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FAILURE ANALYSIS OF LAP AND WAVY-LAP COMPOSITE BONDED JOINTS

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ABSTRACT

This paper addresses the geometric nonlinear FE analysis of a novel design of adhesive joint. A finite element analysis was carried out to analyze the stress field inside the joints. FEA results have shown a considerable increase of strength on loading in wavy-lap joint. This fact may be due to compressive stress field developed inside the wavy-lap joint. In bonded joints, maximum stresses are induced at the edge of bond line. Three dimensional finite element analyses are conducted on bonded joints to determine the stress distribution on the bond length. Values are predicted by finite element analysis using three-failure criterion.

Key words: Light weight, joining, composites, bonded, wavy-lap

1. INTRODUCTION

The potential uses of composite laminates are increasing with the drive force for high strength, lightweight and high stiffness component design. These require joining composites to composites and composites to metal like automobile drive shaft, payload structures in aerospace industries. In many practical applications, it is virtually impossible to create an entire structure in a single piece due to the high costs involved or the geometrical limitations. The solution is the manufacturing of small parts that can be assembled together later on. The assembly process itself requires the use of joints. Joints rely unload transfer from one part of the structure to another, which allows the structure to achieve the required stiffness even though it is composed of small parts. The analytical solutions proposed over the last five decades and described in details by Tong and Steven[1], the finite element method is another source of information for design of adhesively bonded joints. The first finite element analysis (FEA) of adhesive joints dates back to the 1970s when Wooley and Carver[2] conducted a stress analysis on single-lap joints. The mesh required was very refined due to the use of quadrilateral elements. To reduce the amount of computational effort, Carpenter and Barsoum[3] attempted to model the adherent's with two-node beam elements and the adhesive layer by linear plane element with offset nodes. By doing this the number of degrees of freedom was drastically reduced. The work completed by Richardson[4] follows the same idea. They analyzed the single-lap joint using two-dimensional, plane strain conditions and geometric non-linear finite element model. The large deformations generated during the joint loading introduced nonlinearity. Although their model was a two-dimensional formulation, their results were in good agreement with the available theoretical solutions. The non-linear two-dimensional FEA was recently evoked when Li and Lee-Sullivan[5] performed their study on single-lap balanced joints under tension. In this study the use of CQUAD4 shell element was employed under both plane stress and plane strain conditions, with good results. Infact, their results show that there are no practical differences between the finite element predictions made with plane stress and those made with plain strain conditions. The non-linearity issue was also addressed by Andruet et al.[6], who performed both two- and three-dimensional analysis of a single-lap joint. In the two-dimensional analysis, they used Bernoulli beam elements with axial deformation to model the adherent while the adhesive layer was represented by plane stressor plane strain elements. Notice that the Bernoulli beam element is essentially a one-dimensional element in two-dimensional space. A similar approach was considered in which shell elements were used to represent the adherents and fully three-dimensional elements, i.e. brick elements, were employed to represent the adhesive layer. They claim that three-dimensional effects could be observed during their analysis. The main objective of the work described in this paper was to carry out a performance study on a novel design of single-lap bonded joint for laminate composites, the so-called wavy-lap joint. For achieving this goal, a set of conventional single-lap joints following ASTM D 5868-01[8] was manufactured and used as reference.

2. WAVY-LAP GEOMETRY

The wavy-lap joint design was first introduced by Zeng and Sun[9]. According to them, this new design not only avoids the load eccentricity common to single lap joints but also induce the compressive stress at the end of the overlap section. Tong and Steven[1] pointed out the existence of a peel stress at the end of the overlap region of the single-lap joint, which can be disastrous for the adhesive. By changing the stress field from tensile to compressive, the joint could stand a higher load without breaking. Adams et al.[10] pointed out those adhesives have good strength in 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 essence a Variation of the one proposed by Zeng and Sun[9]. The difference between the two models relies mainly on the overlap area. They considered an overlap length of 25.4mm measured at the horizontal line. When comparing the overlap area of the single-lap joint with that of the wavy-lap joint, they are approximately equal. In the present model, we imposed the condition of equal overlap areas. Therefore, the linear overlap length for the single-lap joint is 25.4mm[7]. For the wavy-lap joint, due to the ripple, it is 24.6 mm. Fig 1 and Fig 2 shows the actual dimensions in millimeters of the single- and wavy-lap joints. The joint is 25.4mm wide and the angle is 12° with fillet radius 10mm. The design of wavy-lap joint is done by using CAD soft ware. The adherent used for the joints is a 16-layer plain woven Glass/epoxy composite. The fiber volume fraction is close to 60%. The plain woven fabric has the same number of yarns in both directions. The epoxy resin XR1553 and its hardener HY 951, and the adhesive AW-106 and its hardener HY 951.The adhesive has an average thickness of about 0.20mm in both cases.

3. DESCRIPTION OF FINITE ELEMENT MODEL

The FEA performed in this study was two-dimensional, geometrically non-linear, and under considerations of plane strain. Both single- and wavy-lap joints were modeled. The difference between the present model and the one performed by Li and Lee-Sullivan[5]. The non –overlap length is divided into 200 parts and overlap length is divided into 500 parts. The mechanical properties are listed in Table 1. The single lap joint configuration, composed of two similar or dissimilar generally orthotropic laminates subject to general loading condition, is shown in Fig. (3). the adherends thicknesses are t_1 and t_2 and the thickness of the adhesive layer is t_a

The Fig. (4) Shows adherend element linked with adhesive elements, the link is done by using only translational degrees of freedom, because MSC.Nastran solid elements do not have rotational degrees of freedom.

3.1: CHEXA8 SOLID ELEMENT WITH CORRESPONDING DEGREES OF FREEDOM.

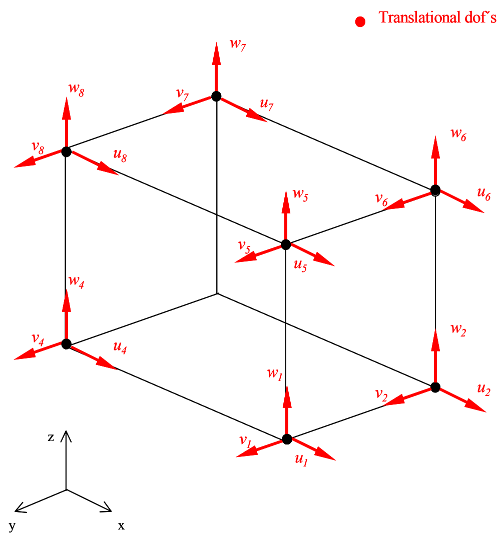

Fig 5.CHEXAB solid element with corresponding degrees of freedom

4. EXPERIMENTAL ANALYSIS

The single-lap joints are manufactured from four different plates. They are prepared by hand lay-up with cure under room temperature. From each of these plates, a group of five single-lap joints is prepared. The plates bonding areas are wiped with acetone and later on abraded by using fine abrasive paper to remove gloss surface. The acetone is again applied to remove all residues from sanding. The adhesive is prepared and the mixture is applied at the bonding surfaces and the adherents are clamped for 24 h for curing.

Fig 5 shows the maximum load distribution for lap joint. As mentioned by Lee and Holl[13], the moisture could be the cause of a decrease on shear properties on the adhesive, which can explain the discrepant behavior. Although the light-fiber tear mode failures, as described by ASTM D 5573-99[14], were noticed in all specimens, some differences were detected. The non-uniform adhesion could induce a non-symmetrical stress distribution. Fig 6 and fig 7 shows the peel and shear stress distribution at single–lap joint at adhesive centerline. Notice that the highest value of peel stress is located at the edges of the overlap area, which leads to adhesive failure. At the same time, the shear stress has its highest value close to the edges; this can trigger failures at the adherent. This could explain the light-fiber tear mode failure for the Eglass/epoxy single-lap joints. Zeng and Sun[8] however, reported a cohesive mode failure for their carbon/ epoxy single-lap specimens. The reason for this behavior could be attributed to the large stiffness difference between adherent and adhesive. The adhesive stiffness is orders of magnitude smaller than the carbon/epoxy stiffness. Therefore, a failure is expected to occur first in the adhesive. Another important fact that must be analyzed is the normalized peel stress highest value. In the present case, this value is around 1.20 while Andruet et al.[6] reported a value close to 0.35, and Gon@alves et al.[16] a value of approximately 1.48. The reason for such discrepancy was attributed by Li et al.[17] to the adhesive thickness. They concluded that thicker adhesives produce larger normalized peel stresses. In Andruet et al.[6] study, the adhesive thickness was 0.10mm while in Gon@alves et al.[16] analysis this value was 0.25 mm. Thus, for the present study, the adhesive thickness is close to 0.19 mm.Therefore, it is possible to conclude that the adhesive thickness has a major influence on normalized peel stress, and as a consequence the 1.18 value seems to be a reasonable result.

Five wavy-lap joints test specimens are fabricated. After the wavy shape profile is defined by a CAD tool, a prototype template is prepared by using Rapid prototype machine. Test specimens were fabricated by using hand lay –up technique. After the stacking sequence is completed it is cured at room temperature. The joint preparation follows the same procedure used for the single-lap joints. The mean value of maximum force is 10.09 KN. Fig.8 shows the maximum load distribution for Wavy- lap joint. The predominant failure modes for the wavy-lap joints are the light-fiber tear. The failure probably initiated at the edges. On the other hand, a second failure mode is also observed. The failure occurred by adherent delamination.The delamination seems to begin at the interface between the first and second ply. Fig 9 shows the peel and shear stress distribution at wavy–lap joint at adhesive centerline. We can Notice that the distribution of normal stress at end of the joint is compressive, although peel stress is present at the joint center, as shown in Fig 8.

The compressive (negative) stress location is at the most critical joint area, i.e. the edges. Tong and Steven [1] pointed out that peel stress, positive normal stress, at the joint edges is one of the key factors that lead to failure. Moreover, the adhesive strength in compression is good. By reversing the normal stress from positive (peel) to negative (compressive) at these areas, the adhesive ‘‘strength’’ seems to increase. When the normalized peel stress distribution from the wavy-lap joint is compared against the one from single-lap joint the advantage is more evident. The maximum normalized peel stress for the wavy-lap joint is close to 0.12, while for the single-lap joint with same adhesive thickness the value is 1.18. This difference can be attributed to two major factors: (a) the presence of undulations on plain weave textiles used in the present work; (b) the adhesive thickness. Notice that the adhesive thickness in reference[8] was equal to 0.1 mm. Furthermore, the small value for the normalized peel stress could be attributed to the wavy shape geometry used into the joint. This geometry is also responsible to the shear loading be transferred to the center of the joint. Finally, this novel design seems to lead to a smaller stress concentration at the edges of the overlap area, a critical region for bonded joints. The normal stress distribution in the X-direction for single- and wavy-lap joints was obtained from FEA analysis. The maximum value of normal stress in the X-direction for the wavy-lap joint is close to 6.5 times smaller than its analogous stress for the single lap joint.Jeng[18] also reported a significant reduction on peel and shear stresses. All these factors combined could play a role in improving the performance of the wavy-lap joints over single-lap joints. In an average sense, the performance of the wavy-lap joint was close to 41% better than that of the single-lap joint. Fig 10 shows deformed shape and peeling stress along the adhesive layer in non-linear analysis.

5. CONCLUSION

- The maximum load carried by the wavy-lap joint was in an average 40% higher than that carried by single lap-joint. This may be due to the compressive stress field developed inside the wavy-lap joint in addition to the shear stress.
- The maximum load carried by the stepped joint was in an average 32% higher than that carried by single lap joint. This may be due to in line application of load with out eccentricity, which can take up more tensile load.
- An adherent failure by delamination is noticed in the wavy-lap joints.
- For the single-lap joints the light tear failure is observed.

- Wavy-lap joint is very useful, especially for structures by considering the above factors

6. REFERENCES

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TABLES

Table1.Material properties.

	Ex=Ey (GPa)	Ez (GPa)	Gxy (GPa)	Gxz=Gyz (GPa)	Nxy	nyz=nzx
Adherent	18.31	8.35	3.19	2.42	0.17	0.37
Adhesive	2.20	2.20	0.84	0.84	0.31	0.31

FIGURES

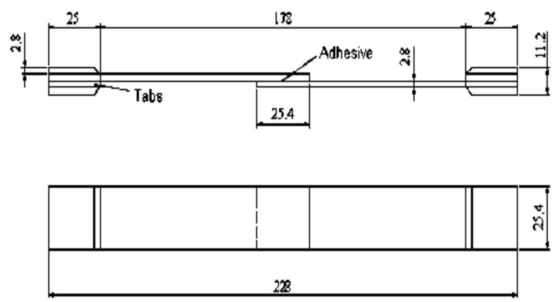

Fig 1: Single Lap joint

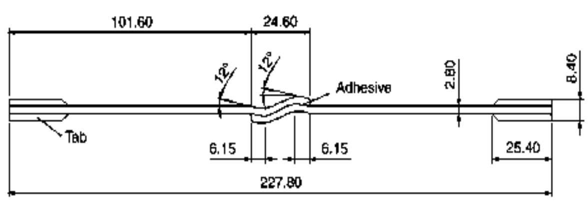

Fig 2: Wavy –Lap joint

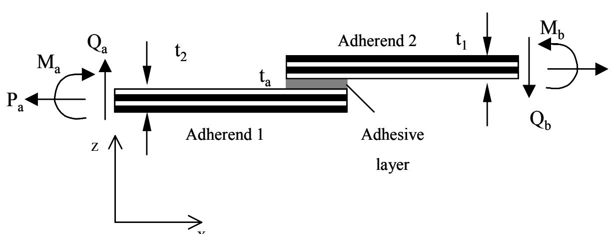

Fig3: single lap joint subjected to general loading conditions.

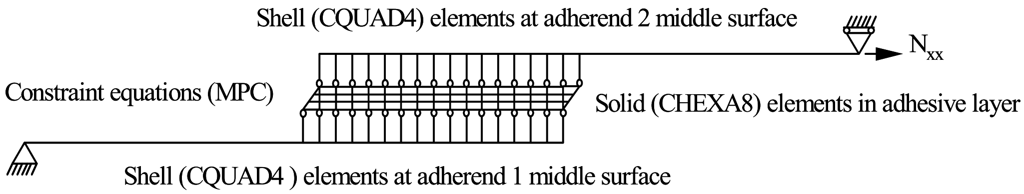

Fig. 4: Adherend element linked with adhesive elements

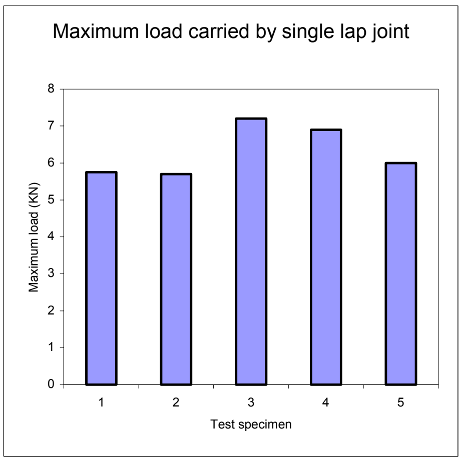

Fig5: Maximum load distribution for Single-lap joint

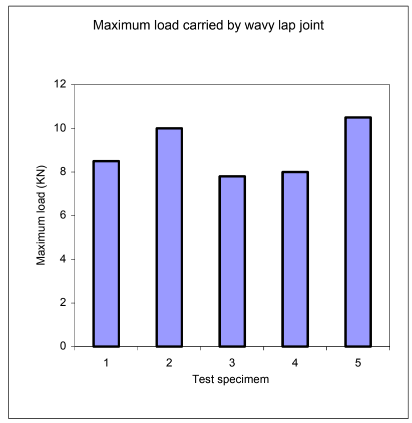

Fig8: Maximum load distribution for Wavy-lap joint

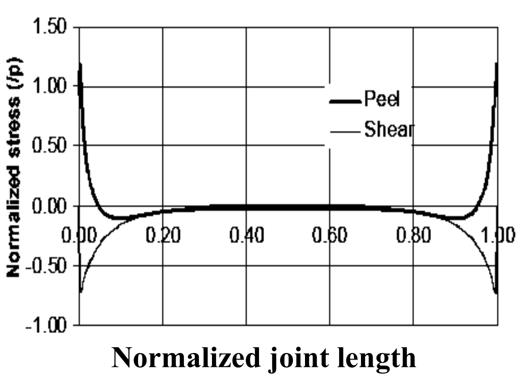

Fig 6: Peel and shear stress distribution at single lap joint

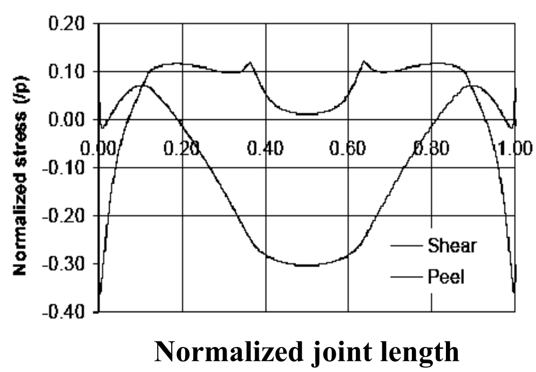

Fig 9: Peel and shear stress distribution at wavy lap- joint

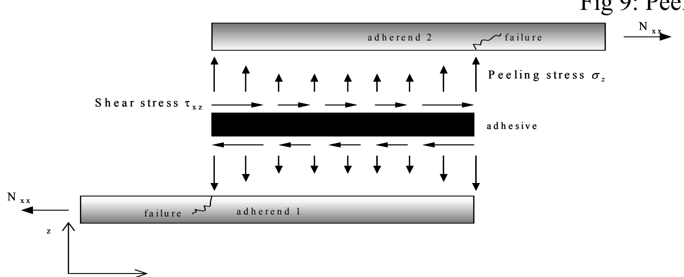

Figure 7: Peeling and shear stresses in single lap

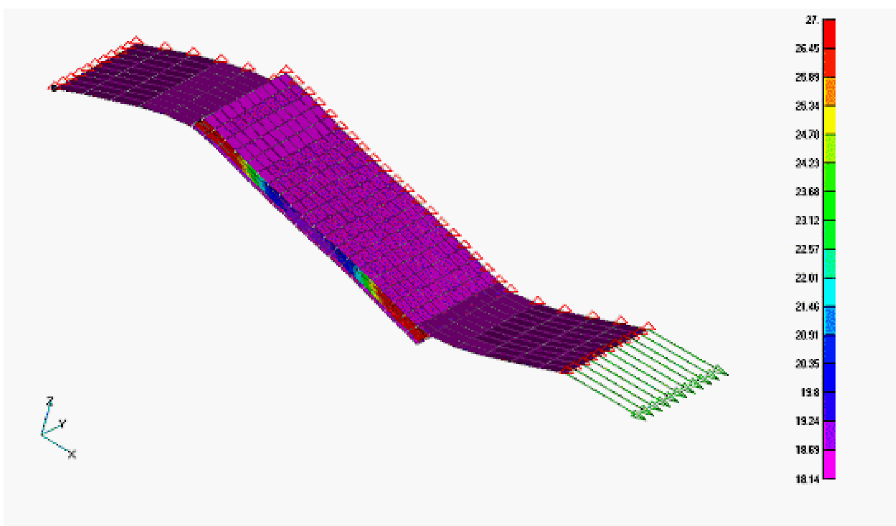

Figure 10. Deformed shape and peeling stress along the adhesive layer in non-linear analysis.