DEVELOPMENT OF TECHNIQUES FOR THE JOINING OF COMPOSITE TUBES

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SUMMARY: Manufacturing and Testing techniques were investigated for the development of efficient joining of composite tubes. The stepped lap joining arrangements were studied. Finite element models were developed using ANSYS finite element code for predicting the stress distribution of the joint under the applied loads. Tubes made of graphite/epoxy were considered. The tubes were tested under both tension and torsion. The joining technique developed provides an average joint strength of 69% of the strength of the substrate when tensile tests were conducted. Reinforcement of the joint with overlay layers improves the joint strength efficiency in tension to 81%. In torsion, the average torsional joint strength is 70% of the torsional strength of a tube with no joint. Reinforcement of the tubular joint with overlay improves the torsional behavior to 86% of the torsional strength of the tube with no joint.

KEYWORDS : joining, tubes, finite element method (FEM), manufacturing

INTRODUCTION

Thin walled tubular composite structures are becoming more important in many applications. One example is the arm boom for the Canadarm. Other possible applications in the future can be components for the robot arms, control rods and truss elements for satellite etc. One particular area of concern is the joining of these tubular structures. There are many techniques for the manufacturing of straight tubular composite structures such as rolling, filament winding, braiding. However, since the structural efficiency of a composite tubular structure depends on its configuration and the configuration of its joints, tubular joint design requires more attention and has become an important area of research.

There are generally two types of joints in composite structure: bolted joints and bonded joints. Among the bonded joints, two types can be identified: bonding composite to metal, and bonding composite to composite. This paper examines the techniques for the development of bonded joint strength between composite tube to composite tube. The advantage of the composite to composite bonded joint is the significant weight saving that can be obtained. To the author=s knowledge, there has been very limited work done on the tubular composite to tubular composite joints. Workers in the chemical processing industry have developed techniques for the composite pipe joints. Groves et al [1] performed experiments by bonding wedge cones around the ends of filament wound cylinders to facilitate testing. Most of the work on composite to composite adhesive bonded joint have been performed on flat plates. A comprehensive presentation on the joint design for composite flat plates was given by Matthews [2]. Information on the adhesives and the effect of environment can be found in References [3,4]. Hart-Smith [5] proposed many different configurations for the adhesive bonding of flat plates. A few researchers have performed analysis on tubular lap joint. Hipol [6] analyzed a joint composed of a steel tube adhesively bonded to a composite tube subject to torsional loads. This researcher found that the maximum stress concentration in the adhesive layer occurs in the end from which the less stiff adherent extends. Chon [7] corroborated this by stating that a large stress concentration is mainly due to Aadherent stiffness imbalance≅. Andersen et al [8] studied the design and performance of a cylinder joint subjected to hydrostatic pressure. Price and Moulds [9] performed computer simulation to observe the effects of changing various test conditions, such as component section, adherent material, adherent thickness and bondline thickness, on stress distributions of lap joints.

STRESS ANALYSIS TO DETERMINE EFFICIENCY

In order to provide guidelines for the development of the tubular composite design, finite element models were developed. For comparison and checking purposes, finite element models for flat plate joints were also carried out. These were analyzed using ANSYS 5.0 program, SOLID 46 elements. The flat plate models consist of a simple flat plate, lap stepped joined flat plate, and lap stepped jointed flat plate with overlay reinforcement (see Figure 1). This figure also shows the different cylindrical models which consist of simple cylinder, cylinder with lap stepped joint, and cylinder with lap stepped joint and over wrapping reinforcing layer. The width of the flat plate model is about the same as the circumference of the cylindrical model.

The models have the following dimensions. Items marked with an asterisk apply to the cylindrical model only. The male and female terms refer to that of the cylinder. For the flat plate, the male and female refer to flat components.

	MALE	FEMALE
Length:	15 cm	15 cm
Width:	8 cm	8 cm
Width*:	8.69 cm	8.69 cm
Inner radius*:	1.27 cm	1.27 cm
Outer radius*:	1.5 cm	1.5 cm
(One) step length:	1.5 cm	1.5 cm
Bond length:	4.5 cm	4.5 cm

Adhesive bond area (approx.)	35 cm^2
Adhesive thickness:	150 :m
Step angle:	3^o (See Figure 2)
Laminate thickness (single):	142 :m
Workpiece thickness (both models):	2.272 mm

Figure 2 shows the details. The adhesive joint occurs over three steps. For the flat plate joint, there is a height difference between the two plates caused by the adhesive layer. The reinforcing overlap layers have a length of twice the bond length (9.0 cm). The overwrap layers are centered over the bond area and extends one-half length over each side.

The materials used was graphite/epoxy NCT-301. Unidirectional layers were used. The properties can be found in Ref. [10].

Figure 3 shows an example of the stress distribution in the male part of the joint. Moving from the end with the constraint (large end with an X) to the bonded area, just after the first bond line, on the first step, a high stress region occurs (shown as a large ring). This high stress region is followed immediately by a low stress region (lighter area). This pattern of elevated/reduced stresses is present at every step. Comparing the maximum axial stress in the simple flat plate and lap stepped joined flat plate shows that the lap stepped joined flat plate has a stress concentration factor of 1.3. For the case of the simple cylinder and lap stepped jointed cylinder, the lap stepped joined cylinder has a stress concentration factor of 1.089. The difference in the stress concentration factor in these two cases can be explained by the symmetrical arrangement in the case of the cylinder and the non-symmetrical arrangement in the case of flat plates. Also, the maximum shear stress in the stepped tubular joint is 7.63 MPa, which is smaller than the maximum shear stress in the stepped flat plate of 11.45 MPa.

Reinforcing the bonded area with additional layers reduces the stresses in the bonded area. However, the stress at the transition region between the reinforced area and non-reinforced area increases. On the other hand, this may not be taken to indicate that the reinforced stepped joined tubes have a lower joint strength efficiency than the non-reinforced stepped joint tubes. This is because the failure may happen due to shear pull out or due to axial fracture.

MANUFACTURING AND TESTING

Male and female tubes were made. Each tube consisted of 16 layers of material placed on its respective mandrel. Cross ply lay-ups (0/90) were used. Figures 4a and 4b show the configuration of the male and female tubes before they were bonded together. The steps on the tubes were carefully sanded, cleaned and bonded together using Hysol adhesive. The male and female tubes were held in alignment during the curing phase with an alignment mandrel. The curing cycle was 65^oC for 1 hour. The tubes were tested in both tension and torsion.

Tension test:

The tensile strengths of the tubes are shown in Table 1. The results are in the range of 54 kN to 65 kN for the 4 tubes tested.

In order to obtain the efficiency of the bonded joint, a tube made by co-curing both the male and female parts of the tube at the same time, (i.e. both the male and female parts are laid up and cured in one step). This tube was made by laying up the male tube first, then lay up the female tube directly over the male tube. The assembly was then cured. The tensile strength of this tube is 84 kN. Examination of the fracture ends reveals that this tube fails in tension. The efficiency of the bonded joint can therefore be calculated by dividing the average of the four tubes (58 kN) by 84 kN to obtain an efficiency of 69%.

The effect of reinforcing the tube with an overlay layer on the outside of the bond area was also examined. The tensile strength of this tube is 68 kN. This tube failed in partial shear and partial tension. This gives an efficiency of 81%.

Lap shear tests were also done for virgin plates and joined plates. For flat plates of 0.813 cm width and of the same lay up as that of the cylinder, the results are 14.7 kN for a single lap joint and 20 kN for a virgin sample. This gives a shear strength of 19.49 MPa and an efficiency of 73.5%

Torsion test:

Strain gages were mounted onto the tube for strain measurements. Table 1 also shows the results of the torsion tests. A virgin tube without any joint gives a torsion strength of 213 Nm. Tubes with joints give torsional strength from 147 Nm to 152 Nm with an average of 150 Nm. This gives an efficiency of 70%. A joined tube reinforced with overlay layers gives a torsional strength of 184 Nm for an efficiency of 86.4%.

Strain variation for the tube was also obtained. The slope of the maximum shear strain versus torque curves (Ref. 10) can be used to obtain the shear modulus of the sample. The average slope is T/(= 14.55 kN-m. Using the equation for elastic behavior under torsion one has:

$$G = 2T/(Br^3 ()$$

Using a radius value of 1.5 cm yields a shear modulus of G = 2.744 GPa. The shear modulus, as obtained from the characterization of the material, using rail shear test, is 2.852 GPa.

DISCUSSION

The agreement between the shear modulus determined using torsion experiment and that obtained using rail shear tests provides confidence on the quality of the manufacturing of the tube, the joining procedure and the testing procedure. This serves as a basis for further discussion.

From the geometric point of view, the lap joint in tubes has the advantage of symmetry over the lap joint in flat plate. The joint strength efficiency in tubes theoretically should be larger than that for flat plates. Finite element results show that the average maximum shear stress in stepped lap joint in flat plate was 11.45 MPa and that for stepped lap cylinder was 7.63 MPa. This confirms the observation. However, in terms of efficiency of the joint strength determined experimentally, the joint strength efficiency of lap joint in flat plate is 73.5% whereas that for lap stepped joint in cylinder is 69%. The explanation for this discrepancy is due to the complexity in the manufacturing of tubular joint. For flat plate joint, the manufacturing procedure is more simple as compared to that of a cylindrical joint. A weight was placed on the joint to press the two substrates together. The adhesive layer between the two substrates therefore can be very small and well controlled. On the other hand, for joint in the cylinder, the clearance between the male and female tubes is very difficult to control, particularly when there are small wrinkles on the outer surface of the male tube. The lower efficiency of the tubular joint as compared to that of the flat plate joint indicates that should improvement be made in the manufacturing technique, particularly the improvement on the control of the surface finish of the outside surface of the male tube, better tubular joint can be obtained.

It is interesting to note that the joint strength efficiency in torsion is about the same as the joint strength efficiency in tension. The efficiency for unreinforced joint in tension is 69% and that in torsion is 70.4%. For reinforced tubes, the efficiency in tension is 81% and in torsion is 86.4%. The similarity in the joint strength efficiency in both modes of loading makes it easy for design for multiple modes of loading. This may be due to the fact that the lay-up for the tubes is balanced cross ply.

TABLE 1

Tension test		**Torsion test**	
Sample No.	Failure load (kN)	Sample No.	Failure Torque (Nm)
1	57	1	151
2	56	2	152
3	65	3	147
4	54		
Reinforced joint	68		184
Co-cure joint	84		213

CONCLUSION

It can be concluded that reasonably good manufacturing and testing techniques have been obtained for the development of bonded composite tubular joints. The joint strength efficiency for the unreinforced tubes is about 70% for both tension and torsion modes of loading. For the reinforcement using overlay, the efficiency increases up to about 82%. Reinforcement tends to increase the axial stress but reduces the shear stress.

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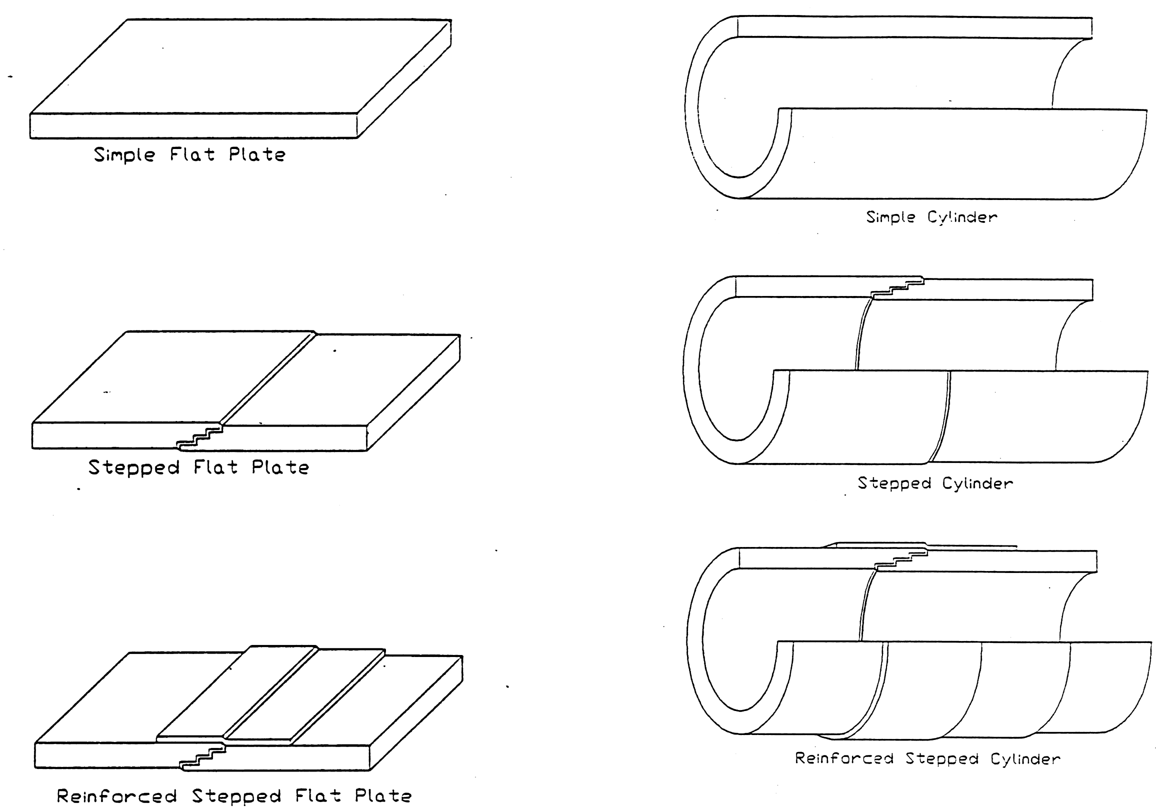

Figure 1: Flat plate models and cylindrical models

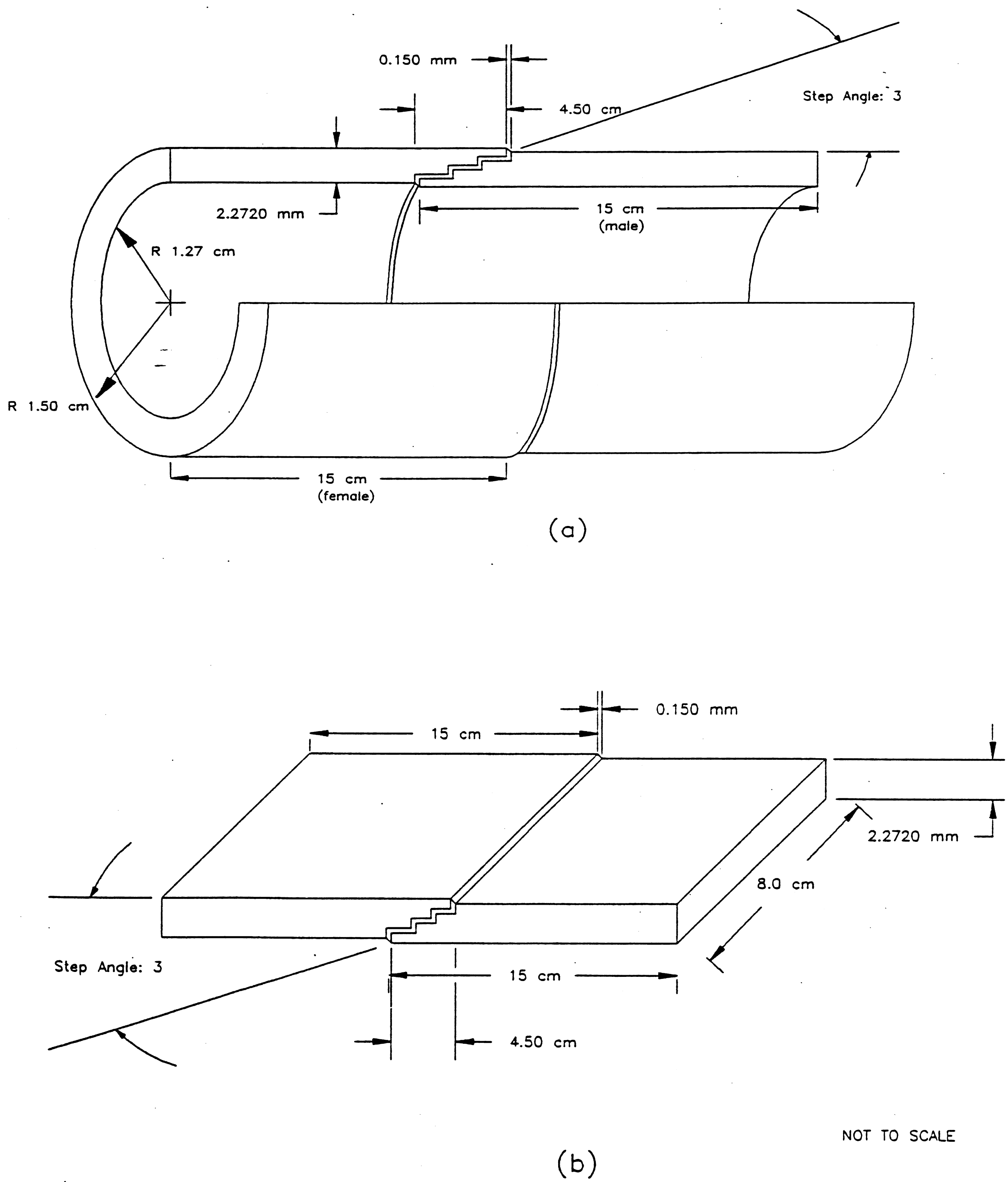

Figure 2: Dimensions of models: (a) cylindrical, (b) flat plate

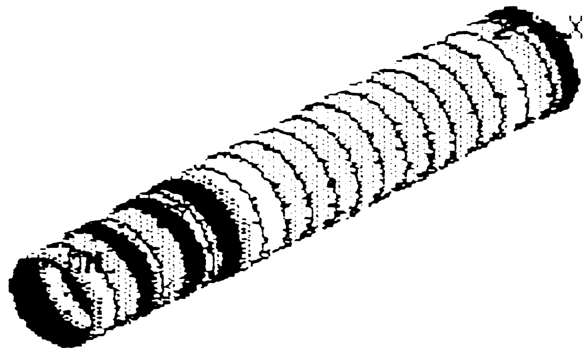

Figure 3: Stress distribution in male tube in step lap joint

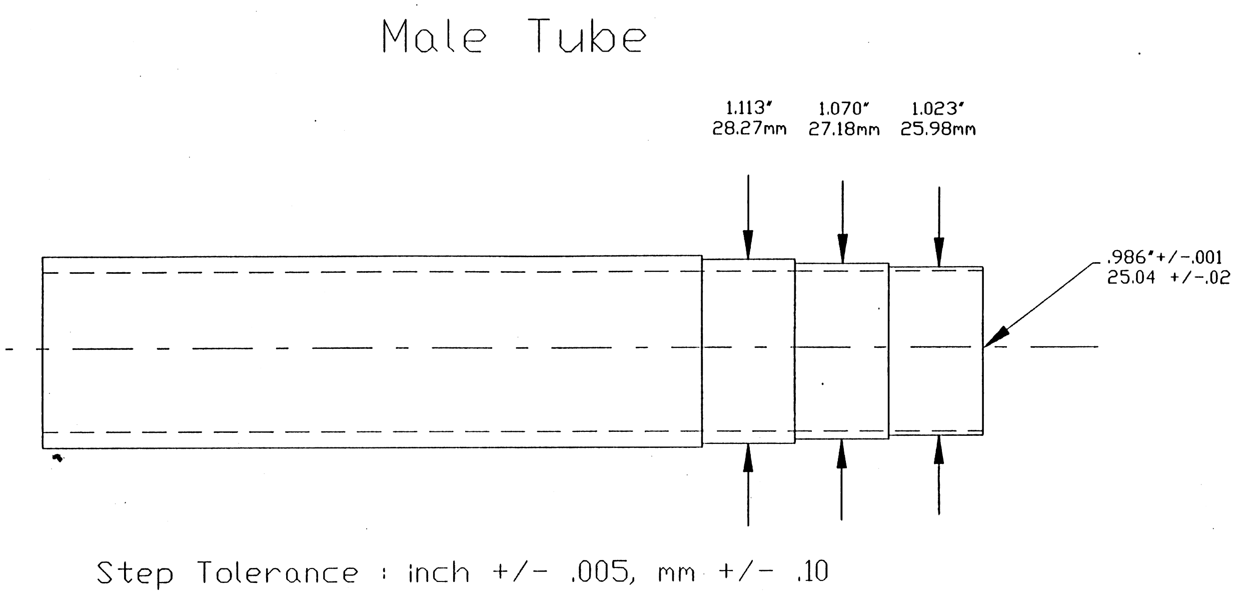

Figure 4a: Dimensions of male tube

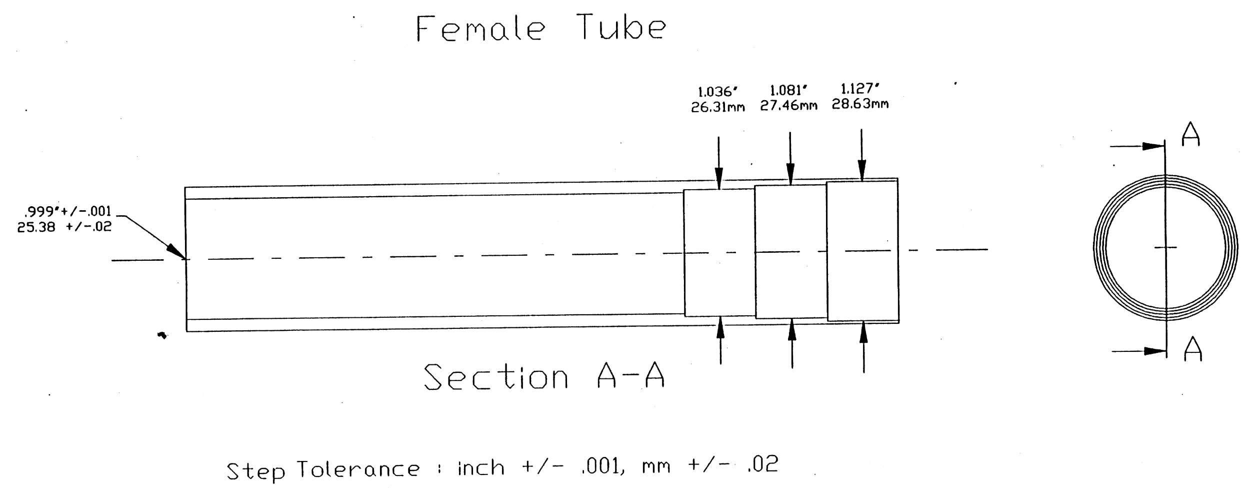

Figure 4b: Dimensions of female tube