Effects of Winding Angles on the Strength of Filament Wound Composite Tubes Subjected to Different Loading Modes

A.F. Hamed, Y.A. Khalid, S.M. Sapuan, M.M. Hamdan, T.S. Younis and B.B. Sahari
Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

Received: 21 March 2006 Accepted: 7 August 2006

SUMMARY

Filament wound pipes constructed from a corrosion resistant epoxy resin and E-glass filament fiber wound at nine different wind angles were tested. Experimental data are presented to show the effects of winding angle on the strength of 46.05 mm diameter tube and 300 mm length under three different loading modes. The pipes were tested to failure under hoop pressure loading (mode I) biaxial pressure loading (mode II), and biaxial pressure with axial compressive loading (mode III). Stress/strain response up to fracture for three different winding angles under different loading modes were obtained. The test results show the effect of the winding angle on elastic constants and on non linear stress strain behaviour. The test results also show that the optimum winding angles for filament wounded pipes depend on the loading modes applied. It shows that for loading mode I the filament wound pipe should be wound at 55°, for loading mode II the filament wound pipe should be wound at 75°, while for loading mode III the filament wound pipe should be wound at 85°.

INTRODUCTION

Filament winding is one of the few automated processes currently available for producing composite components with continuous fiber reinforcement arranged in carefully controlled directions. The simplest filament-wound components are axisymmetric shells with fibers wound in helices at angles of + θ and –θ to the axis of symmetry. High strength, low weight and corrosion resistance have led to the use of such components in many load-bearing applications (e.g. pipe work) where they are subjected to biaxial stresses. The winding angle is a major variable determining their mechanical performance[1].

Filament wound pipes made from glass-reinforced plastics (GRP) have a number of potential advantages over pipe made from conventional materials. However because of the highly anisotropic characteristics of this type of material the design of pipes and piping systems and in particular the prediction of failure is much more complicated[2].

Structures of this type are commonly subjected to complex loading conditions, which result from internal pressurization and superimposed axial loads during installation and/or operation of the cylindrical component. Examples of such components are pressure vessels, piping systems for the transportation of fluids, and shell structures for aerospace applications[3]. Although reference has been made in the literature to the so-called optimum angle of 55° for filament wound pipe, the optimum angle varies with test conditions. An angle of 55° is only valid for test conditions equivalent to biaxial loading.

Thus large cylindrical pressure vessels are subjected to biaxial whereas pipes connected by sliding joints experience mainly hoop stresses. Pipes which are buried underground are subjected to various stress conditions including bending and compression due to traffic loads. These considerations emphasize the importance of defining failure criteria under combined loading conditions and the need to correlate the results from different test conditions[4-6].

The effect of winding angle for glass fiber reinforced polyester filament wound pipes at six different wind angles have been investigated under biaxial pressure loading, hoop pressure loading and tensile loading[7]. It was found that the optimum wind angle for filament wound pipes depends primarily on the state of loading. It appears that filament wound pipe should be wound at 54.75° for biaxial pressure loading, 75° for hoop pressure loading and the lowest possible angle for tensile loading.

The objective of this paper is to gather experimental data which show the influence of the winding angle on the deformation and strength of filament wound glass fiber reinforced tubes subjected to a variety of uniaxial and biaxial membrane stresses. Data of this type are needed for direct application in the design of pipes and other cylindrical components and also to test the validity of theories, which are available for predicting the strength of the laminated structures in general. The experimental results presented show the variation of burst strength of different winding angles for different loading modes. Stress/strain curves are also presented for different winding angles for tubes subjected to three different types of loading modes.

SPECIMEN FABRICATION

A simple ± helical winding pattern with a single winding angle was employed. The pipes used in this work were helically wound at angles of [70°], [75°] and [80°] for loading mode I, [50°], [55°] and [60°] for loading mode II, and [80°], [85°] and [90°] for loading mode III using filament winding machine which has been designed and fabricated by Hamed *et al*.[8].

For winding angles 50° to 85° the tubes were manufactured with one cover which gave a minimum of one $+\theta$ and one $-\theta$ layer at every point on the surface (cover means two layers) while for 90° angle tubes were manufactured with two layers. The pipes had a nominal inside diameter of $D_i = 46.05$ mm while the outside diameter $D_o = 70$ mm at the tube ends. The overall test length of the tube was fixed as L = 300 mm while the wall thickness was taken as average thickness measured at 36 positions in the central part of the tube as t = 3.135mm. The gripping length was fixed to A = 100 mm. A schematic diagram of the specimen and basic dimensions are given in **Figure 1**.

The materials that were used were DRS 240-R510 E-glass filament fiber (Lan Pu Industrial District, Zhuhai, China) characterized by even tension, fast wet-out and impregnation and excellent pay-out. The epoxy resin consists of white viscous liquid WM-215TA (Wah Ma Chemical Sdn. Bhd., Malaysia) and colorless liquid WM-215 TB (Wah Ma Chemical Sdn. Bhd., Malaysia) mixed together with the ratio of 4:1 weight. The features of the epoxy resin are: the two components cured at room temperature, long poor-life, high heat distortion temperature and good mechanical properties. The pressurizing fluid used is Shell Tellus 37 oil.

END REINFORCEMENT AND GRIPS

The ends of each specimen were reinforced by circumferential over-winding with E-glass fiber reinforced epoxy resin over a length of 100 mm at each end and were usually mounted in aluminum inner and outer grips so that this resulted in a gauge length of 100 mm. The grips consist of two parts. The inner grip which slid into the bore of the filament wound tube was fitted with three rubber O-ring seals and the outer grip slides into the outer diameter of the tube ends depending on the loading mode as shown in **Figure 2**. The specimen reinforcement and grips had been carefully designed to avoid end failures within the grips and to minimize stress concentrations near the end of the gauge length of the filament wound tube. This was also done in order to prevent the structural fracture failure to occur at the test section away from the specimen ends.

LINER

Two distinct types of failure need were distinguished when testing pressurized components. First is a functional failure, which means that a specimen is not able to contain the fluid used for pressurization. This failure is characterized by a matrix cracking that enables fluid to weep through the tube wall. The specimen structure however may still be able to carry the applied load.

The second detected failure type is the structural failure that is the tube is unable to carry the applied load. In some cases commercial filament wound tubular structures are equipped with polymeric or metallic liner systems for ease of manufacturing and/or prevention of leakage. Liners are not considered to contribute to the load carrying of the tube but it prevents any leaking that may occur before bursting. So in order to facilitate testing for structural failures and to eliminate any functional failures that may happen before structural failure occurs specimens produced for this work were equipped with an internal UPVC plastic tube BS 3506 40 mm (Class O) of 1.175 mm thickness, which was used also as a mandrel.

Figure 1. A schematic diagram of the specimen (all dimensions are in mm)

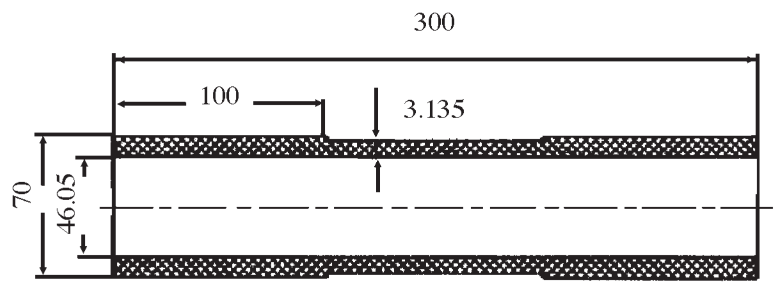
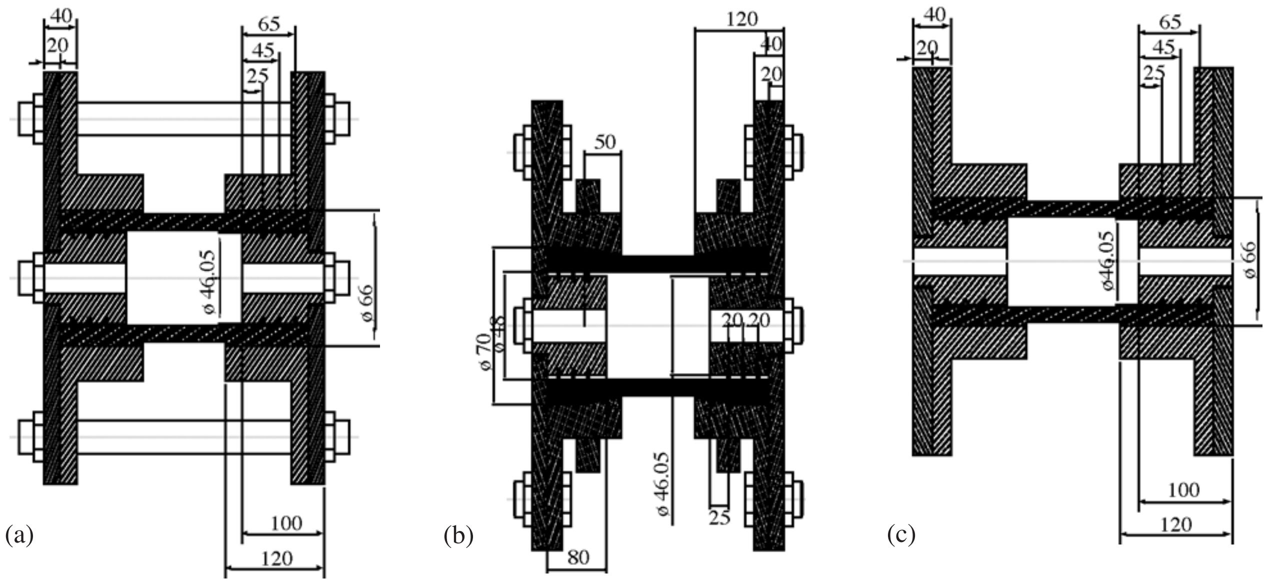


Figure 2. End reinforcement and grips for (a) mode I (b) mode II (c) mode III



TESTING PROCEDURE

All the tests were carried out using tensile testing machine (Servo-Hydraulic Instron 8500 digital testing machine with a full scale load range of 250 KN) and hydraulic cylinder piston mechanism model CD210 F-63/45 200Z to apply internal pressure for different loading modes. Testing of the pipes with various wind angles was carried out using three methods which are illustrated in **Figure 3**. Two of the methods require internal pressure alone while the third method needs an axial compressive loading in addition to internal pressure. In all of the test modes, two 90^0 strain gauge rosettes were aligned in axial and hoop directions of a tube and attached in the center of the gauge section.

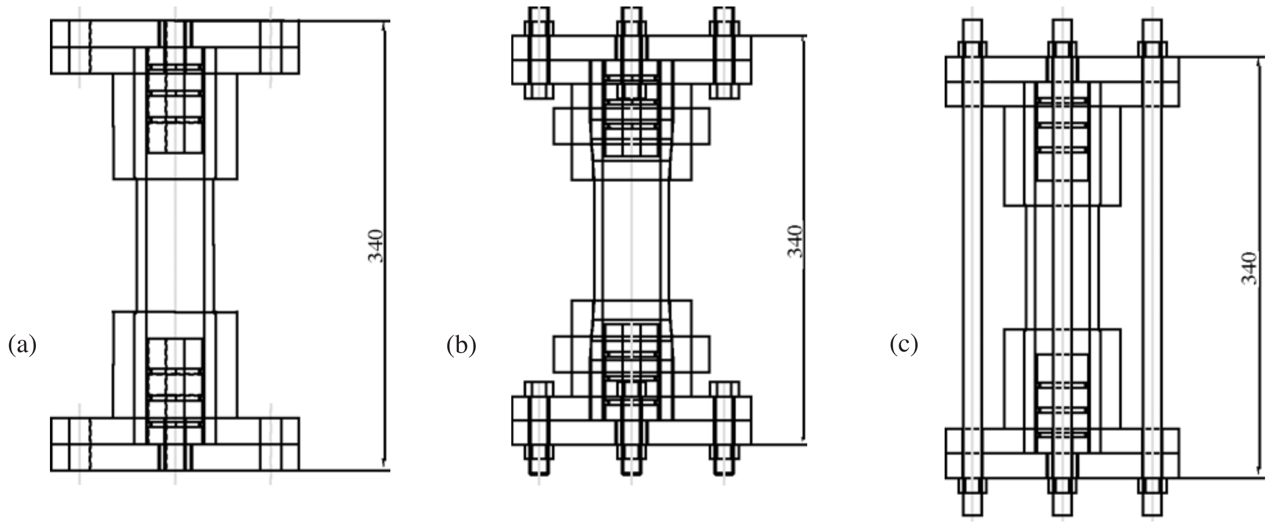
The three basic methods for different loading are:

1) Hoop pressure loading - mode I
In this type of loading the ends of the specimens were closed by an aluminum grips. The grip consists of two parts, inner and outer parts. The inner part, which slides into the bore of the tube is plug with three rubbers O-ring seals while the outer part which slide into the outer surface of the tube ends is a straight hollow plug. Aluminum flanges were placed over the aluminum grips at the tube ends and six restraining rods were positioned to hold the flanges together. As the pressure was applied the plugs transferred the axial load to the restraining rods, which carried the entire axial load. The pipe was then stressed only in the hoop direction so that the stress ratio of hoop stress to the axial stress (S) is given by $\sigma_h : \sigma_a = 1{:}0$.
2) Biaxial pressure loading - mode II
In this type of loading the ends of the specimens were closed by an aluminum grips. The grip consists of two parts. The inner part, which slides into the bore of the tube is plug with three rubber O-ring seals while the outer part which fixed to the specimen outer surface is a tapered hollow plug. The two parts will be tightening together so that the stress ratio of hoop stress to the axial stress (S) is given by $\sigma_h : \sigma_a = 2 : 1$.
3) Biaxial pressure with axial compressive loading- mode III
For this loading a rig with hydraulic cylinder piston was used to apply axial compressive in the axial direction while another hydraulic cylinder piston was used to push the oil inside test tube for internal pressure loading. Aluminum plugs with three rubbers O-ring seals were used to seal the pipe ends. Steel flanges were placed over the tube ends and aluminum plugs with steel ball to ensure axial loading on the specimen so that the stress ratio of hoop stress to the axial stress (S) is given by $\sigma_h : \sigma_a = 3.15 : 1$.The axial compressive load applied was about 50% of the initial crushing load of the same tube under axial compressive loading alone.

RESULTS AND DISCUSSIONS

A total of 27 one-cover (two layers) specimens were tested to determine the stresses at which the final fracture occurred. All specimens tested to rupture. All the specimens have failed by fracture or rupturing of the composite tube within the test section and none of them failed by weepage or leaking. Any weepage that might occur during testing before reaching the

Figure 3. Testing methods (a) mode III (b) mode II (c) mode I



maximum pressure is prevented due to the use of plastic tube as a liner.

As usual with composite materials there was some variation in the data, which may be attributed to both material and testing factors but the scatter was not large and not considered excessive. The scatter is largely due to local variation in wall thickness and glass content. The standard variations up to ±5% in measured thickness at various positions on individual tubes (i.e. variation of ±5% mm on 1 mm wall thickness).

Figure 4. Pressure *versus* orientation for composite tube under loading mode (I)

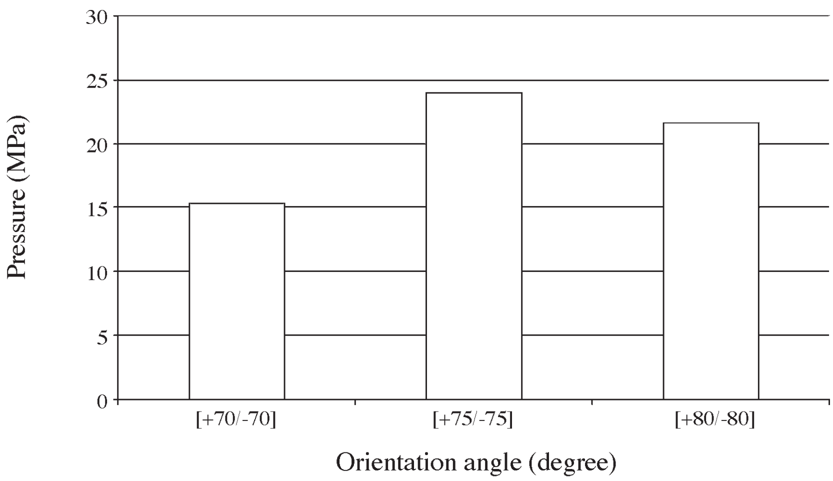


Figure 4 shows the maximum pressure values recorded for different winding angles for composite tube of E-glass fiber reinforced plastic of two layers under loading mode I. It shows that the maximum pressure is obtained for winding angle of [±75°] which was 24.0 MPa, the minimum pressure is obtained for winding angle of [±70°] which was 15.3 MPa while the pressure obtained for winding angle of [±80°] was 21.7 MPa. The percentage difference is 36.25% between winding angles [±75°] and [±70°] and 9.58% between winding angles [±75°] and [±80°].

Figure 5 shows the maximum pressure values recorded for different winding angles for composite tube of E-glass fiber reinforced plastic of two layers under loading mode II. It shows that the maximum pressure for winding angle of [±55°] was 12.1 MPa and the minimum pressure for winding angle of [±50°] was 10.3 MPa. The pressure obtained for winding angle of [±60°] was 10.5 MPa. Therefore the percentage difference is 14.88% between winding angles [±50°] and [±55°] and 13.22% between winding angles [±55°] and [±60°].

Figure 6 shows the maximum pressure values recorded for different winding angles for composite tube of E-glass fiber reinforced plastic of two layers under loading mode III. It shows that the maximum pressure is for winding angle of [±85°] was 29.3 MPa and the minimum pressure is for winding angle of $[90°]_2$ was 19.6 MPa. The pressure obtained for winding angle of [±80°] was 20.4 MPa. The percentage difference is 30.38% between winding angles [±80°] and [±85°] and 33.11% between winding angles [±85°] and $[90°]_2$.

Tables 1, 2 and **3** present the test results of composite tubes reinforced by two layers of E-glass fiber reinforced

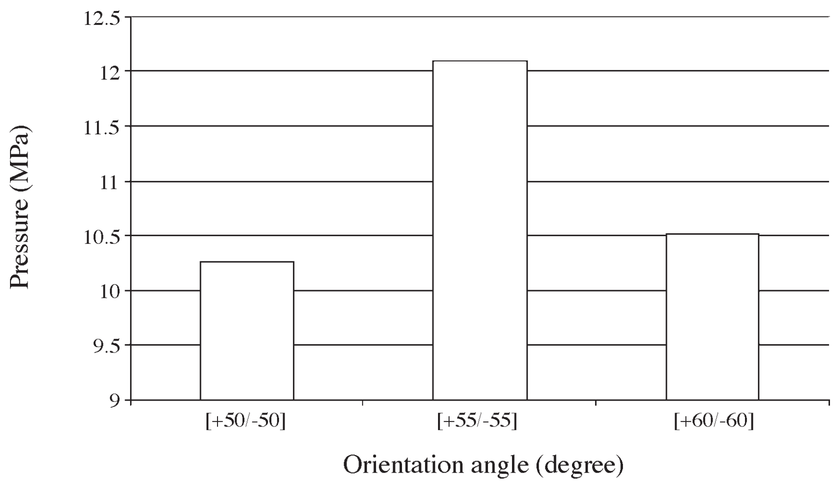


Figure 5. Pressure *versus* orientation for composite tube under loading mode (II)

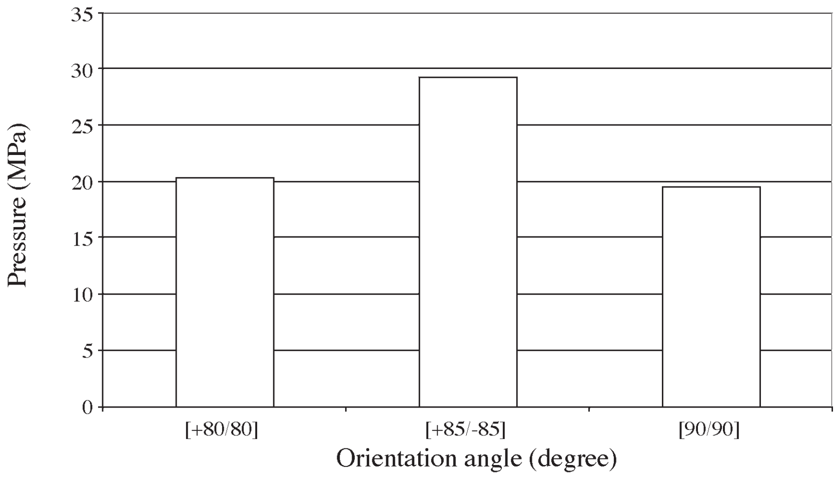


Figure 6. Pressure *versus* orientation for composite tube under loading mode (III)

Table 1. The test results of composite tubes reinforced by two layers of glass fiber reinforced plastics of different winding angles under loading mode I (zero axial stress; stress ratio 1)

Lay-up (Degree)	Ultimate Hoop Stress (MPa)	Ultimate Axial Stress (MPa)
[±70^0]	113.868	0
[±70^0]	112.699	0
[±70^0]	111.379	0
[±75^0]	172.296	0
[±75^0]	180.489	0
[±75^0]	176.393	0
[±80^0]	160.609	0
[±80^0]	158.363	0
[±80^0]	159.487	0

Table 2. The test results of composite tubes reinforced by two layers of glass fiber reinforced plastics of different winding angles under loading mode II (Stress ratio 2)

Lay-up (Degree)	Ultimate Hoop Stress (MPa)	Ultimate Axial Stress (MPa)
[±50^0]	78.039	39.019
[±50^0]	76.319	38.159
[±50^0]	71.913	35.956
[±55^0]	88.897	44.448
[±55^0]	90.197	45.099
[±55^0]	87.464	43.732
[±60^0]	84.587	42.294
[±60^0]	72.549	36.274
[±60^0]	74.717	37.358

Table 3. The test results of composite tubes reinforced by two layers of glass fiber reinforced plastics of different winding angles under loading mode III (Stress ratio = 3.15)

Lay-up (Degree)	Ultimate Hoop Stress (MPa)	Ultimate Axial Stress (MPa)
[±80^0]	159.975	50.531
[±80^0]	145.475	43.286
[±80^0]	143.166	42.132
[±85^0]	218.997	80.022
[±85^0]	209.517	75.285
[±85^0]	216.162	78.606
[±90^0]	139.933	40.517
[±90^0]	146.417	43.757
[90^0]$_2$	144.509	42.803

plastics of different winding angles under different loading modes I, II and III respectively.

The hoop and axial stresses at failure presented in **Tables 1, 2** and **3** were calculated using the original tube dimensions from thin cylinder membrane theory:

For mode I $\sigma_h = \frac{PD}{2t}$
and $\sigma_a = 0$ (1)

For mode II $\sigma_h = \frac{PD}{2t}$
and $\sigma_a = \frac{PD}{4t}$ (2)

For mode III $\sigma_h = \frac{PD}{2t}$
and $\sigma_a = \frac{PD}{4t} - \frac{F}{\pi D t}$ (3)

Where
F : is the axial compressive force.
P : is the internal pressure recorded at failure.
t : is the measured wall thickness.
D : is the tube internal diameter.

The strains were all recorded at positions near the middle of the gauge length using electrical resistance strain gauges. The stress ratio of the hoop stress to axial stress (S) was calculated from the actual stresses.

An understanding of the mechanisms of deformation and failure of composite materials requires knowledge of the stresses and strains which act parallel and transverse to the fibers. This is a complex problem in filament wound pipe because the material has a layer structure in which each layer is elastically and micro structurally anisotropic. The pipes used in this work consist of two layers at fiber angles of ± θ to the pipe axis. The fiber arrangement is symmetrical with respect to the pipe axis and the hoop direction and a special case of orthogonal anisotropy or orthotropy exists. The axes of symmetry are the axes of orthotropy.

Figure 7 shows typical stress/strain curves for different winding angles specimens tested to destruction in closed ended burst (S = 1:0) of internal pressure alone (mode I). The test results show that the stress/strain curves for [±70°], [±75°] and [±80°] tubes under loading mode I for stress ratio (S = 1:0) are nearly linear up to failure. Fracture occurs at average ultimate hoop stress 112.649 MPa and 0.639% hoop strain for [±70°] winding angle, 176.393 MPa and 0.889% hoop strain for [±75^0] winding angle while 59.486 MPa and 0.886% hoop strain for [±80°] winding angle.

Figure 8 shows typical stress/strain curves for different winding angles specimens tested to destruction in open ended burst (S = 2:1) of internal pressure alone (mode II). The stress/strain curves for [±50°], [±55°] and [±60°] tubes loaded at loading mode II for stress ratio of (S = 2:1). The test results show that the stress strain measurements is linear up to very low strains (0.0888% - 0.2904% hoop strain) and then become non linear up to fracture point. It can be seen from the test results that the maximum hoop stress at failure for [±50°] tube was 75.424 MPa and 0.951% hoop strain, for [±55°] was 88.852 MPa hoop stress and 0.846% hoop strain while for [±60°] was 77.284 MPa hoop stress and 0.320% hoop strain.

Figure 9 shows typical stress/strain curves for different winding angles specimens tested to destruction in combined loading of internal pressure and axial compressive loading (mode III). The test results show that the stress/strain curves for [±80°], [±85°] and [±90°] tubes under loading mode III for test ratio (S = 3.15:1) are nearly linear up to failure. Fracture occurs at average ultimate hoop stress 149.539 MPa and 0.996% hoop strain for [±80°] winding angle, 214.892 MPa and 0.798% hoop strain for [±85°] winding angle while 143.619 MPa and 0.628% hoop strain for $[90°]_2$ winding angle.

MODES OF FAILURE

Final failure was by fracture for all specimens and they were afterwards unable to support further loads. The appearance of the fractures was

Figure 7. Hoop stress versus hoop strain for different winding angles under loading mode (I)

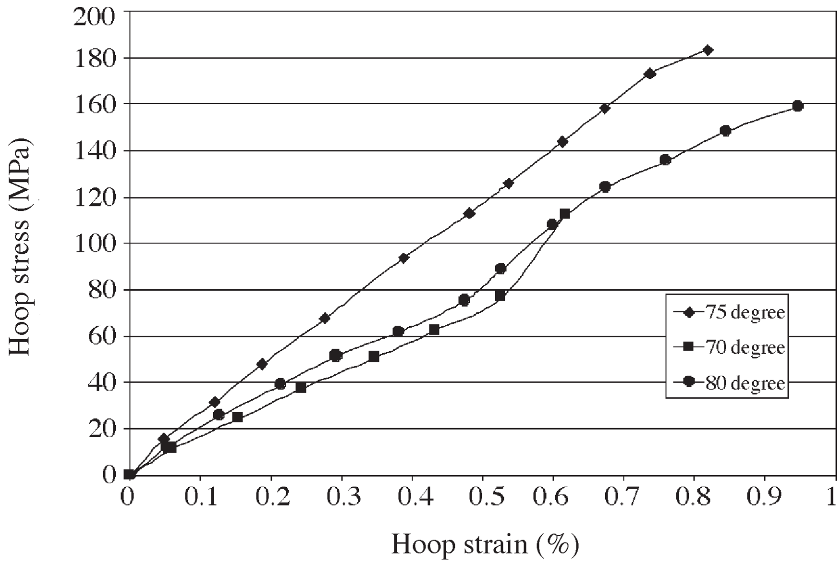
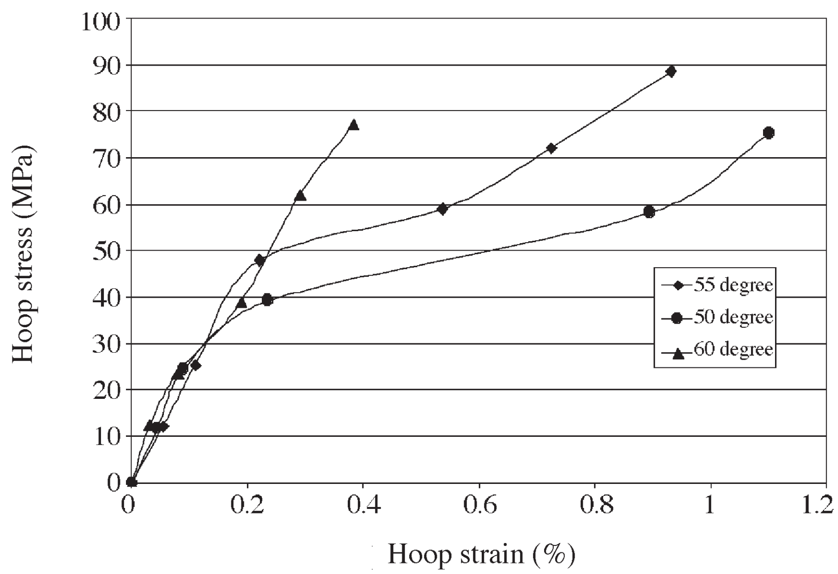


Figure 8. Hoop stress versus hoop strain for different winding angles under loading mode (II)



different at different stress ratios. Examples of all the failures are given in **Figures 10, 11** and **12**. In all cases there was whitening in the region of the fracture indicating failure of the resin. In addition to the whitening there were usually obvious resin and fiber fractures. Most of the specimens exhibited pronounced resin cracking and delaminating and large deformations before final failure occurred.

For loading modes I and II aligned slot-like perforation could be observed or only a small localized perforation in the pipe wall with frayed fiber strands protruding from the opening. While for loading mode III the failure appears with a large circumferential perforation around the pipe which leads to complete or partial collapse of the specimen splitting it in two halves along the circumferential in some cases.

COMPARISON WITH PREVIOUS RESULTS

Hull *et al.*[3] have investigated failure mechanisms in glass-reinforced filament wound tube wound at 54.73° the pipes were loaded to failure under biaxial pressure and uniaxial hoop pressure. It is found that a well-defined transition to a non linear behaviour in the stress/strain curve occurred at a hoop stress of between 30 and 50 MPa and was associated with many fine white streaks parallel to the glass fibers. Weepage occurred at a hoop stress of between 95 and 110 MPa. In the uniaxial hoop pressure loading case non-linearity occurred at 45 MPa hoop stress due to resin shear. Only isolated white lines parallel to the glass fibers present in these test sections.

Spencer and Hull[4] carried out the investigation of failure mechanisms to include filament wound pipes wound at 35°, 45°, 65° and 75°. Testing was under both biaxial pressure loading and uniaxial hoop pressure loading. With biaxial pressure loading a negative

Figure 9. Hoop stress *versus* hoop strain for different winding angles under loading mode (III)

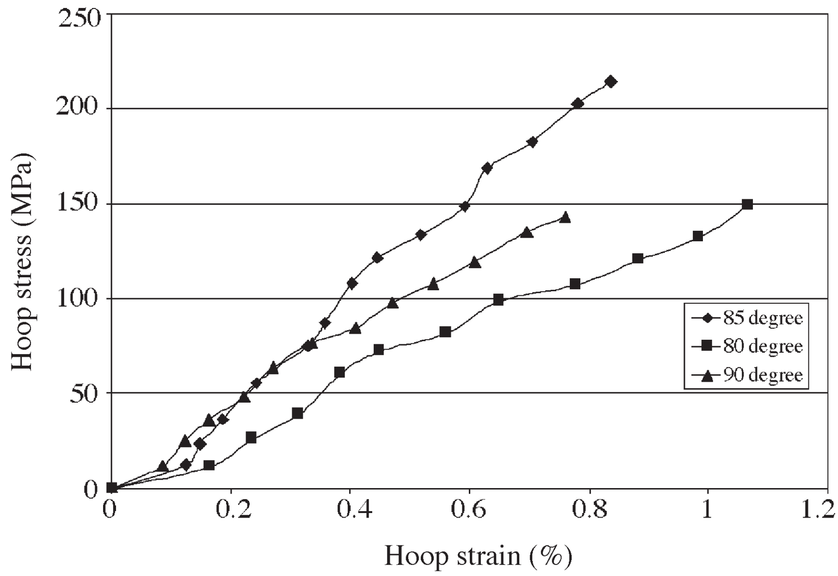


Figure 10. Samples of composite tubes failed under loading mode I

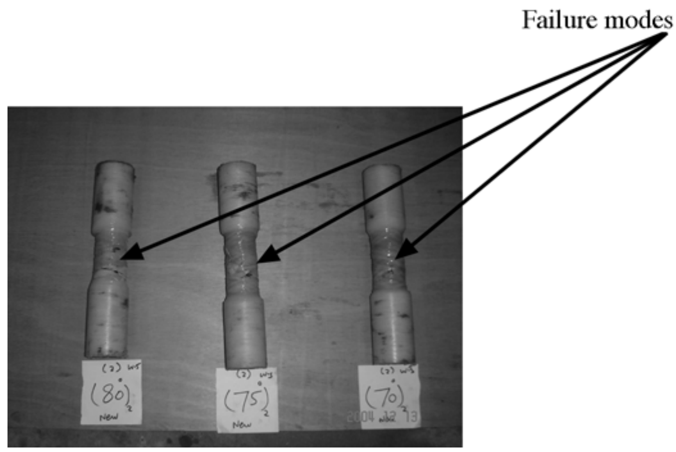


Figure 11. Samples of composite tubes failed under loading mode II

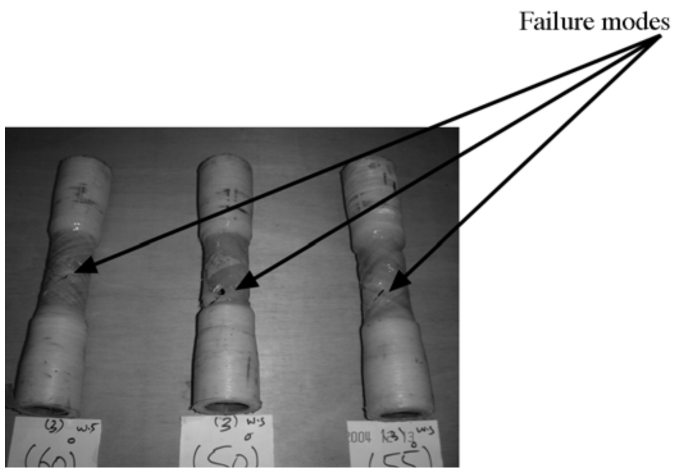
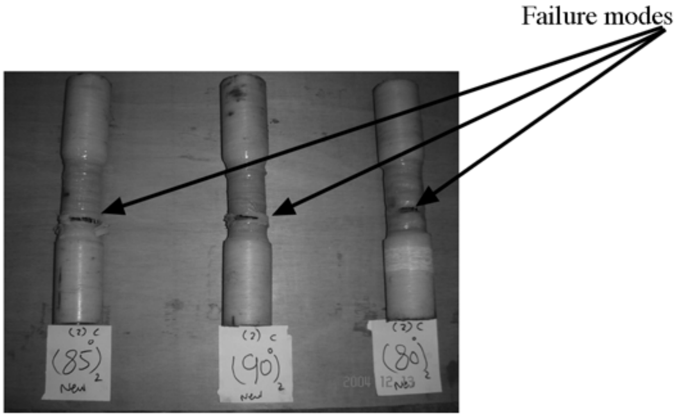


Figure 12. Samples of composite tubes failed under loading mode III



axial strain was observed with wind angle less than 35° and the maximum weepage stress was found to be at 55°. With uniaxial hoop pressure loading where the axial stress is zero, all the axial strain where negative and the hoop strains positive. Spencer concluded that in biaxial pressure testing maximum axial and hoop stresses for non-linearity whitening and weepage occur at the winding angle 55°. With uniaxial hoop pressure loading Spencer found that the deformation and the stress to fracture increased progressively with increasing wind angle.

Rosenow[7] used the classical laminated plate theory to predict the stress and strain response of pipes with winding angle varying from 15° to 85° and he compared his predictions to experimental results. A 55° winding angle was shown to be the optimum angle for filament winding pipe with a hoop-to-axial stress ratio of 2:1, but the optimum angle had to be about 75° in the case of pressure without axial loading.

CONCLUSIONS

The main conclusions that can be drawn from this experimental work are:

- Comparing the failure envelope for the different winding angles revealed systematic trends. As expected the higher pressure and then the higher hoop stress depend on the winding angle and winding angle is different from one to another depending on the loading mode applied. In this study it was found that the optimum wind angle for filament wound pipes depends primarily on the loading modes. The experimental results showed that filament wound pipes should wound at 55° for biaxial pressure loading (mode II), 75° for hoop pressure loading (mode I) while 85° is suitable for biaxial pressure with axial compressive loading (mode III).
- It is also found that the stress/ strain response of the filament wound pipe is dependent upon the loading mode applied and wind angle.
- In this work it is found that the use of the UPVC non pressure plastic tube as a liner instead of rubber polymer eliminates any possibility of leaking of the oil through the tube wall (functional failure) before reaching the bursting pressure (structural failure) which is the required.
- The experimental results provide more information than can be predicted by netting analysis or simple linear elastic laminated theory and should be useful for comparison with more advanced theories.

ACKNOWLEDGMENTS

The authors would like to express their gratitude and sincere appreciation to the Ministry of Science, Technology and Innovations, Malaysia (MOSTI, Project No. 09-02-04-0824-EA001) for the financial support, and the Department of Mechanical and Manufacturing Engineering of the Universiti Putra Malaysia for supporting the group in undertaking the project.

REFERENCES

1. Soden P.D., Kitching R., Tse P.C., Tsavalas Y. and Hinton M.J., "Influence of winding angle on the strength and deformation of filament wound composite tubes subjected to uniaxial and biaxial loads", *Composites Science and Technology*, **46** (1993) pp 363-378.
2. Mertiny P., Ellyin F. and Hothan A., "An experimental investigation on the effect of multi-angle filament winding on the strength of tubular composite structures", *Composite Science and Technology*, **64** (2004) pp 1-9.
3. Hull D., Legg M.J. and Spencer B., "Failure of glass/polyester filament wound pipe", *Composites*, **9** (1978) pp 17-24.
4. Spencer B. and Hull D., "Effect of winding angle on the failure of filament wound pipe", *Composites*, **9** (1978) pp 263-271.
5. Xia M., Takayanagi H. and Kemmochi K., "Analysis of multi-layered filament wound composit pipes under internal pressure", *Composite Structures*, **53** (2001) pp 483-491.
6. Soden P.D., Kitching R. and Tse P.C., "Experimental failure stresses for ±55° filament wound glass fiber reinforced plastic tubes under biaxial loads", *Composites*, **20** (1989) pp 125-135.
7. Rosenow M.W.K., "Wind angle effects in glass fiber reinforced polyester filament wound pipes", *Composites*, **15** (1984) pp 144-152.
8. Hamed A.F., Mutasher S.A. and Khalid Y.A., "Filament winding machine design and development", Proceedings of the 1st International Conference on Product Design and Development (ICPDD) 20th – 22nd (2004) pp 129-133. Published by School of Engineering & Information Technology, Universiti Malaysia Sabah (UMS), Locked Bag 2073, 888999 Kota Kinabalu, Sabah, Malaysia.