EXPERIMENTAL PARAMETRIC STUDY OF SINGLE-LAP ADHESIVE JOINTS BETWEEN DISSIMILAR MATERIALS

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Abstract
This work presents an experimental parametric study of adhesively bonded Single Lap Joint (SLJ) geometries between relatively thick dissimilar adherents. The primary objective of this study is to investigate the effect of various parameters, i.e. adherents' thicknesses, adhesive thickness and overlap length, on the failure load and failure mode of joints with dissimilar materials. For this purpose, mild steel and carbon fiber reinforced polymer (CFRP) laminates have been considered as the structural adherent materials. Seven SLJ cases have been considered for fabrication and experimental testing. The SLJ specimens were tested under a uni-axial tensile quasi-static displacement. The force-displacement and force-strains recordings are presented and conclusions regarding the joints stiffness and strength are obtained.

1 Introduction
Many methods exist for bringing together similar or dissimilar structural materials, in terms of the joining technique utilized. Conventional mechanical joints, such as bolted, pinned or riveted are preferred due to their simplicity and the disassembly ability that they offer for joining metal or composite materials [1, 2]. However, when a mechanical joint is loaded, local damage is induced at the fastener holes due to stress concentrations [3]. This fact leads to the structural degradation of a joint and jeopardizes the structural integrity of the assembly structure.

The demands for designing lightweight structures without any loss of stiffness and strength have turned many researchers and design engineers to seek for alternate joining methods. Thus, the field of adhesive bonding for load-bearing primary structures has matured with the development of a wide range of adhesives and has its roots in the field of aeronautics. By extrapolating the experience gained from aeronautics, adhesives have been adopted more and more by other industries like the marine industry, wind turbines, piping and civil engineering to mention just a few. Adhesive bonding has been adopted by the marine industry at the decade of 1980. It has been a field of research by several scientists since then, with the design of adhesive joints in marine structures (deck-to-hull, bulkhead-to-hull joints) gaining the greatest focus. Specific structural parts of a ship, such as superstructures, bulkheads, masts or even the entire deck, may be replaced with composite materials accordingly designed and adhesively bonded either to composite or metal parts. Regardless of the complexity of the geometry of the practical adhesive joint, it is common to evaluate the cooperation of the adherents and the adhesive system utilized by examining the behaviour of simple geometries under axial loading, e.g. Single Lap Joint (SLJ).

Research on SLJs has been conducted through experimental and/or numerical methods. Most researchers have assessed bonded joints with similar adherents [4-6]. On the other hand, a limited number of papers have been published regarding joints with dissimilar materials and in particular joints consisting of steel and composite adherents. Owens et al. [7, 8] studied composite-to-aluminum joints in terms of their stiffness behavior due to fractures. Seong et al. [9] investigated the effects of various parameters, such as bonding pressure, overlap length, adherent thickness and material type on the failure load and failure mode of joints with dissimilar materials. They concluded that, unlike the load–displacement curve of a composite-to-composite joint, plastic deformation was found in composite-to-aluminum joints when the stiffness of the aluminum adherent was not sufficient. According to the authors, larger adherent thickness leads to higher joint strength and failure load. All above references correspond to joints with relatively thin adherents (1.5 – 3.5 mm) and a lack in the literature body exists regarding joints with thick adherents.

The motivation of this work is to bridge the gap found in the literature between composite-to-steel adhesive joints and joints with thick adherents. For this purpose, an experimental parametric study has been conducted of adhesively bonded single lap joint geometries that involve thick CFRP and steel materials and a ductile adhesive layer.

2 Materials, fabrication and coupons tested

Initially, two CFRP composite laminated panels were manufactured which differ in the number of the constituent layers utilized (i.e. 15 and 22), hence achieving two different thicknesses. The fabrics were made from 200 g/m^2 unidirectional carbon fibers (CST 200 supplied by SGL Group) and the polymer system utilized was epoxy resin LH 160 with the 135-136 hardener, both provided by HAVEL Composites. The UD fabrics were initially impregnated with the epoxy/hardener matrix system by the hand lay-up method and afterwards the plates were cured at 25^oC for 48 hours under constant 0.6 bar pressure with the aid of vacuum bagging.

After curing, two pairs of plates with dimensions (200 x 200) mm and (200 x 150) mm, respectively, were cut out from the 22 layer panel. On the other hand, one pair of plates and a single plate with dimensions (200 x 200) mm and (200 x 150) mm respectively were cut out from the thinner 15 layer panel. As for the tabs, which are necessary to fabricate the SLJ geometry, four and three rectangular plates have been subtracted from the 22 and the 15 layer panel, respectively. All cuts were made with the use of the water jet technique with a cutting tolerance of ±0.2 mm.

Additionally, for the metallic substrates, plates from mild steel with the corresponding dimensions of the CFRP subtracted plates have been utilized. The structural adhesive Araldite 2015 provided by Huntsman Container Corporation Ltd., which is a two-part and relatively stiff epoxy adhesive material, has been utilized as the joining material of the metallic and CFRP substrates.

All substrates were first degreased with acetone before the application of the specific surface preparation procedure. The bonding areas of the CFRP plates were polished using first a coarse sandpaper (100), followed by a finer one (200). For the treatment of the corresponding bonding areas of the metallic plates, the common in the shipbuilding industry Sa2½ near-white grit blast cleaning was applied (approx. 2.5 mm grit size), according to the Swedish standards. This procedure yielded an average surface roughness Ra of the metallic bonding areas equal to 4.15 μm.

Initially, each metallic plate was bonded with its corresponding metallic tab plate and provisions were taken (short tough steel wires) in order to maintain a constant adhesive thickness. After the completeness of the curing process of the adhesive bonds of the tabs, each CFRP substrate-tab system was adhesively bonded with its corresponding steel substrate - tab system, as shown in Figure 1.

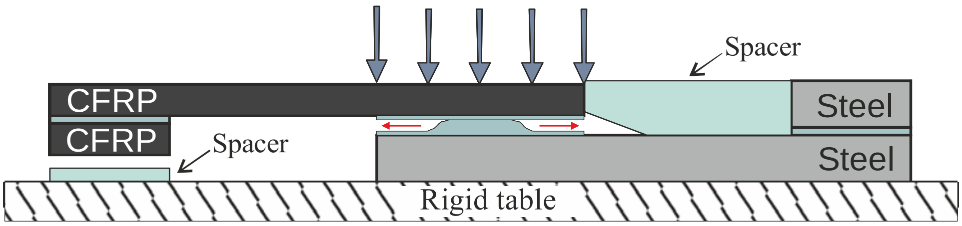

Figure 1. Configuration utilized for the fabrication of the dissimilar SLJ adhesive joints (polyurethane was used for the spacers).

After the assembly, the specimens were cured in an oven under a uniform pressure loading. According to the adhesive material manufacturer, curing procedure consisted of heating the specimens in 70°C for 45 minutes, followed by a slow cooling to ambient temperature. The specimens were left in ambient temperature for 48 hours before performing the tests. After the completion of the curing process, the specimens were cut out from the parent plates with the use of water jet. Seven cases have been considered that differ in the overlap length (25 or 75 mm), in the adhesive thickness (nominal 0.5 or 0.8 mm) and in the stiffness ratio (0.175 or 0.35). **Error! Reference source not found.** shows a schematic view of the considered SLJ cases and Table 1 lists the corresponding dimensions of each case. Finally, three specimens were fabricated and tested for each SLJ case, resulting in a total of 21 specimens.

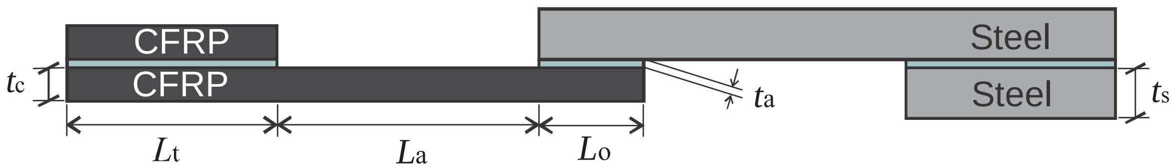

Figure 2. Schematic representation and geometry of the fabricated SLJ specimens.

Case	t_c [mm]	t_s [mm]	L_t [mm]	L_a [mm]	L_o [mm]	t_a [mm]	w [mm]
SLJ-1	7.98	8	40	75	75	0.52	23.76
SLJ-2	8.60	8	40	75	75	0.89	24.00
SLJ-3	9.56	5	40	75	75	0.51	23.93
SLJ-4	9.29	5	40	75	75	0.84	23.89
SLJ-5	9.99	5	40	75	25	0.51	23.83
SLJ-6	9.99	8	40	75	25	0.85	23.99
SLJ-7	8.12	8	40	75	25	0.50	24.04

Table 1. Dimensions of the SLJ cases considered in the parametric study.

Figure 3 depicts a side view of a 75 mm long overlap area respective SLJ coupon. It can be clearly seen that the adhesive layer has a uniform thickness along the overlap length.

Figure 3. Side view of a typical SLJ with 75 mm overlap length.

3 Testing conditions

All specimens were loaded by uniaxial static tensile displacement, applied with a speed of 0.1 mm/min by an MTS hydraulic testing machine. Three 5 mm gage length strain gage sensors (SG-1, SG-2 and SG-3) were placed on each SLJ specimen, at the locations shown in Figure 4. Their aim was to monitor strains at these three locations in order to provide local insight and for reasons of comparison with future numerical results. During the tests the applied displacement together with the reaction forces were monitored. Figure 5 shows a typical SLJ-4 specimen under experimental conditions.

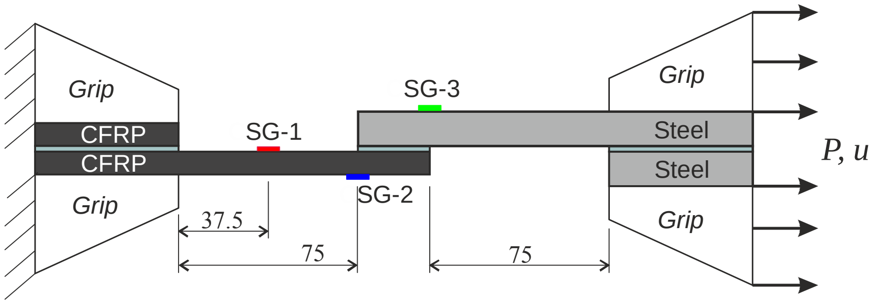

Figure 4. Experimental set-up of the SLJ specimens (dimensions in mm).

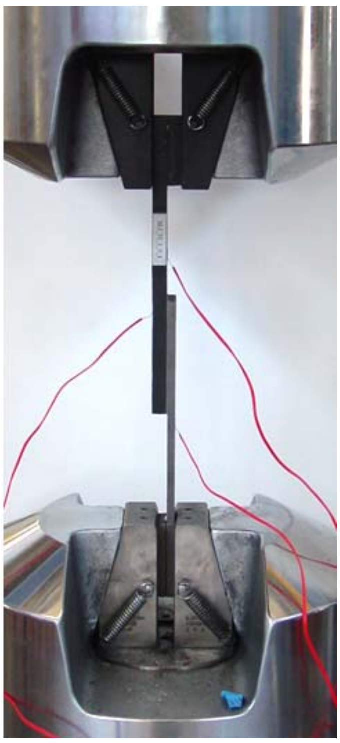

Figure 5. A typical CFRP-to-Steel SLJ with 75mm overlap length under experimental conditions.

4 Experimental Results

In order to draw confident conclusions regarding the parametric study and the effect of the corresponding parameters (adhesive thickness, overlap length and stiffness ratio), a comparison between the experimental global response and strength (maximum attained force) is presented in the following.

Figure 6 presents the strengths from all seven cases considered (see Table 1 and Figure 2) as experimentally measured. To begin with, a relatively increased deviation from the average value of the experimental strengths is obtained for the SLJ cases with 75 mm overlap length compared to the SLJ cases with 25 mm overlap length, resulting in a maximum coefficient of variation (CoV) equal to 5.7% and 1.4%, respectively. According to Figure 6, the effect of the selection of either adhesive thickness (0.5 mm or 0.85 mm) or stiffness ratio (0.175 or 0.35) on the corresponding obtained average strength is very small, irrespective of the overlap length. On the other hand, as expected, there is a significant effect of the overlap length on the strength of the joints, regardless of the selected adhesive thickness and stiffness ratio. Moreover, a 70% increase of the adhesive thickness results in only a 5% maximum increase of the strength of the corresponding SLJ cases with 25 mm overlap length. The same conclusion is drawn out for the effect of the stiffness ratio on the strength of the joints, where a 100% increase results in only a 5% maximum increase of the strength. However, the joints with three times longer overlap (200% increase) yielded a 100% maximum increase in their strength, compared to the joints with short overlap lengths.

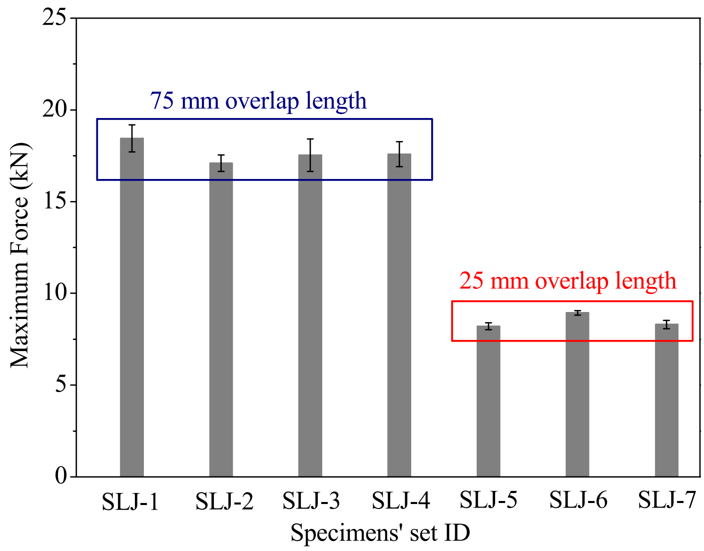

Figure 6. Experimental strengths of the 7 SLJ cases considered.

Figure 7 presents the force-displacement and force-strains relations of all three experimentally tested coupons from the SLJ-1 case. Similar behaviour was obtained for the SLJ-2 specimens. According to the experimental measurements shown in Figure 7, a very good repeatability has been obtained regarding their behaviour. The P - u relations are globally characterized by a linear behaviour up to the maximum attained load, where further increase in the applied displacement lead to the decay of the force and the subsequent failure of the joint. The crack was oscillatory within the adhesive bond, in a way that both cohesive and adhesive failure modes were present in the adhesive bond of all SLJ-1 and SLJ-2 specimens. The developed strains at the three measurement locations follow a linear pattern (see Figure 7b), which denotes that both the CFRP and the steel substrate remain within the linear elastic region. It is noteworthy that at the force level of 15 kN a change in the slope of the P - Strain relation has been recorded in location SG-3. This inflexion point is consistent with the global P – u

response, where, at the same force level, a non-linear region is registered up to the strength of each joint. These changes in the slopes are attributed to the damage initiation and propagation occurring within the adhesive layer underneath the SG-3 location.

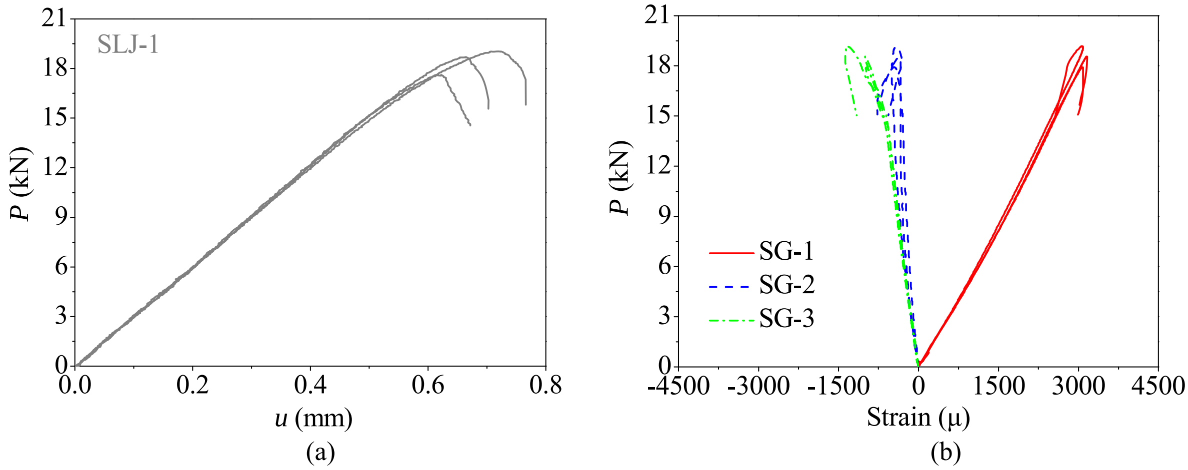

Figure 7. Experimental force – applied displacement (a) and force – strains (b) relations of the tested SLJ-1 coupons (similar behaviour obtained for SLJ-2 coupons).

Following the evaluation of the SLJ-1 and consequently of the SLJ-2 cases, which involve SLJ geometries with 8 mm thick steel substrates, the SLJ-3 and consequently SLJ-4 cases are examined, which involve 5 mm thick steel substrates. The corresponding results are shown in Figure 8 for the SLJ-3 coupons (similar behaviour has been obtained for SLJ-4 case).

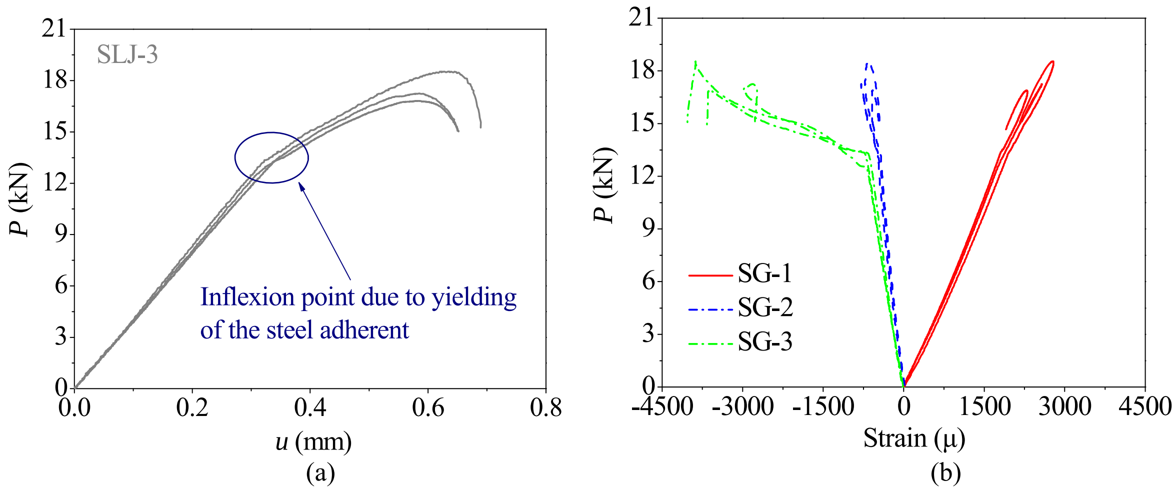

Figure 8. Experimental force – applied displacement (a) and force – strains (b) relations of the tested SLJ-3 coupons (similar behaviour obtained for SLJ-4 coupons).

An examination of the fracture surfaces revealed that the bond failed under both cohesive and adhesive fracture modes. According to Figure 8, a very good repeatability of the *P*-*u* and *P*-Strains experimental relations has been obtained. All three respective experimental *P*-*u* curves of SLJ-3 case share a common behaviour, which can be divided into three regions. The first region is described by a linear behaviour bounded by the inflexion point at the force level of 13.2 kN. The second region is bounded by the inflexion point and the load carrying capacity level of each joint, whereas the third region is described by a softening behaviour, which denotes the inability of each joint to carry further load. In this region, failure mechanisms are developing in the adhesive/substrate system, i.e. plasticity of the ductile adhesive, void nucleation in the adhesive, debonding at the adhesive/adherent interface, micro-cracking, etc. The change in slope (inflexion point) and the subsequent bilinear behaviour of the *P-u* plots are of significance importance and further examination must be done. According to the *P*-Strains relations shown in Figure 8b, a change in the slope is additionally observed at the same force levels for the strains measured at the SG-3 location. In fact, this particular location refers to strain measurements on the free surface of the steel substrates at the overlap edge, as shown in Figure 4. This change in slope is attributed to the yield (plastic zone creation) of the steel substrate at the opposite to the SG-3 location, as experimentally observed. Figure 9 presents a typical SLJ-3 specimen (the same occurs with the SLJ-4 specimens) after the failure of the bond, where the permanent deformation of the steel adherent can be seen with a naked eye.

Figure 9. Typical failure mode of a specimen of the SLJ-3 or SLJ-4 case denoting permanent plastic deformation of the steel substrate

Having evaluated the behaviour of the cases which involve single lap joint geometries with 75 mm overlap length (SLJ-1,2,3,4), the behaviour of the remaining cases that involve 25 mm overlap length will be examined. Figure 10 presents the force-displacement and force-strains relations of all three experimentally tested coupons corresponding to case SLJ-5. Similar behaviour is also obtained from SLJ-6 and SLJ-7 cases. According to this figure, the experimental data are in very good agreement regarding both their behaviour and maximum joint strength. The *P-u* curves exhibit an initial linear response followed by increasing non-linearities as the adhesive layer enters plasticity. As in Figure 7, a change in the slope of the *P*-Strain relation has been recorded in the SG-3 location at the force level of 6 kN. This inflexion point is consistent with the global $P - u$ response, where at the same force level, a non-linear region is registered up to the strength of each joint. These changes in the slopes are attributed to the damage initiation and propagation occurring within the adhesive layer.

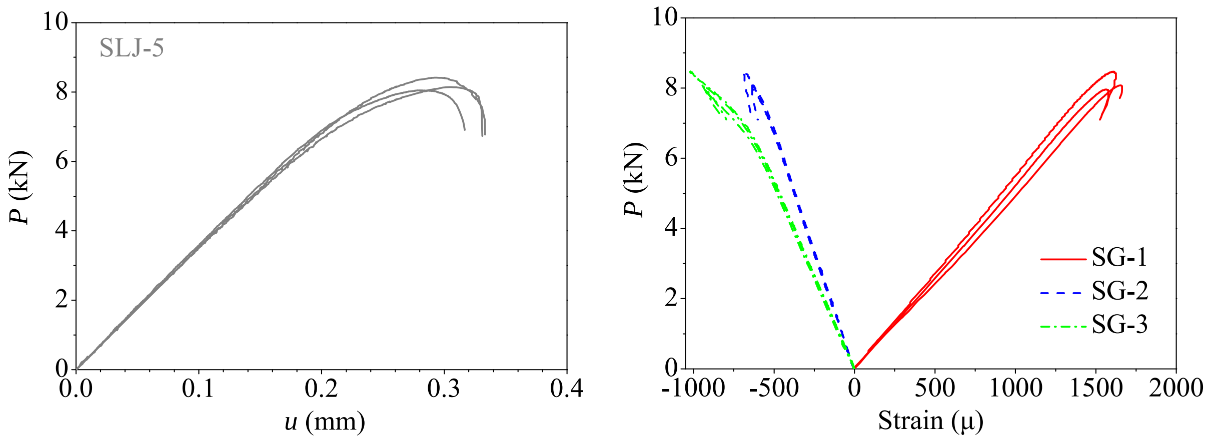

Figure 10. Experimental force – applied displacement (a) and force – strains (b) relations of the tested SLJ-5 coupons (similar behaviour obtained for SLJ-6 and SLJ-7 coupons).

5 Conclusions

For the cases considered where relatively thick substrates were utilized, the effect of the adhesive layer thickness and the stiffness ratio on the experimental strength of the joints was small. On the other hand, as expected, there was a significant effect of the overlap length on the strength of the joints, regardless of the selected adhesive thickness and stiffness ratio. In particular, a 70% increase of the adhesive thickness resulted in a 5% maximum increase of the strength of the corresponding SLJ cases with 25 mm overlap length. The same conclusion was drawn out for the effect of the stiffness ratio on the strength of the joints, where an increase of 100% resulted in a 5% maximum increase of the strength. However, the joints with three times longer overlap length (200% increase) yielded a 100% maximum increase in their strength than the joints with short overlap lengths. In the case where a long overlap length (75 mm) and a relatively thin steel adherent (5 mm) was utilized, the steel entered plasticity at the vicinity of the adhesive overlap edge.

Acknowledgments

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