressure cover all the
102 overlap area compared to the washers that provide only partial lateral clamping
103 pressure. As the first significantly reduce the maximum peel stress at the adhesive-
104 substrate interface and thus help to improve the joint performance. Kelly (2006)
105 investigated the strength and fatigue life of the bonded/bolted hybrid single lap joints
106 with CFRP using adhesives with different elastic modulus for automotive application.
107 They found that with lower modulus adhesives, the hybrid joint allowed for load
108 sharing between the adhesive and the bolts, and have greater strength and fatigue life
109 in comparison to adhesive bonded joints. No significant improvement in the strength
110 of hybrid joints was found with high modulus adhesive although the presence of bolt
111 increased the joint fatigue life. Kweon et al. (2006) investigated failure loads of
112 bonded/bolted hybrid joints between carbon composite and aluminum plates. The
113 hybrid joint was found to improve joint strength when the mechanical fastening is
114 stronger than the bonding. Matsuzaki et al. (2008) proposes a bolted/co-cured hybrid
115 joining method between GFRP and aluminum plates, and experimentally investigated
116 the strength of these joints as compared to simply co-cured joints or simply bolted
117 joints. Their joining technique was different from the conventional bonded, bolted or
118 bolted/bonded joining technique in that the curing and the joining process for
119 composite structures were achieved simultaneously so that adhesive and FRP adherent
120 were united. For simply bolted and bolted/co-cured hybrid joints, the bolts were
121 inserted before the co-curing process to avoid any damage of the glass fibers. Their
122 study shows that bolted/co-cured hybrid joint have 1.84 times higher maximum shear

strength compared to co-cured bonded joints. However, compared with bolted joint, no increased in the peak load was measured. Sadowski et al. (2011) performed an experimental and numerical analyses of hybrid double-lap joints. The double lap hybrid joint was made of aluminum plates, polyurethane adhesive and reinforced by five rivets. It was found that the five rivets reinforcement do not substantially increase the carrying force by the hybrid joint. Several authors have investigated the fatigue life performance of hybrid joints as compared to simply bolted or simply bonded. Joints for the benefit of aircraft industry. Study reported by Chowdhury et al (2015a) on thin carbon fiber adherents reveals that there is not significant difference in the static strength of the bonded joints and hybrid joints. However, the fatigue resistance of a hybrid joint is superior to that of a bonded joint, particularly in the case where defects are present in the adhesive bondline. In another paper, (Chowdhury et al.; 2015b), their Finite Element (FE) analysis reveals that the position of the first row of fasteners is critical in determining the crack growth rate. The crack growth rate in the adhesive was found to be reduced when it enters into the fasteners' clamping zone, resulting to an improvement of the fatigue resistance of the hybrid joint. In their experimental analysis and numerical simulations on aluminum alloy 2024-T3 loaded in double lap configurations, Esmaeili et al. (2014a; 2014b; 2014c; 2015) and Samaei et al. (2016) also found a better fatigue performance of hybrid joint compared to simply bolted joints. Their investigation also revealed the positive effect of tightening torque on the fatigue life of bolted and hybrid joints. One of the few analyses reported for the benefit of civil engineering applications was performed by Hai et al. (2010). They performed an experimental investigation on the tensile behavior of double lap joints in pultruded hybrid CFRP/GFRP laminates. They found that adhesive bonding can improve considerably the slip resistance and the stiffness of the bolted joints. The

energy absorption by the hybrid joint was found to be approximately equal to the summation of the energy absorption of the simply bonded and that of the simply riveted joints. However, as for Matsuzaki et al. (2008), no significant increase in the joint strength was found. Since limited research work is reported for civil engineering applications, the research program reported here was performed to cover some gaps in the contribution of the adhesive in aluminum-steel and GFRP-steel one-bolt connections. Several research papers on the use of Finite Element (FE) methods to simulate the behavior of hybrid joints have been published. The behavior of simply bonded aluminum-to-steel and GFRP-to-steel joints loaded in tension is presented first. The effects of surface preparation and types of adhesives are investigated. Then experimental results of simply bolted connection are presented. Finally, the behavior of bolted/bonded (hybrid) connections is compared to simply bonded connections or simply bolted connections.

EXPERIMENTAL PROGRAM

Overview of the experimental program

The aim of this study is to investigate if adding the adhesive in single-lap one-bolt aluminum-steel and GFRP-steel connections with minimum geometric parameters will improve their strength and failure mode. These minimum geometric parameters for GFRP bolted plates have an end-distance (e) equal to 3 times the bolt diameter ($3d$) and the side-distance (s) two times the bolt diameter ($2d$) (Bank 2006). For aluminum bolted plates, although CSA-S157 (2010) recommends the minimum values of $e=1.5d$ and $s=1.25d$, $e=s=1.5d$ were considered. Methacrylate and epoxy adhesives were used. At first the effects of surface preparation and types of adhesive on simply bonded joints are analysed. Then, simply bonded and simply bolted joints are compared to bolted/bonded joints.

Materials and properties

Three methacrylate adhesives and one epoxy adhesive were used for the tests. Methacrylate type L is Loctite H8500 adhesive, methacrylate type W is the Weld-On SS605 adhesive and methacrylate type W* is a new formulation of adhesive type W. It is commercially available under the name SCIGRIP SG600-05-OW and according to the manufacturer's technician; it provides similar strength as Weld-On SS605. Epoxy type S is the Sikadur 330 adhesive. All these adhesives are two-component products with a mix ration of 10:1 for methacrylate types L, W and W* and 4:1 for epoxy type S. According to the manufacturer's technical data sheet, methacrylate adhesives are recommended for bonding thermoplastics, composites and metals materials with minimum surface preparation. While epoxy type S is reported to have good adhesion to many substrates. Adhesive properties taken from the manufacturers technical data sheets are reported in Table 1. The strength of these adhesives will depend on strength and stiffness of the substrate (bonded plates). The lap shear strength for methacrylate types W and W* were measured in aluminum substrates based on ASTM D1002 method. The lap shear strength of methacrylate type L is based on ISO 4587 method and is reported for many substrates including steel, aluminum and FRP. The lap shear strength of epoxy type S is not provided. However, tensile strength and Elastic modulus are measured according to DIN 53452.

The GFRP specimens were taken from Extren 500 series panels. Extren 500 is manufactured by Strongwell Corporation. It is made of E-glass fibres and polyester resin. It is typically reinforced with 50% Continuous Strand Roving (CSR) and Continuous Strand Mat (CSM). The roving provided strength in longitudinal (pultrusion) direction while the mat provided multi-directional strength properties. Aluminum and steel were cut from 6061-T6 and grade 350W flat bars respectively.

Tension tests of GFRP coupons were conducted according to ASTM Standards D3039 (2006) for longitudinal and transversal tensile strength and D3518 (2007) for in-plane shear strength. For grade 350W steel and 6061-T6 aluminum coupons, ASTM Standard A370 (2005) was used. Specimens were un-notched for GFRP and notched for aluminum and steel. Figure 3 shows the typical stress-strain curves of GFRP, steel and aluminum coupons. As specified by the appropriate testing standard, strength was measured from the peak load divided by the net section area of each coupon. Strain was measured by an axial extensometer. As can be observed in this figure, GFRP plates behaves linearly up to brittle failure at 2% deformation. Steel and aluminum show an elasto-plastic behaviors. The average tensile strength of GFRP and aluminum tested coupons are summarized in Tables 1. For steel, the average ultimate tensile and yield strengths were approximately 540 MPa and 370 MPa respectively. ASTM A325 bolts with $d=12.7$ mm and nominal washer were used for bolted and hybrid connections. The bolts were not tested. However, their nominal guaranteed tensile strength is 825 MPa and nominal shear strength is 495 MPa, assuming the shear strength equals to 0.6 times the nominal tensile strength.

Surface preparation of the bonded interfaces

The bonded surfaces of GFRP plates were prepared with two different techniques. The first technique involves no specific surface treatment on the GFRP plate (non-sanded). However, the plates surfaces were cleaned with acetone to remove all dust, grease and surface residue. For the second technique, GFRP plates were sanded with the medium grit sandpaper to remove the first coat without damaging the fibers. Then, an industrial vacuum was used to remove all dust from the sanded surface. The bonded surface of aluminum and steel plates were all sandblasted inside a sand blasting equipment. Then, the surfaces were vacuumed and cleaned with acetone to

remove all dust and grease. All bonded specimens were prepared according to the manufacturer's technical data sheet. To form the bond, the adhesive was applied on one plate. The surfaces were then pressed together with hands to remove air voids. Two types of simply bonded specimens were tested. The first type involve specimens without a bolt-hole. For these specimens, the adhesive thickness was not controlled in order to more accurately reproduce field conditions. However, special attention was taken to maintain a uniform thickness of the adhesive by applying the same pressure with a square concrete block on the bonded joints. After the tests the thickness of these adhesives were measures and are reported in Tables 2. Although an attempt was made to maintain the bonded length of these specimens constant, little variations were observed. After the tests the bonded length (L) were measured and are also reported in Tables 2. For these specimens, adhesive types L, W and S were used and GFRP-steel bonded interface were between 2500 mm² to 2650 mm² (about 50 mm width times 50-53 mm length). Aluminum-steel bonded interface were approximately 1500 mm² (about 38 mm width to 38 mm length). The second type of bonded joints involve specimens with bolt-hole. As shown in Figure 4, adhesive thickness was controlled by including two metal wires of 0.8 mm diameter between the bonded plates. Then, the bolt was tightened at finger tight plus one half-turn of the nut to ensure that the resulting pressure will be similar to that of bolted/bonded joint. These bolts were removed before the tests. Adhesive types L, W* and S were used for these specimens. Compared to the first type of bonded joints, the bonded length of GFRP-steel joints was increases, to about 76 mm as that of hybrid joint, resulting to an increase of the bonded surface to approximately 3600 mm². However, that of aluminum-steel joints was not increase as the bonded length was already similar to that of Hybrid joint. Therefore, the presence of bolt-hole reduced the bonded interface to 1290 mm².

Hybrid joints were prepared in a similar way than bonded joint with bolt-hole, with the difference that the bolt was not removed before the tests. In Tables 2 and 3, the reported lengths for plate with a bolt-hole included the hole diameter. However, the surface of the bolt-hole was excluded from the bonded surfaces reported in these tables. The bonded surface of GFRP-steel and aluminum-steel are different in this study because, as mentioned earlier, the aim of this study is to investigate the contribution of adhesive for one-bolt joint with minimum geometric parameters recommended by design references. These minimum geometric parameters for GFRP bolted plates have $e=3d$ and $s=2d$. For aluminum bolted plates, they are $e=s=1.5d$. According to the manufacturer technical data sheets, the curing time for the adhesives to achieve their full capacity at 24° C is within 24 hours for adhesives types L, 72 hours for methacrylate types W and 7 days for adhesive type S. In this study, at least 7 days curing time were allowed for bonded and hybrid joints at 20°C.

Specimen names

For simply bonded and bolted/bonded connections, three specimens were tested for each type of adhesive and surface preparation. The list of the tested specimens and their geometric properties are presented in Tables 2 and 3. The specimens were named with respect to the type of connector (bonded [B] or hybrid [H]), the joint configuration (GFRP-steel [G] or aluminum-steel [A]), the type of adhesive (types L, W or S), and the surface preparation (sanded [_s], non-sanded [_{ns}] or sandblasted [_{sb}]), the presence of hole in bolted plates (no hole [], bolt-hole [_h], and the specimen number (three specimens per configuration [0₁] to [0₃]). As it was evident that hybrid connections had all a bolt-hole, it was not necessary to use the symbol that characterise this state for these joints. For example BGS_{01-ns} stands for bonded GFRP-steel connection with adhesive type S, specimen number 01 with GFRP non sanded

interface. BGW_{02-sh} stands for specimen number 02 of sanded GFRP-steel connection with bolt-hole, bonded with adhesive type W. HAW_{03-sb} stands for hybrid aluminum-steel joint with adhesive type W, specimen number 03 and sand blasted aluminum to steel interfaces.

Experimental setup and measurement

GFRP specimens were cut from 6.35 mm thick pultruded plates while aluminum and steel were taken from 6.35 mm thick flat bars. GFRP pultruded plates were loaded along the longitudinal direction (0 degree) to achieve maximum tensile strength. The simply bonded (Figure 4a), simply bolted and bolted/bonded (Figure 4b) connections were loaded in a single-lap configuration. The tests were conducted up to failure of the joint using a 500 kN hydraulic testing machine. For these single-lap configurations, the end connections were designed to make the loading axis to coincide with the interface of the two plates so that the connectors (bolt or adhesive) were principally loaded in shear (Figure 4a and 4b). The test set-up of multi-material connection is presented in Figure 4(c). Specimens were clamped by the grips of the testing machine at both ends. Tensile force was applied at the bottom end while the top end was fixed. The load was applied at the rate of 1 mm/min and the load and displacement were recorded by the control system of the testing machine.

EXPERIMENTAL RESULTS OF SIMPLY BONDED CONNECTIONS

Effect of surface preparation GFRP-steel and aluminum-steel bonded joints

This part is a preliminary study conducted to investigate if it is better to sand or not the GFRP plate. To this aim, GFRP-steel connections with sanded and non-sanded GFRP plates bonded with the adhesives types W, L or S are compared. This

comparison is presented in Figure 5. For this part, plates without bolt-hole were used and bonded interface were approximately 2500 mm². Here, the adhesive thickness was not controlled. However, the same pressure was applied on all the specimens to form the bond. After the tests, the adhesive thickness was measured and is reported in Table 2.

The failure modes of bonded connections with methacrylate and epoxy adhesives types L, W and S are presented in Figures 5(a), 5(c) and 5(e) for GFRP non-sanded and sanded interfaces respectively. For specimens with sanded and non-sanded GFRP plates with methacrylate types L and W presented in Figures 5(a) and 5(c), it can be observed that failure occurred by a complete debonding of the adhesive from the GFRP plate. This type of failure is named adhesive failure. This suggests that sanding the GFRP plate does not change the failure mode of connections bonded with methacrylate adhesives. However, with epoxy type S, two different failure modes are observed on specimens with sanded and non-sanded GFRP plates. Specimens BGS_{-ns} also shows adhesive failure from the GFRP plate while on BGS_{-s}, it can be observed that part of the adhesive remains on the sanded GFRP plate and the rest remained on the steel plate. The adhesive that remained on steel has a film of GFRP. This suggests the presence of debonding on the GFRP Continuous Strand Mat (CSM). This failure can be classified as a mixed failure due to the combination of adhesive failure and light-fiber-tear failure.

The effect of surface preparation on connections failure load when bonded with adhesive types S, L and W is presented in Figure 5(b), 5(d) and 5(f). The peak load and displacement at peak load of all bonded specimens are presented on Table 2. For all these adhesives, a linear behaviour of the force-displacement curves up to a brittle failure of the connections is shown. Some specimen shows a light drop after the peak

load to about 2.5 kN before the brittle failure of the joint. For joint with sanded GFRP plates bonded with the three types of adhesive, the average peak load is 24.93 kN, 23.19 kN and 23.45 kN for adhesive types S, L and W respectively. The displacement at peak load is between 0.6 and 0.7 mm. For joints with non-sanded GFRP plates, the average peak load is 19.73 kN, 17.27 kN and 16.46 kN for adhesive types S, L and W respectively. For these specimens, the average displacement at peak load is between 0.5, 0.6 and 0.45 mm for adhesive types S, L and W respectively. In general, for all these adhesives, sanding the GFRP plate improves of the joint strength and displacement. Therefore, this surface preparation was used to evaluate the contribution of adhesive on bolted/bonded connections.

Structural performance of methacrylate and epoxy adhesives

In this part, the structural performance of methacrylate adhesives (types W* and L) is compared to that of epoxy adhesive (type S) in bonded GFRP-steel and aluminum-steel configurations. As reported in Table 1, it is to be noted that the elastic modulus of epoxy adhesive type S is 7 to 9 times higher than that of methacrylate adhesive type W* and 3.4 times higher than the one of methacrylate adhesive type L. The effect methacrylate compared to epoxy adhesives is presented in Figure 6 for bonded GFRP-steel and aluminum-steel connections. Connections with bolt-hole and controlled thickness were used for this comparison. Only the typical and representative failure modes and force-displacement curves obtained from each type of bonded configurations are presented. All other results are reported in Table 2.

In the previous section, adhesive failure was observed for methacrylate adhesives while mixed failure due to the combination of adhesive failure and light-fiber-tear failure was observed with epoxy adhesive for sanded GFRP-steel bonded joints. On GFRP-steel configurations with a bolt-hole presented in Figure 6(a), identical failure

348 modes per adhesive are also observed for specimens BGS_{-sh}, BGW*_{-sh} and BGL_{-sh}.
 349 For aluminum-steel configuration with epoxy adhesive type S (BAS_{-sh}) presented in
 350 Figure 6(c), the failure mode is mainly due to debonding of the adhesive on the steel
 351 and/or aluminium substrates adhesive failure. With methacrylate type L (BAL_{-sh})
 352 shows a cohesive failure characterized by separation or fracture within the adhesive.
 353 With methacrylate type W*, two specimens show adhesive failure due to complete
 354 separation of the adhesive from the aluminum plate. However, on the third specimen
 355 presented on Figure 6(c) as BAW*_{-sh}, a small proportion of the adhesive is observed
 356 on the aluminum plate. Despite this light difference, this failure mode can still be
 357 classified as adhesive failure. In summary, methacrylate types W* adheres better on
 358 steel than GFRP or aluminum plates. With epoxy type S a higher proportion of
 359 adhesive was observed on GFRP and aluminum plates than on steel plate.
 360 Methacrylate type L shows good behavior on aluminum and steel plates resulting in a
 361 cohesive failure when these two are bonded which, is not the case when used in
 362 GFRP-steel configuration.

363 The typical force-displacement curves of BGS_{-sh}, BGL_{-sh} and BGW*_{-sh} are
 364 compared in Figure 6(b) for GFRP-steel configurations. With the three adhesives, the
 365 force increases linearly with the displacement up to a brittle failure at peak load. The
 366 load performance of BGS_{-sh} and BGL_{-sh} are quite similar. From Table 2, an average
 367 peak load of 29.6 kN and 30.6 kN is measured with adhesive type S and L
 368 respectively. However, the displacement at which BGS_{-sh} achieved its peak load about
 369 0.64 mm and that of BGL_{-sh} is 0.8 mm. In the other hand, BGW*_{-sh} is found to
 370 provides better strength as the average peak load is around 40 kN for an average
 371 displacement of 1 mm. For aluminum-steel configurations, the force-displacement
 372 curves of BAL_{-sbh} and BAW*_{-sbh} appear to be more ductile than that of BAS_{-sbh}. The

maximum displacement is around 1mm for methacrylate adhesives compared to 0.3 mm for epoxy adhesive. However, the average peak load of epoxy type S is 16.3 kN which, is slightly higher than methacrylate type L that is 15.4 kN. From the three adhesives, methacrylate type W* have a better performance with an average peak load at 24.8 kN. In summary, despite the lower elastic modulus of methacrylate adhesives compared to epoxy adhesive, the shear strength obtained in GFRP-steel and aluminum-steel configurations were at least similar to that of epoxy type S. There was clear evidence that methacrylate type W* provides better strength than epoxy type S and methacrylate type L. The higher peeling resistance of methacrylate type W* may result from their capacity to undergo large plastic deformations. In their study on GFRP-steel bonded joints, Rameshni et al. (2013) used methacrylate adhesive with similar properties than that of type W* used in this study. They found that methacrylate provides higher bond strengths than epoxy adhesive. Their FE analysis reveals that the ductility of methacrylate allowed it to yield at locations of stress concentrations, providing higher splice capacity, despite their lower nominal shear strength as compared with epoxy adhesive. Due to its better performance, methacrylate type W* will be used for bolted/bonded (hybrid) joints.

Structural performance due to plate rigidity

In Figure 7, the structural performance of the adhesives in aluminum-steel compared to GFRP-steel bonded connections is presented. For this comparison, the average shear strength obtained in plates with bolt-hole was considered as the adhesive length and thickness were better controlled here. The average strength is the peak load divided by the bonded surface reported in the second column of Table 2.

Figure 7 clearly shows that the high stiffness (product of elastic modulus and the plate cross-section $E.w.t$) of the aluminum plate produces better structural

performance for the bonded connections. The average shear strength of aluminum-steel specimens is about 1.75, 1.4 or 1.55 times higher than that of GFRP-steel specimens for bonded specimens with methacrylate type W*, L and S respectively. Moreover, cohesive failure is more likely to occur when bonding two metal plates with methacrylate adhesives than when at least one of the substrate is a GFRP plate.

HYBRID JOINTS COMPARED TO SIMPLY BONDED OR BOLTED JOINTS

In this part, simply bonded and simply bolted connections are compared to hybrid connections in GFRP-steel and aluminum-steel configurations. For each of these configurations, the plates geometric parameters either for bonded, bolted or bolted/bonded (hybrid) are the same. Hybrid specimens were bonded with adhesive type W* and the thickness of the adhesive was controlled. The experimental results for these hybrid connections are presented in Table 3.

Simply bolted joints

In this part, results of aluminum-steel single-lap bolted connections reported in Tajeuna et al. (2015) were used. More information on the failure mode and force-displacement curves of this configuration is provided in the next subsection. For GFRP-steel single-lap bolted connections, five specimens were tested and results are presented in Figures 8. For this configuration, no deformation was observed on the steel plates and on the A325 steel bolt until GFRP reached failure. In Figure 8(a), the inner and outer face of specimens with typical failure modes is shown. Cleavage failure was the predominant mode within the five tested specimens. However, the propagation of crack was not always consistent. In some case, crack propagates from one side of the bolt-hole up to the plate free end edge. Additional crack could also be

observed on one side of the net-section line (Test 1 and Test 3). For other specimens the inner and outer faces show different failure modes. For instance, the inner face of specimen Test 5 show sign of shear failure while it outer face shows and association of bearing and cleavage failure. Figure 8(b) show the force-displacement curves of bolted joints. It is observed that the GFRP plates behave linearly up to approximately 5 kN. Then the loads continue to increase, but with a reduced stiffness up to the peak load. The reduction of the stiffness is probably due to the reduction of the clamping pressure between the two plates during loading. The average peak load is observed between 30 kN and 35 kN for a maximum displacement of 2.5 to 3 mm. After the peak load, some curves suddenly drops down suggesting a partial failure on the GFRP. Other specimen shows a more ductile behavior before this sudden drop. This last behavior is shown on Test 5 that experiences bearing follows by cleavage failure on its outer face. After the sudden drop to about 10 to 20 kN, the GFRP undergoes a progressive failure. The displacement to which the complete failure occurred is unknown because the tests were stopped at this stage as the maximum load was achieved and load was less than 50% of the maximum value.

GFRP-steel hybrid connections

For GFRP-steel connections, Figure 9(a) shows adhesive failure from the GFRP bonded interfaces of bolted/bonded specimen. This same failure mode was observed in bonded connections also reported in this figure. This failure is followed by either cleavage HGW^*_{01-s} , or an association of bearing and cleavage failure in the outer face and shear in the inner face (HGW^*_{02-s}). Similar failure modes were also observed in simply bolted connection presented in Figure 8(a). Therefore, adding methacrylate type W* in the bolted connection did not improved the GFRP failure mode.

In Figures 9, the typical force-displacement curves of bonded, bolted and bolted/bonded joints are presented. From the force-displacement curve, a linearly elastic behavior up to an average peak load of 40 kN is observed with an average displacement of 1 mm. In this part of the curve, it is difficult to assume if the effect of the bolt and the adhesive is combined due to its similarity in load and displacement with simply bonded joints. After the failure of the adhesive, there is a sudden drop in the load between 20 kN to 25 kN. This drop in the joint capacity suggests that the adhesive has failed. This explanation is supported by the fact that a loud noise was heard at the peak load and the presence of cracks in the bonded interface could clearly be observed. From this point, an increase of the curve is observed up to a partial failure in the GFRP plate around 35 kN with an average displacement of 2.5 mm. This part is similar to the behavior of simply bolted joint also presented in this figure. In summary, adding methacrylate type W* in the bolted joint improves the overall peak load and provides stiffer behavior than that of simply bolted joint.

Aluminum-steel hybrid connections: Failure modes and force-displacement curves of bolted, bonded and bolted/bonded aluminum-steel joints are presented in Figures 10. As in the case of GFRP-steel configurations, the failure mode in the bonded interface of bolted/bonded (hybrid) in aluminum-steel was similar to that observed in the simply bonded aluminum-steel joint with same type of adhesive. For instance, adhesive failure is observed on the bonded joint (Figure 10(a)). This same failure mode is also shown in Figure 10(a) for bolted/bonded joint. In the hybrid connection, the failure of the adhesive is followed by shearing of the aluminum plate. This same failure mode was observed in simply bolted aluminum-steel connections reported in Tajeuna et al. (2015). The typical failure mode of aluminum bolted joint is also

presented in Figures 10(a). Therefore, adding adhesive in the bolted joint did not improved its failure mode.

In Figures 10(b), the typical force-displacement curves of bonded, bolted and bolted/bonded aluminum-steel joints are presented. An elasto-plastic behavior is observed from the force-displacement curve of the hybrid joints. The peak load is observed around 40 kN for an average maximum displacement of 6 mm. This behavior is similar to the one of the simply bolted connection also presented in this figure. There is no clear evidence of the contribution of the adhesive in the load-displacement history. This is probably related to the fact that the shear strength provided by bonded interface was low compared to the tensile strength provided by the bolted plates alone. Therefore, appropriate adhesive with higher lap shear strength is required to enhance the connection strength of aluminum-steel hybrid joint. A bonding technique that could enlarge the bonded interface is an option to improve the strength of the aluminum-steel joint with minimum geometric parameters. In his study performed in single-lap composite material, Sun et al.; (2009) were able to improve the strength of their hybrid joint by using a small flat piece of composite laminate attachment to create an alternate load path to transfer part of the load from the adherent to the bolt (stepped attachment). This bonding procedure could be an alternative option to improve the strength performance of aluminum-steel hybrid connections.

CONCLUSIONS

An experimental analysis was performed to investigate the behavior of single-lap bonded and bolted/bonded connections. Multi-material GFRP-to-steel and aluminium-to-steel joints loaded in one shear plane (single-lap) were considered. The analysis

was divided into two parts. The behavior of simply bonded joint was presented first. In this part, the effect of surface preparation and types of adhesives on the joint strength were investigated. Then, the behavior of simply bolted connections was presented. Finally bolted/bonded (hybrid) joint was compared to simply bonded or simply bolted connections. From this analysis the following observations can be drawn:

For bonded connections;

- 1) Sanding or not sanding the GFRP plate did not change the failure mode of the bonded joint with methacrylate adhesives. Debonding of the adhesive was either observed on steel or on GFRP plates depending on the adhesive used.
- 2) Despite their lower elastic modulus, methacrylate type W* were found to provide better strength than methacrylate type L and epoxy type adhesives in aluminum-steel and GFRP-steel configurations.
- 3) A higher adherent (plate) rigidity produces a higher strength for bonded joints, regardless of the type of adhesive.

For hybrid connections;

- 1) For GFRP-steel configuration, methacrylate type W* was found to increase the capacity of the bolted joint and contributes to improve its elastic behavior. However, the joint failure mode was not improved.
- 2) The effect of adhesive in the aluminum-steel bolted joint was not noticeable due to reduce bonded surface and the higher stiffness and strength produces by the bolted plates alone.

3) For both GFRP-steel and aluminum-steel connections, the hybrid joint has adhesive failure before the joint failure. After adhesive failure, the hybrid joints behave as simply bolted joints.

Future works include the evaluation of alternative bonding procedure for aluminum-steel hybrid connections, and the experimental testing for bonding of typical multi-bolt structural joints.

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Figure 1. Typical failure modes of bonded connections: (a) adhesive failure, (b) cohesive failure, (c) thin-layer cohesive failure, (d) fiber-tear failure, (e) light-fiber-tear failure, (f) stock-break failure (ASTM D5573-99; 2005)

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Figure 2. Failure modes of bolted connections: (a) Bearing, (b) net-section, (c) shear tear-out, (d) Block shear (e) cleavage

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Figure 3. Stress-strain relationships of materials

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Figure 4. Joints parameters (a) simply bonded, (b) bolted/bonded (Hybrid), (c) Test set-up.

Figure 5. Effect of surface preparation on simply bonded joints : (a) FM adhesive type L, (b) FD of adhesive type L, (c) FM adhesive type W*, (d) FD of adhesive type W*, (e) FM adhesive type S, (f) FD of adhesive type S

FM: Failure mode, FD: force-displacement curves

Figure 6. Effect of methacrylate compared to epoxy adhesives on: (a) FM GFRP-steel (b) FD GFRP-steel, (c) FM aluminum-steel, (d) FD aluminum-steel

FM: Failure mode, FD: force-displacement curves

Fig. 7 Effect of Plates rigidity on the connection strength
 (P : peak load, A : bonded surface)

Figure 8: Behavior of simply bolted GFRP-Steel connections: (a) Failure modes joint, (b) Force-displacement curves

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Figure 9. Hybrid compared to bolted or bonded GFRP-steel joints (a) Failure modes (b) Force-displacement curves

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Figure 10. Hybrid compared to bolted or bonded aluminum-steel joints (a) Failure mode (b) Force-displacement curves

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Table 1. Mechanical properties of the materials

	Extren 500 GFRP Plate		6061-T6 Aluminum Flat bar		Epoxy	Methacrylates		
	Tested	Extren Design Manual	Tested	CSA Design manual	Type S	Type L	Type W	Type W*
					Reported values from manufacturers Technical Data Sheets			
Modulus								
Lt (GPa)	18.6	17.2	69.38	70	4.5	1.11	0.41-0.52	0.69-0.83
Tt(GPa)	4.03	5.52	-	-	-	-	-	-
Ip-sh(GPa)	4.80	-	-	-	-	-	-	-
Strength								
Lt (MPa)	340-382	207	330	260	30	17	18-21	21-23
Tt (MPa)	88.40	48.30	-	-	-	-	-	-
Ip-sh (MPa)	104.16	-	-	-	-	-	-	-
Ls (MPa)	-	-	-	-	-	(15/11/7)*	(19-22) [#]	(21-25) [#]
μ	-	0.33	-	0.30	-	-	-	-
t (mm)	6.1	6.35	6.35	6.35	-	-	-	-
$\epsilon_{\max}$ (%)	0.2	-	0.35	-	0.9	28	>140	65-105

Lt: longitudinal, Tt: transversal, Ip-sh: In plane shear, Ls: Lap shear, μ : poisson ratio, t: plate thickness, $\epsilon_{\max}$: maximum elongation, ()^{*} : Steel/Aluminum/FRP substrates, ()[#] aluminum substrate

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Table 2. Experimental results simply bonded connections

Specimen name	Bonded Surface (mm ²)	Bonded length (mm)	Adhesive thickness (mm)	Peak load (kN)	Ave load /St. Dev	Displacement (mm)	Failure mode
GFRP-Steel							
BGS _{01-s}	2600	52	5	25.19	24.9/1.03	0.65	adhesive and light-fiber tear
BGS _{02-s}	2500	50	4	23.56		0.60	
BGS _{03-s}	2600	52	5	26.07		0.65	
BGS _{01-ns}	2500	50	4	18.51	19.7/0.9	0.44	adhesive
BGS _{02-ns}	2600	52	5	20.57		0.60	
BGS _{03-ns}	2600	52	5	20.12		0.50	
BGS _{01-sh}	3646	76	8	27.60	29.6/1.8	0.63	adhesive and light-fiber tear
BGS _{02-sh}	3646	76	8	29.12		0.57	
BGS _{03-sh}	3646	76	8	31.97		0.72	
BGL _{01-s}	2550	51	5	23.71	23.2/1.7	0.61	adhesive
BGL _{02-s}	2500	50	4	20.92		0.65	
BGL _{03-s}	2550	51	5	24.96		0.70	
BGL _{01-ns}	2550	51	5	17.43	17.3/0.3	0.58	adhesive
BGL _{02-ns}	2550	51	5	17.58		0.57	
BGL _{03-ns}	2500	50	5	16.80		0.58	
BGL _{01-sh}	3646	76	8	31.97	30.6/4.4	0.83	adhesive
BGL _{02-sh}	3646	76	8	35.13		0.95	
BGL _{03-sh}	3646	76	8	24.71		0.65	
BGW _{01-s}	2450	49	3	21.36	23.5/1.5	0.62	adhesive
BGW _{02-s}	2650	51	4	24.77		0.71	
BGW _{03-s}	2550	51	4	24.24		0.67	
BGW _{01-ns}	2550	51	4	16.93	16.5/1.6	0.48	adhesive
BGW _{02-ns}	2650	53	4	18.13		0.49	
BGW _{03-ns}	2500	50	4	14.33		0.39	
BGW* _{01-sh}	3646	76	8	43.94	40/3	1.06	adhesive
BGW* _{02-sh}	3646	76	8	39.49		1.00	
BGW* _{03-sh}	3646	76	8	36.64		0.97	
Aluminum-Steel							
BAS _{01-sbh}	1290	38	8	15.12	16.3/0.9	0.63	adhesive
BAS _{02-sbh}	1290	38	8	16.31		0.60	
BAS _{03-sbh}	1290	38	8	17.39		0.71	
BAL _{01-sbh}	1290	38	8	14.85	15.4/0.4	0.96	cohesive
BAL _{02-sbh}	1290	38	8	15.54		0.60	
BAL _{03-sbh}	1290	38	8	15.78		0.85	
BAW* _{01-sbh}	1290	38	8	24.49	24.8/1.3	1.03	adhesive
BAW* _{02-sbh}	1290	38	8	26.49		1.03	
BAW* _{03-sbh}	1290	38	8	23.47		0.97	

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Table 3. Experimental results of hybrid joints

Specimen name	Bonded Surface (mm ²)	Bonded length (mm)	Adhesive thickness (mm)	Peak load (kN)	Ave load /St. Dev	Displacement (mm)	Failure mode
GFRP-Steel							
HGW* _{01-s}	3646	76	8	42.34	44.3/1.7	1.01	Adh+ C
HGW* _{02-s}	3646	76	8	43.98		1.11	Adh+B/S/C
HGW* _{03-s}	3646	76	8	46.55		0.99	Adh+C
Aluminum-Steel							
HAW* _{01-sb}	1290	38	8	43.65	43.6/1.3	6.0	Adh+S
HAW* _{02-sb}	1290	38	8	42.02		6.0	
HAW* _{03-sb}	1290	38	8	45.07		6.0	

Adh: adhesive failure, C: cleavage, Shear failure, B: bearing failure, Ave. average,
St. Dev: standard deviation

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