A COMPARATIVE STUDY ON SINGLE-LAP AND WAVY-LAP ADHESIVE BONDED COMPOSITES

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Abstract. *The high peel stress concentration usually found at the edges of ordinary single lap joints are due to the load excentricity. Moreover, these high values of stresses are the main cause of the adhesive failure. In order to minimize this effect, Zeng and Sun (2000) proposed a novel design of a bonded lap joint. In this joint, the eccentricity of the load is avoided and the efforts of traction in the end of joint become compressive. Base on Zeng and Sun's idea the wavy-lap joint was modified by Bueno (2002). To be able to evaluate the wavy-lap performance a set of experiments was carried out and their results compared against those obtained from conventional single-lap joints. The composites used were plain weave E-glass/epoxy. All joints are tested under uniaxial tensile loading. The results had shown that the wavy-lap joints are significantly more resistant to the tensile. Geometrically nonlinear two-dimensional numerical analyses had been performed. The results show that in fact, in the new model, the interfacial normal stress are compressive in the overlap end and the shear stress is more evenly transferred over the length of the joint.*

Keywords: composites, bonded joints, experimental data, numerical simulations, single-lap joints.

1. Introduction

In many practical applications is virtually impossible to create an entire structure in a single piece due to the high costs involved or simply for geometrical limitations. An efficient way of overcome these limitations is the manufacture of small parts that will be assemblage together later on. The assemblage process itself requires the use of joints. The idea behind joints relies on load transfer from one part of the structure to another. This allows the structure to achieve the required stiffness even though it is composed of small parts. Notice that although the required stiffness have been achieved, the joints are regions of weakness. Moreover, as mentioned by Bahei-El-Din and Dvorak (2001), their use is not restricted to close related materials. Complete dissimilar materials, e.g. composites and metals, can be joining together.

Joints can be classified according to different criteria; one of them is the manufacturing process. According to Tong and Steven (1999), joints are divided in bolted/riveted, weld and bonded. Each of one of these three joints categories has its advantages and limitations. Benatar et al. (1997), for example, mention that the introduction of holes in the composite (or in any material) leads to stress concentration near the hole. In his study, Jones (1999) pointed out that non-uniform circumferential stress distribution around the hole can lead to a possible failure of the bolted/riveted joint. When the welding process is taken in consideration two points must be marked. According to Benatar and Gutowski (1986), due to intense localized heat and the cooling process, there will be a region where the mechanical properties will be affected. The phenomenon was observed by Cogswell (1983) in his study of carbon/epoxy composites, where the presence of spherulite formations were noticed when different cooling rates were applied. Furthermore, he established a relationship between theses microstructures and changes on the adhesive strength. Li et al. (2001) pointed out that the key advantage of adhesive bonded joints over other joint approaches, e.g. mechanical fasteners (bolting or riveting), is that it enables the development of large, cost-effective, and highly integrated structures. Furthermore, the use of bonded joints leads of a more uniform load distribution. Tsai and Morton (1994) stated that the most commonly used adhesive bonded configuration is the single-lap joint due to its combined simplicity and efficiency.

The mathematical formulations for lap-joint designs dated back to late 1930's and early 1940's with the work of Volkersen (1938), Goland and Reissner (1944), which provided the initial studies on stress and strain fields in the adherents and adhesive of a single lap joint. In early 1970's, Hart-Smith (1973) recalled the work done by Goland and Reissner, and he went further. He considered not only the adherents relatively flexible but also the individual deformations on the upper and lower adherents, dealing with them as decoupled beams. By doing this Hart-Smith was allowed to apply the end conditions to the adherents independently, which overcomes the Goland and Reissner deficiency. Oplinger (1994) gave one step forward. He took Hart-Smith's model and added to it the consideration of large deflection into the overlap area. Nevertheless, according to Tsay et al. (1998), the solution provided by Oplinger is only valid for thin and flexible adhesives.

Another source of solutions for adhesive bonded joints is the finite element method. Tsai and Morton (1994) analyzed a single-lap joint using a two-dimensional, plain strain conditions, and geometric nonlinear finite element model. The non-linearity was introduced due to the large deformations generated during the joint loading. Although their model was a 2D formulation, their results were in good agreement with the available theoretical solutions. Richardson et al (1993) demonstrated that for a number of bonded joints the 2D results are accurate enough to be acceptable. The main objective here is to carry out a performance study on a new design of single lap bonded joint for laminate composites, the so-called wavy-lap joint.

To be able to achieve this goal, a set of conventional single-lap joints following ASTM D 5868-01 (2001) were manufactured and used for comparison. Figure 1 shows the single-lap in a schematic form (all dimensions in millimeters).

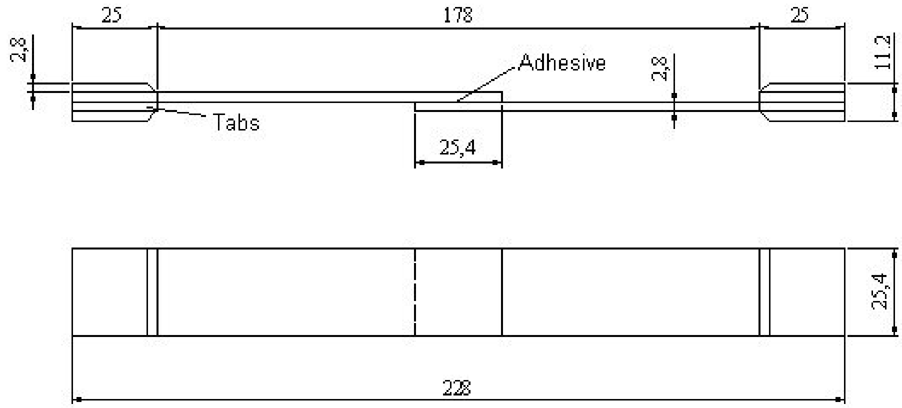


Figure 1: Schematic form of a single-lap joint

2. The wavy-lap joint design

The wavy-lap joint design was first introduced by Zeng and Sun (2001). According to them, this new design not only avoids the load eccentricity, common on single lap joints, but also allows the development of compressive stress at the joint's end of the overlap section. Tong and Steven (1999) pointed out the existence of a positive normal (peel) stress at the end of the overlap region of the single-lap joint, which is critical for the adhesive. By reserving the stress field, the joint could stand a higher load without breaking. Adams et al. (1997) that pointed out that adhesives have good strength to compressive and shear loading, but when the peel or cleavage is considered their performance is poor.

The wavy-lap used for this study is in its essence the one proposed by Zeng and Sun (2001) with a slight variation. The difference between the two models relies mainly on the overlap area. They considered the overlap length of 25.4mm (one inch). When comparing the overlap area of the single-lap joint and the wavy-lap, it is possible to conclude that they are approximately equivalent, i.e. they are close but not equal. In the present model, we imposed the condition of same overlap area. Therefore, considering the ASTM D 5868-01 (2001), the linear overlap length for the single-lap joint is 25.4 mm. For the wavy-lap joint, due to the ripple, it is 24.60 mm. In both cases, the actual bonded area is 625.16 mm^2 (one square inch). Figure 2 shows the actual dimensions in millimeters of the wavy-lap studied. Notice that the fillet radius is equals to10 mm and the joint is 25.4 mm wide. Besides, the undulation angle in the present model is equal to 12 degrees; while for the model proposed by Zeng and Sun this value is 14 degrees.

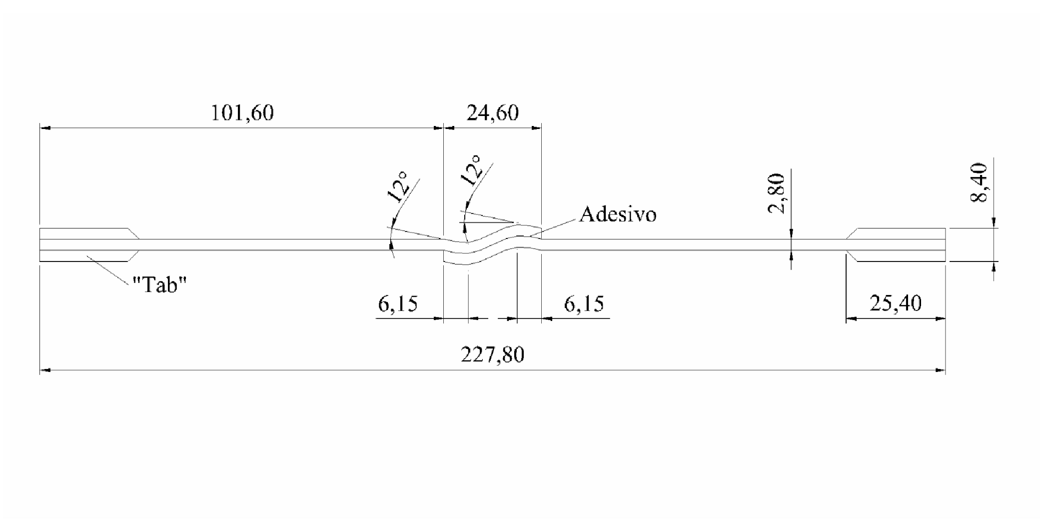


Figure 2:Wavy-lap scheme

For the present model, the initial configuration is an equilibrated zigzag joint. The next step is an iterative procedure looking for a wave configuration with small stress concentration that will fit into the specified overlap area. Zeng and Sun (2001), however, considers three straight segments with ratio1: 2:1. This assumption allows them to compute the length of each segment into the horizontal plane as ¼, ½, and ¼. Notice that overlap length projection into the horizontal plane for Zeng and Sun is equal to one inch. Once it is done, a curve fitting and smoothing is performed to reduce the stress concentration. The differences between the two models are shown in figure 3.

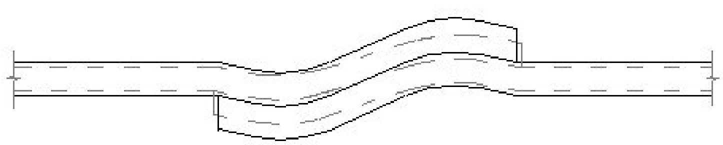


Figure 3: Distinctions between the two models

Besides the differences between the two models, the type of composite used is also dissimilar. Zeng and Sun (2001) studied two multidirectional carbon fiber/epoxy laminate configurations, i.e. $[90/0/90/0]_{2s}$ and $[0/90/0/90]_{2s}$, while in the present study a plain weave E-glass/epoxy composite is used. Although the fibers are complete unlike, carbon and E-glass, the focus of this research is the study of plain weave undulation effects into the wavy-lap overall behavior.

The adherent used into the joints, single and wavy, is a 16-layer plain weave E-glass/epoxy composite. The fiber volume fraction is close to 60%. The plain weave woven fabric (WR-200) has density of $200 g/m^2$, and the same number of yarns on both directions (TEXIGLASS, 2001). The epoxy resin XR1553 and its hardener HY 1246, and the adhesive AW-106 and its hardener HV953U are from Vantico (2001). A top and side view of the wavy-lap joints produced is show in figure 4.

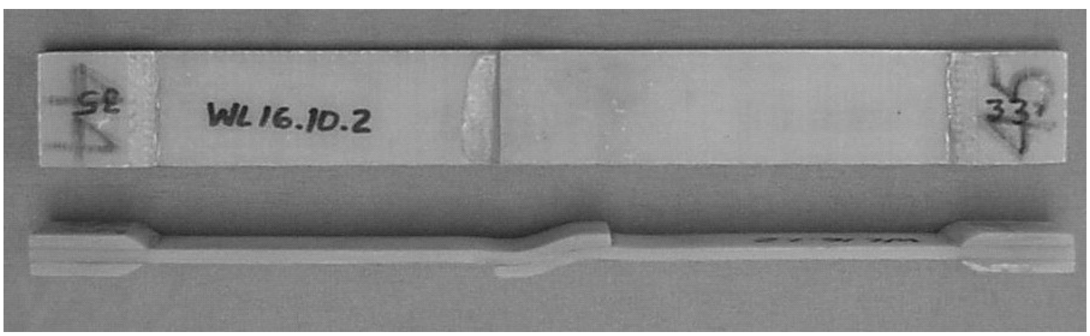


Figure 4: Wavy-lap joint top and side views

3. Experimental data analysis

To be able to evaluate the wavy-lap joint performance a design of experiment must be fulfilled. It is considered that the same sample size could be applied to both populations, single and wavy-lap. Moreover, considering the methodology proposed by Montgomery (2001), a sample population of 10 single-lap joints were tested, and their maximum loading were measured. For this population the mean value (μ) and the variance (σ^2) obtained are 7.24 KN and 1.34 KN, respectively. Following Montgomery (2001) the probability of type I error, often called the level of significance of the test (α) and the probability of type II error (β) are fixed equal to 0.01 and 0.05, respectively. Moreover, it is established that a difference in maximum loading between the two types of joints around 30% is enough to consider the two ones statistically distinct. Zeng and Sun (2001) reported an increase on maximum loading close to 50%. For safety reasons, it is assumed this value as 30%.

Once all data was defined the iterative process recommended by Montgomery (2001) can be applied. The result is a sample size of at least 15 samples, which leads a ($1-\beta$) probability of 0.985. Considering the possible failures during the bonding process, it is assumed a sample size population of 20 samples for each joint type. All tests are performed following the ASTM D 5868-01 standard.

The single-lap joints are manufactured from four different plates. From each of one of these plates a group of five single-lap joints are prepared. Figure 5 shows the maximum load obtained, while a typical load-displacement curve is shown in figure 6. A statistical analysis in these data indicates that the mean value for the maximum force is 7.18 KN, and 95% interval of certainty is between 6.67 and 7.69 KN. Besides, the standard deviation for the single-lap entire population is 1.10 KN. The groups 1 and 4 have a similar behavior, i.e. a close mean value for maximum load, while groups 2 and 3 are close to each other. To explain these behaviors two aspects must be analyzed, i.e. the adhesion process and the failure modes. The single-laps joints for groups 2 and 3 were bonded at same day with air humidity around 41% and temperature of 28 C. For groups 1 and 4 the humidity was close to 65% and 70%, respectively, with no significant changes on temperature. The increase on humidity could trigger a non-uniform adhesion between the adherents during the cure process.

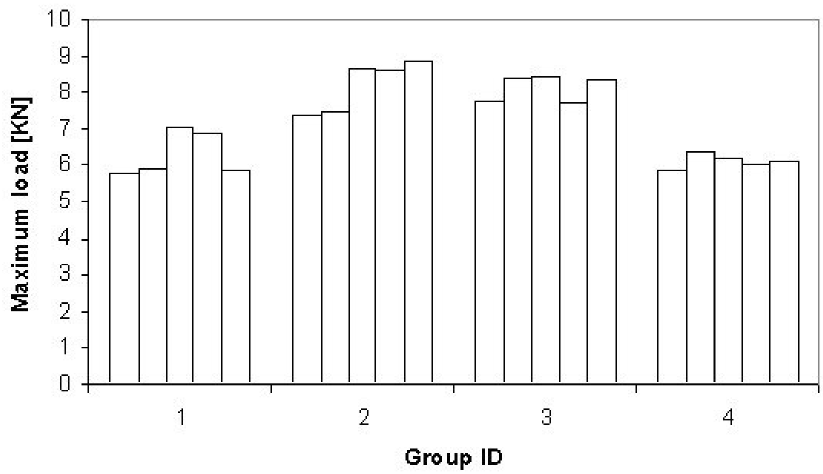


Figure 5: Maximum load distribution for single-lap joints

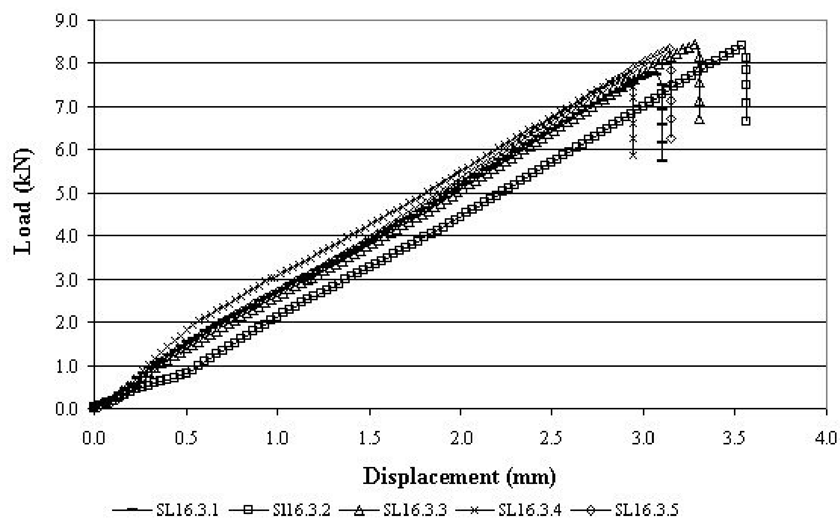
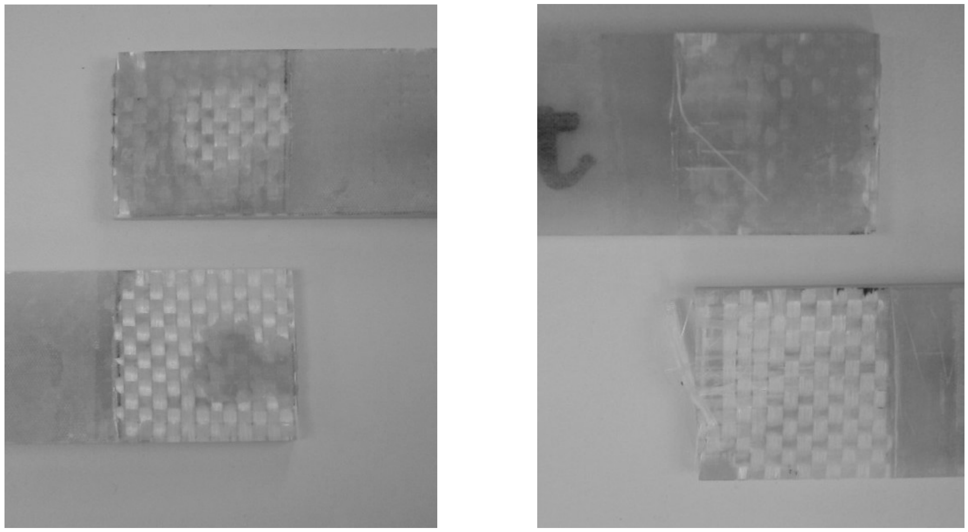


Figure 6: a typical load-displacement for the single-lap joints

The light-fiber tear mode failure, as described by ASTM D 5573-99 (1999), were observed in all specimens, but some differences can be noticed. A non-uniform fracture was observed into the specimens from groups 1 and 4 (see figure 7A). The opposite behavior was noticed for groups 2 and 3. By looking into the fracture itself, it is possible to identify the fracture path, i.e. it begins at the edges of the overlap area and ends at the joint center. This path is clear observed in Figure 7B.

To be able to understand why this type of failure could happened, a finite element simulation was performed. Figure 8 shows the shear and peel stress distribution at adherent/adhesive interface. Notice that the highest value of peel stress is located at overlap area edges leading to adhesive failure. At same time, the shear stress gets its highest value close to the edges which can trigger failures at adherent. This could explain the light-fiber tear mode failure for the E-glass/epoxy single-lap joints. It is important to mention that for carbon/epoxy composites single-lap joints tested by Zeng and Sun (2001) a cohesive mode failure was observed. The same stress distribution for peel and shear was obtained by Zeng and Sun. However, as the carbon/epoxy adherent is much stiffer that the adhesive the failure is expected to occur at the adhesive first.



A B

Figure 7: Fracture view: specimens from groups 1 and 2

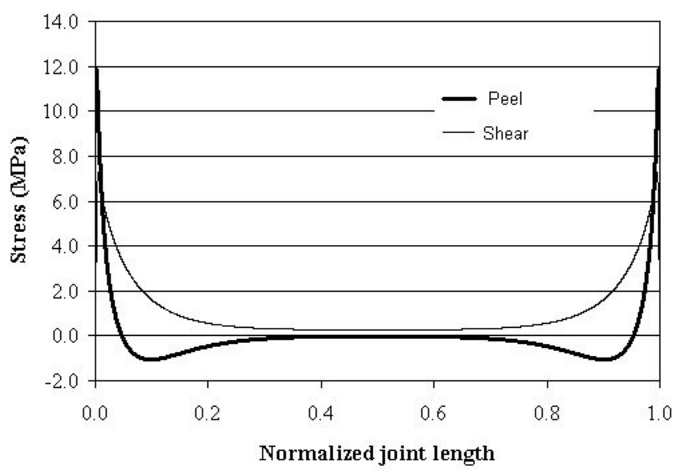


Figure 8: Peel and shear stress distribution at single-lap joint

Three wavy-lap joints can be obtained from each plate manufactured. Due to problems of resin infiltration in some of these plates less than three joints were prepared. However, the total number of specimens was kept equal to 20. The maximum force mean value obtained during the tests was 10.09 KN, and 95% interval of certainty is between 9.47 and 10.71 KN, and they are shown in figure 9. Besides, the standard deviation for the group of wavy-lap specimens was 1.32 KN. A typical load-displacement curve for this type of joint is shown in figure 10.

The predominant mode failure for the wavy-lap joints was the light-fiber tear, and it can be seen at figure 11A. On the other hand, a second failure mode was also observed. In 25% of wavy-lap joint specimens, the failure occurred by adherent delamination as shown in figure 11B. It is important to mention that, the joint itself does not failure. The delamination seems to begin at the interface between the first and second ply, shown in figure 11C. Again, to better understand the failure mechanism a finite element simulation was performed. Notice that normal stress distribution at end of the joint is compressive, although the peel stress is present at the center, see Figure 12. The compressive (negative) stress location is around on the most critical joint area, i.e. the edges. Tong and Steven (1999) pointed out that peel stress, positive normal stress, at the joint edges is one of the key factors that guide to failure. Moreover, the adhesive strength to compression is good. By reversing normal stress from positive (peel) to negative (compressive) at these areas the adhesive “strength” increases. Another interesting fact is that most of shear loading is transfer to the joint center. These two factors combined could lead to the delamination failure, as the adhesive becomes “better” and the stress field at laminate reaches the failure limit.

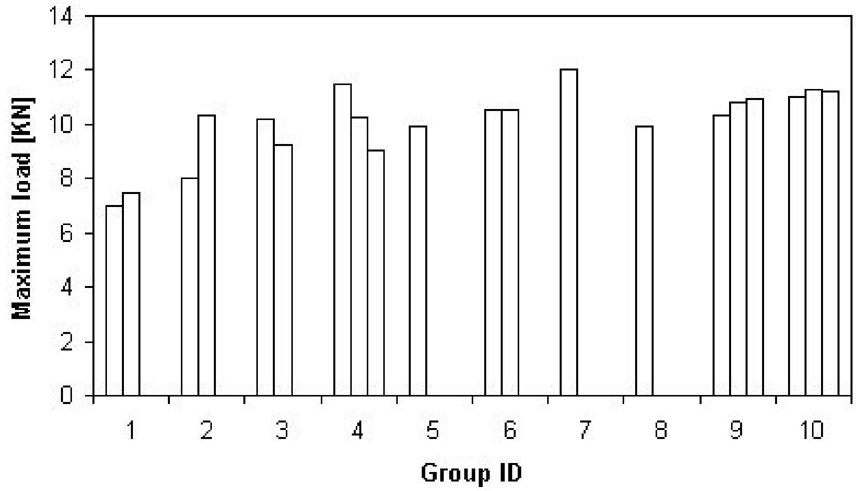


Figure 9: Maximum load distribution for wavy-lap joints

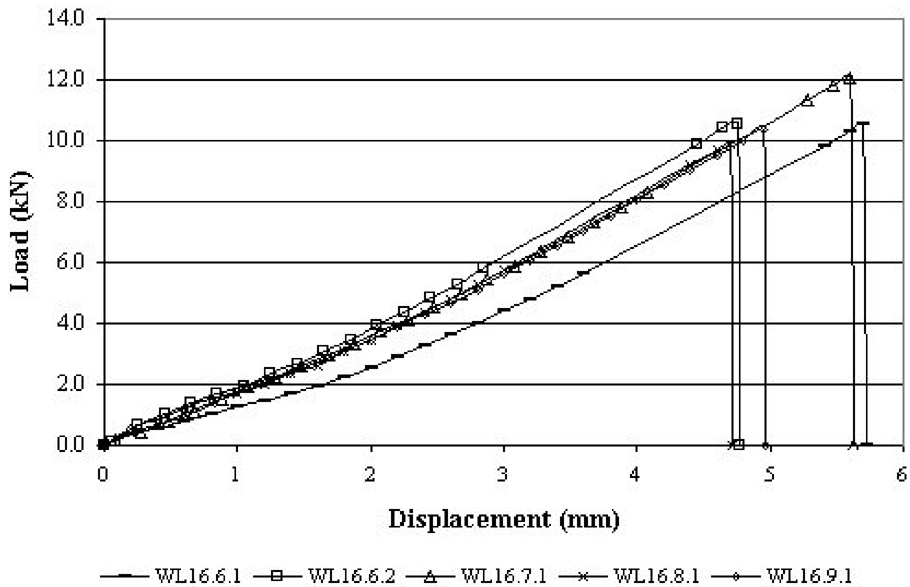
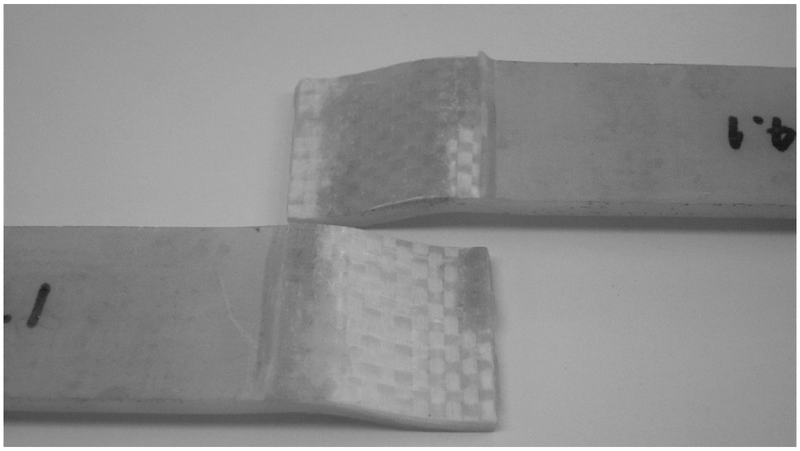


Figure 10: Typical load-displacement curve for wavy-lap joints

Although the present wavy-lap has a thickness 40% higher than the one designed by Zeng and Sun (2001), its mean value for the maximum load is 90% of the value obtained by Zeng and Sun. The adherent used by Zeng and Sun is a carbon/epoxy composite with stiffness eight times higher that the E-glass/epoxy used in the present work. The explanation for this good performance could be on the fiber configuration. The undulation of the plain weave textile could allow a better fiber allocation inside the plate mold and reducing the interlamina stress concentration.



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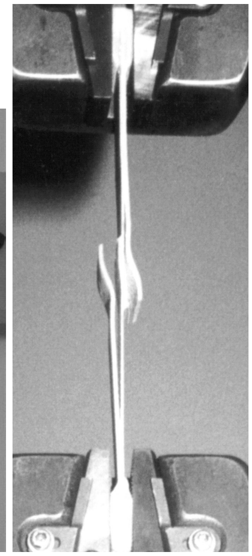

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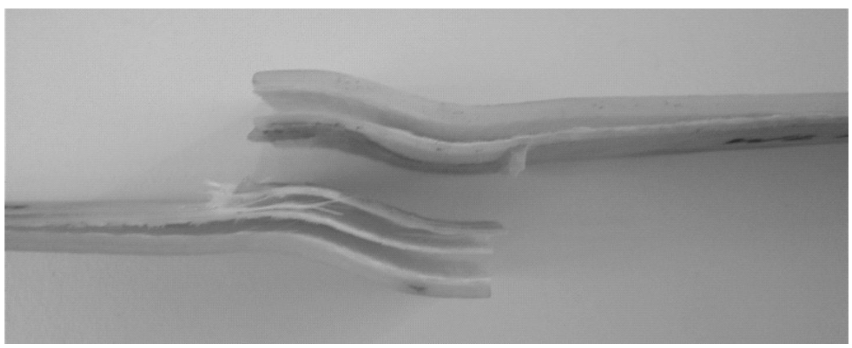

C

Figure 11: Mode failures for wavy-lap joint

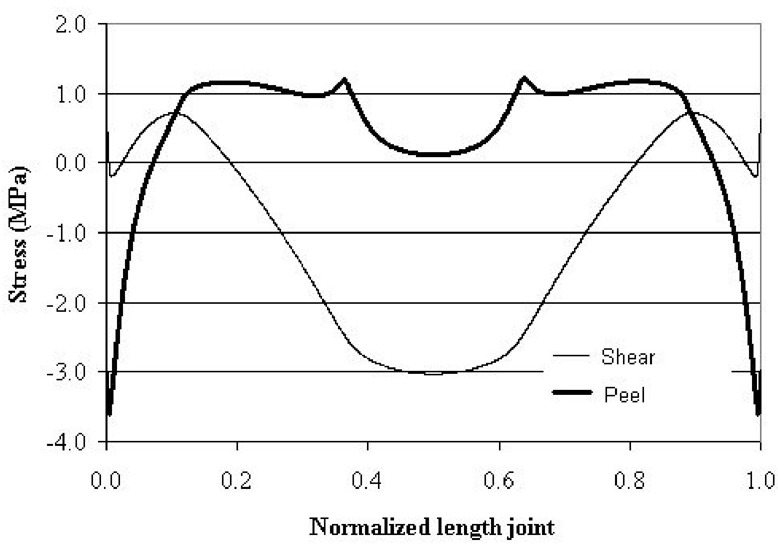

Figure 12: Stress distribution for the wavy-lap configuration

4. Closing Comments

The modified wavy-lap joint designed has a superior performance when compared against conventional single-lap joints. The mean value for the maximum force of the single-lap joints is close to 7.2 KN, while for the wavy-lap the average value of the maximum force is around 10.1 KN. These values represent a 40 % increase on strength. A statistical analysis considering the design of experiment formulation was applied to this study. Moreover, the results obtained indicate that they are statistically consistent.

By analyzing the stress field in each bonded joint, it was possible to conclude that increase on strength can be due to the inversion of the stress field, in other words, for a single-lap joint the stress field is positive (traction) while for the wavy-lap the stress field is mainly negative (compression). As the adhesive has a higher strength when under compression the failure occurs in much higher loadings. Another interesting fact is the failure mode itself. For the single-lap joints a light fiber tear mode was observed, while in the wavy-lap joints an adherent delamination was noticed. The reason can be attributed to the stress field distribution, which could lead to a premature delamination.

This new design of bonded joints seems to be very helpful for some practical applications were high strength is required, e.g. connection rods and command cables for small airplanes. The results are encouraging.

5. Acknowledgments

The authors would like to acknowledge of the financial support provided by Brazilian Research Council (CNPq). The authors are also thanks to the additional financial support supplied by the Universidade Federal de Minas Gerais (UFMG) and the Graduate Studies Program in Mechanical Engineering (PPGMEC).

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