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EFFECTS OF FILAMENT REINFORCED PLEXIGLAS PRESSURE VESSEL ON FAILURE ANALYSIS

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ABSTRACT

This paper presents an investigation into the effect of reinforcing a Plexiglas tube with fiberglass/epoxy threads wound at different angles. This paper shows an experimental analysis approach to find the ultimate failure pressure of these vessels. The properties of the Plexiglas, fiberglass, orientation (wind) angle and the matrix were taken into account to determine their effects on the ultimate failure pressure of the vessels. Mandrels were wound at ±75, ±65, and ±55 degrees, and specimen were cut out from each to 19.05 centimeters long, 7.62 centimeter inner diameter and outer diameters dependent of the wind angle. The composite material used is an E-type Fiberglass and Epoxy Laminating Systems EZ-10 epoxy with EZ-83 hardener. The Dura-Wound Inc. Cobra Filament Winding Machine was used to wind the specimens. The specimens were tested with a hydrostatic test-rig to analyze the ultimate failure pressure and failure modes. An INSTRON machine was used to test the specimens under compression to determine the Young's modulus and Poisson's ratio. The experimental results indicate that the wind angle affects the mechanical properties and has strong effects on the failure modes of the reinforced vessels. The failure mode however does not differ by varying the wind angle.

KEY WORDS: Fiberglass, Filament Winding, Pressure Vessels

1. INTRODUCTION

With the ever-increasing need for space bound materials to be lighter and stronger, the demand for composite materials has increased unceasingly since the beginning of the space race. Space bound systems, their components, and payloads are constantly evolving so as to allow large quantities of payloads to a constant payload weight vehicle. The cost of placing a system into orbit is directly proportional to its weight. By making both the system and the vehicle lighter the cost per system being placed in orbit can be

decreased. This goal has been met and continues to be an issue today. Composite materials have evolved tremendously and have steadily been replacing the traditional materials such as aluminum and titanium. The latter is especially true for the aircraft industry, where weight savings can mean extra fuel weight for longer missions or improved strength can mean a longer structural life for aircraft. With an exceptional strength to weight ratio it is no secret why military and commercial spacecraft and aircraft companies have spent billions to further develop composite materials.

The use composite reinforced pressure vessels has been common practice for several decades. While it may be applied to number of industries such as biomedical and commercial fuel storage, it has played a more critical role in the aerospace industry. Composite pressure vessels are included in the most critical parts of spacecraft vehicle deployment systems, propulsion systems, and life supporting systems. While the there is a wide array of proven composite reinforced and all composite pressure vessels, there is a need to continue the study of their properties to fully understand and ultimately predict their mechanical behavior.

One of the key aspects of filament winding is the angle in which the fibers are wound. Early studies done by Professor M. Uemura at the University of Tokyo (1) showed that Young's modulus in the lateral direction increased by 75 percent. The optimum wind angle may vary for the specific use and constraints of a pressure vessel. This paper contains the results of a study where the effects of different angles on several specimens are observed. The primary effects studied are the mechanical properties and failure modes of the specimen with varying wind angles.

2. PROCEDURE

2.1 Manufacturing of the Composite Specimens The manufacturing procedure consists of the three stages, preparation, winding and post-winding procedures. The first part of the procedure is the most critical and lengthiest but if done properly the second and third stages will be completed more efficiently.

2.1.1 Preparation For Filament Winding Once the machine was adjusted to wind at the angle desired, the fiberglass spools were wound with the fiberglass to be fed to the winding machine. The next step was to mark measurement cups for the accurate amounts of resin and hardener would me mixed to there. Once the fiber was fed into the system and the mandrel mounted on the machine, the resin and hardener were mixed and poured into to the impregnation trough on the machine.

2.1.2 Winding The Specimen Mandrels The preparations were complete winding began by manually pulling the fiberglass strands through the impregnation trough and wrapping the first inches of impregnated fiber on the mandrel. The machine was then turned on and winding began and continued at a slow rate so as to allow the fiber to be thoroughly impregnated.

2.1.3 Post Winding Procedures Once each mandrel was completely wound, they were left rotating on the machine during the curing cycle. This was done to avoid resin concentration on one portion of the mandrel due to gravity, if left static. The rest of the machine was cleaned thoroughly with Methyl Ethyl Ketone so the machine would run smoothly during each of the following windings.

2.2 Curing The Composite In this study the E-Z resin epoxy resin provided by the Aircraft Spruce & Specialty Company was used. The E-Z resin systems curing requirements and its potlife were the two reasons for using the system. One of the most critical aspects of winding is the time constraint due to the pot life of the resin. The E-Z systems one hour potlife allowed just enough time for slower more thorough winding and allowed time for any corrections to be made to the winding systems, such as problems with the fiberglass feeding. The 24 hours curing cycle was the second reason for using this system. No autoclave or complicated curing cycles were needed since the parts were wound and were cured at room temperature.

2.3 Cutting The Specimens A total of three mandrels wound at three different wind angles. The mandrels where then cut using a wet Target Tile Saw, (Model #TA1010071, serial #257468). Three specimens where cut out of each of the three fiber composite mandrels and three specimen were cut from a piece of stock Plexiglas tube for a total of 12 specimens.

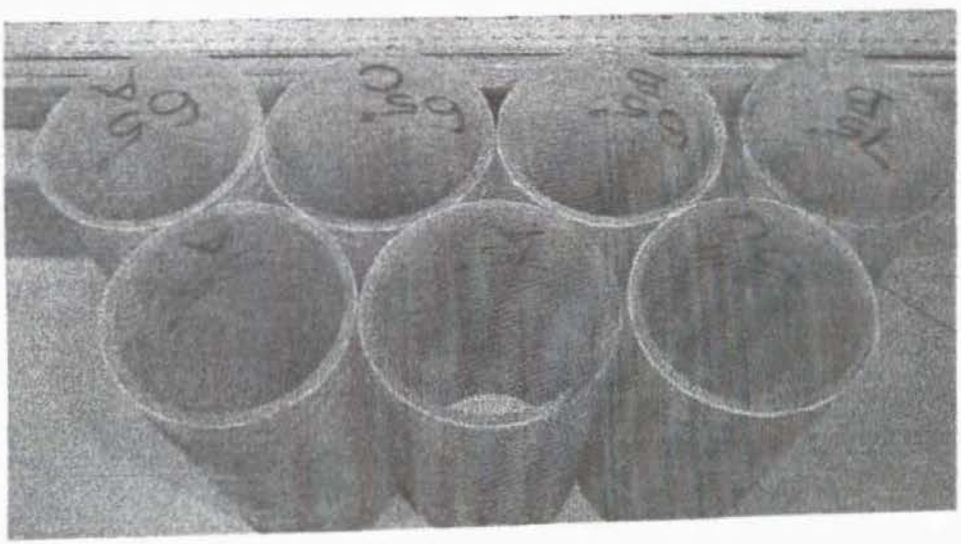

Figure 2: Specimen Prior To Testing

Figure 2 shows some of the specimen prior to testing. Figure 3 illustrates the typical dimensions for the specimen. Note that the outer diameter includes Plexiglas liner and composite layer. The outer diameter for the bare Plexiglas pipe is three and a quarter inches.

2.4 Strain Gages The strain gage rosettes, (University Precision Measurement Co. 28-R), were attached to the sterilized areas using 3M 3501 Epoxy Adhesive. Special care was taken to carefully align the rosettes gages parallel and perpendicular to the specimen. This constituted the first set of specimens that were used for determining the mechanical properties of the materials.

2.5 Testing For Mechanical Properties Once all sets of specimens were prepared, the testing phase was begun. These specimens were specifically prepared to determine the mechanical properties of the different wind angle. The INSTRON machine (model TTCML serial number 1160) located in the Aerospace Composites & Structures Laboratory was used to load the specimens under compression at a machine rate of 0.508 millimeters per second. A temperature compensated Wheatstone bridge configuration was used with the aid of a Measurements Group strain indicator (model #P-3500, serial #60245) and a Measurements Group switch and balance unit (model #SB-10, serial #61103) to read the data from the strain gages.

2.4 Hydrostatic Pressure Test Rig Shown in Figure 3 is a picture of the hydrostatic pressure test rig system used to find the experimental ultimate strength and failure modes of the pressure vessels. The test rig was specifically designed to test this form of ultimate failure for the pressure vessel. The test rig consists of the following parts:

1) A hand operated water pump of 13.79 MPa maximum operating pressure
2) Two non return valves
3) A shut-off valve
4) A water line tapped into a constant flow water faucet
5) A pressure gauge

2.5 Testing For Failure Modes Once all the all the specimen were labeled they were cleaned and The following steps were taken:

1) The pressure vessel was filled with water and all air was bled out of the system.
2) The water pump was then used to slowly and steadily raise the water pressure inside the vessel until the failure occured.
3) The maximum failure pressure was then recorded.
4) These steps were repeated with all the specimens tested.

Figure 4 illustrates the constraints for the specimen which were specially designed and manufactured for testing these specimen. The system constrains the specimens on both sides of the walls for three quarters of an inch on each end.

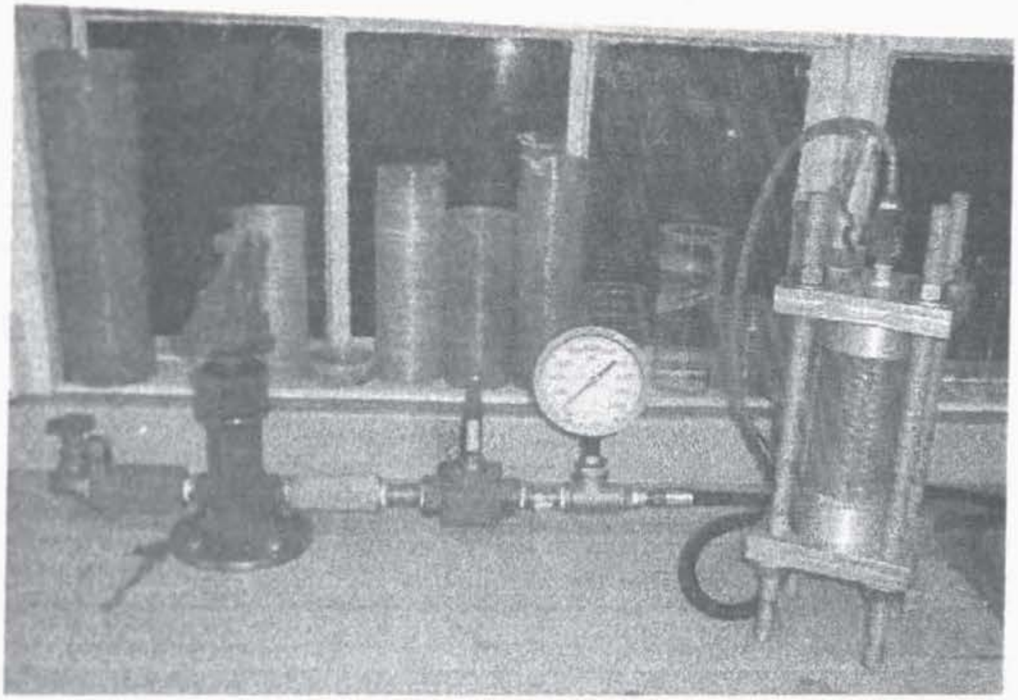

Figure 3: Hydrostatic Pressure Test Rig With Specimen

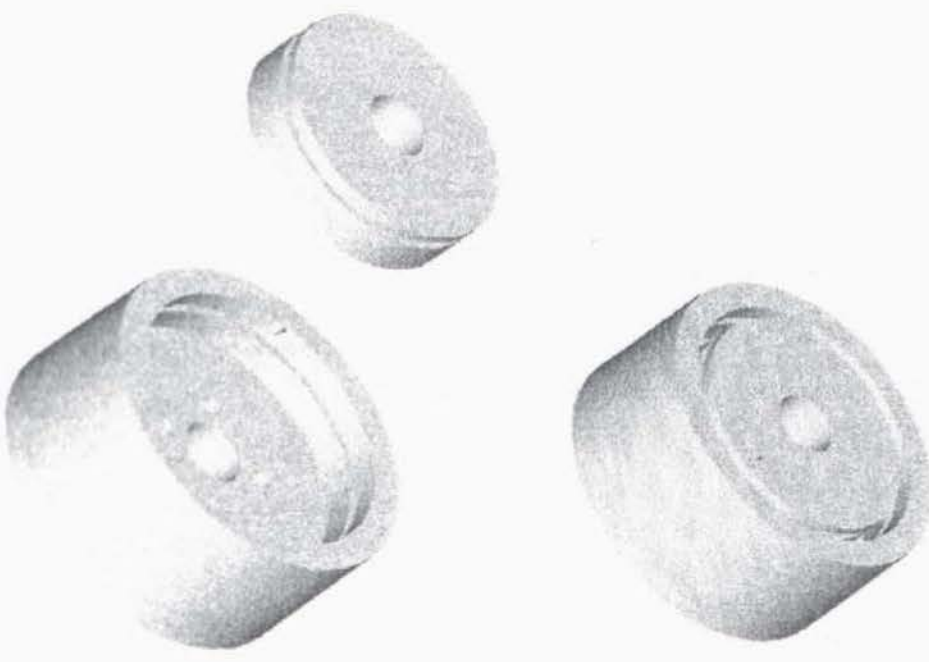

Figure 4: End Constraints For Hydrostatic Pressure Test

3. RESULTS AND DISCUSSION

3.1 Mechanical Properties Of Composite Specimens And Plexiglas The mechanical properties obtained from using the INSTRON machine, in which conventional strain gage technology was used. Shown in Table I, are the computed experimental values for Young's modulus of elasticity.

TABLE I- Mechanical Properties

Specimen	E (longitudinal)	v
Plexiglas	-3483	-0.442
±55	-2840	-0.347
±65	-3451	-0.100
±75	-32765	N/A

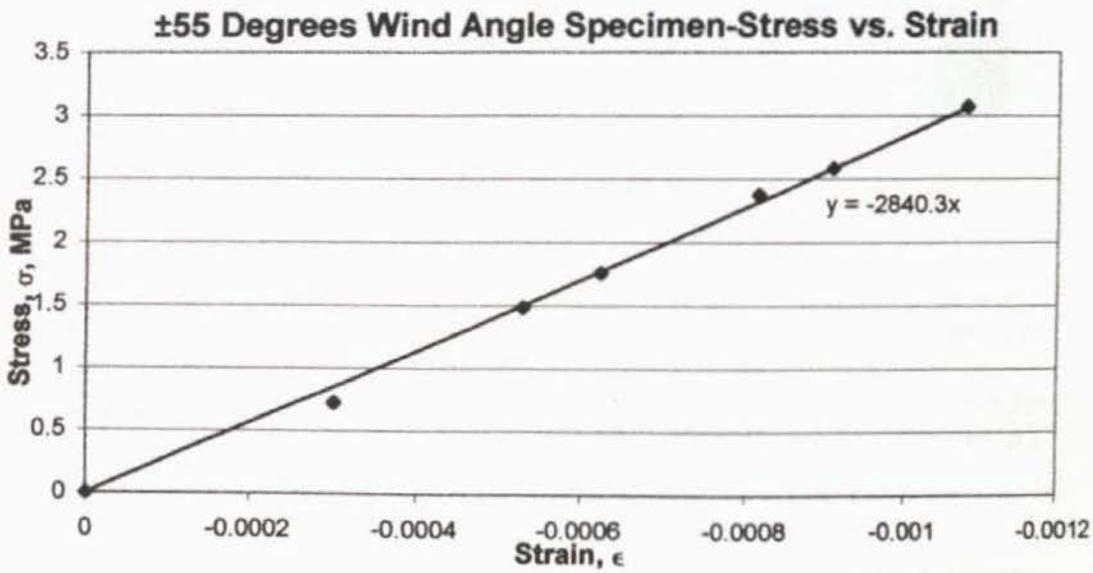

Figure 5: ±55 Degree Wind Angle Specimen Stress vs. Strain

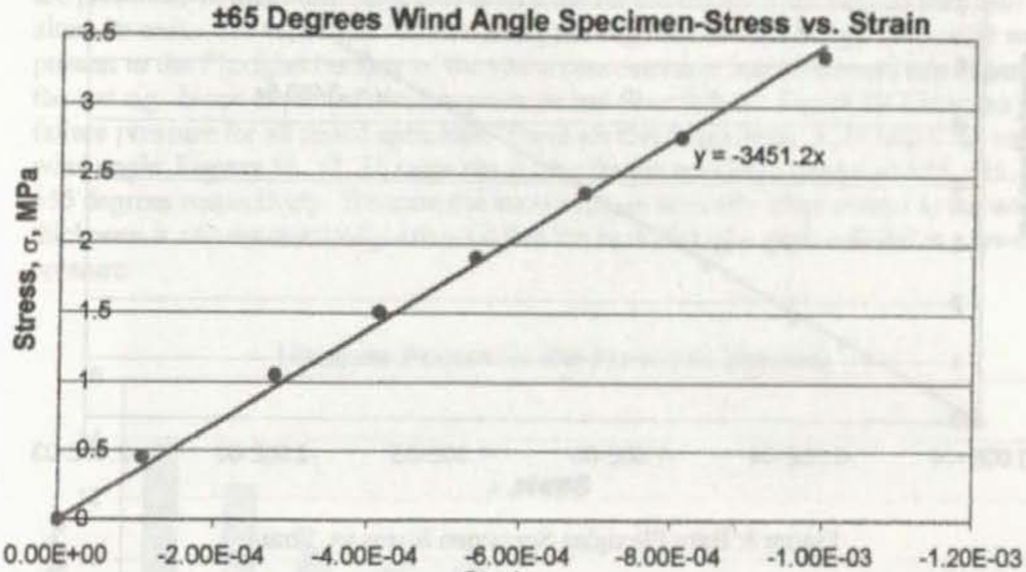

Figure 6: ±65 Degree Wind Angle Specimen Stress vs. Strain

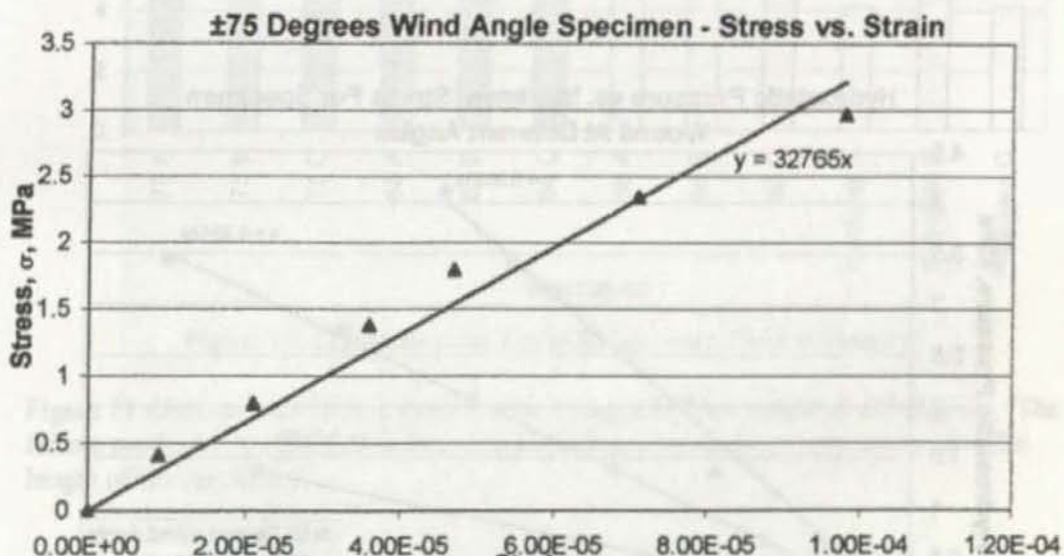

Figure 7: ±75 Degree Wind Angle Specimen Stress vs. Strain

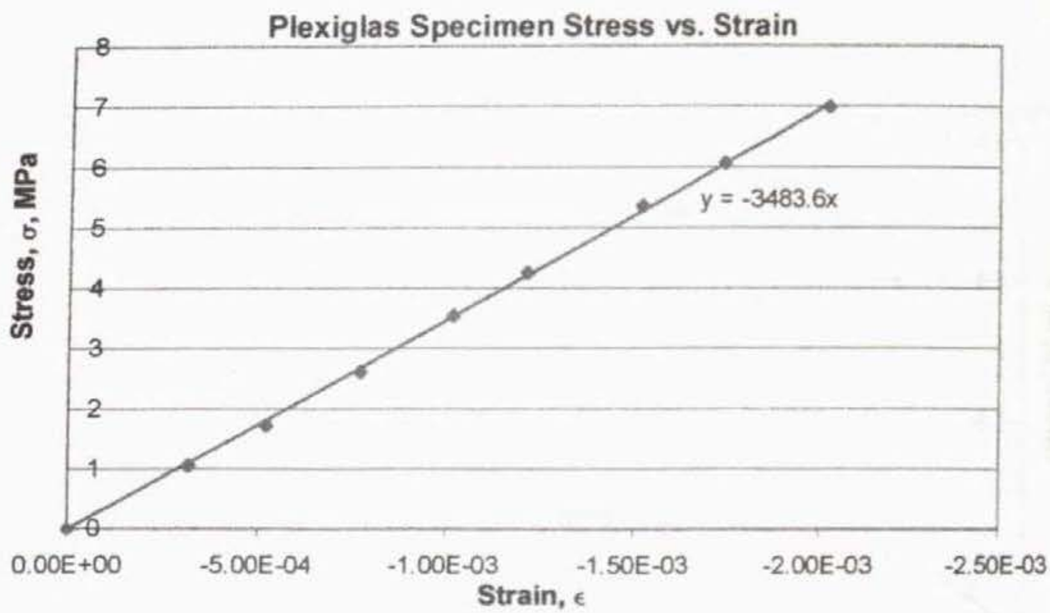

Figure 8: Bare Plexiglas Specimen Stress vs. Strain

Figure 9 illustrates the difference in the maximum stress from angle to angle. Moving from right to left on the chart, it is evident that the higher larger the wind angle is, the larger the maximum stress is for the constant pressure.

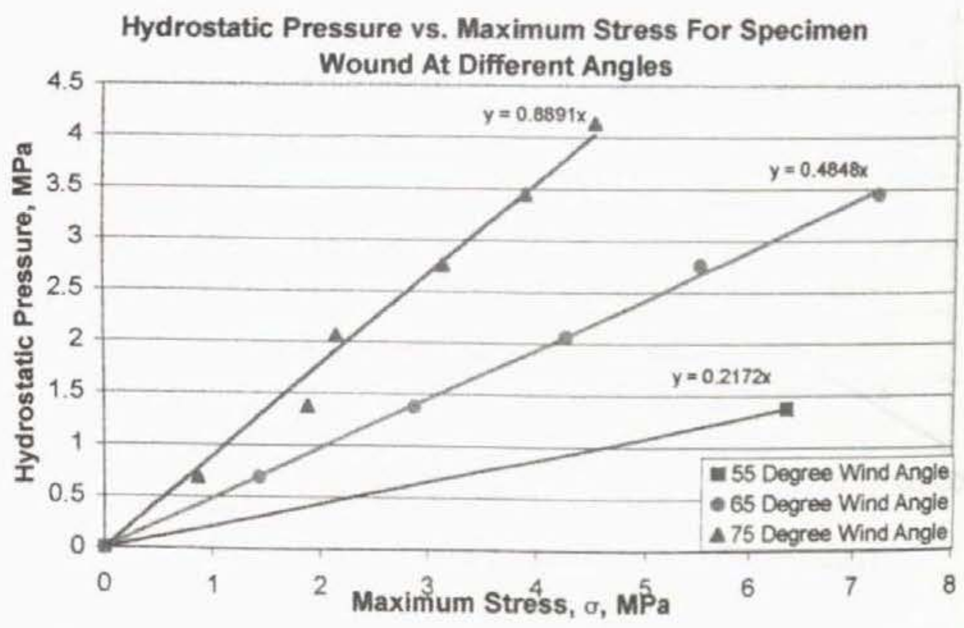

Figure 9: Test Pressure vs. Maximum Stress for Composite Specimens

3.2 Failure Modes For Filament Wound Pressure Vessel And Plexiglas Following the data acquisition and mechanical strength computations of the specimens, a failure analysis for each of the stacking sequences was conducted. There are two kinds of failure are presented in this study. The first is an axial failure in which the acrylic liner fails along its axis. The second is a failure along the edge due to the fittings. The latter was present in the Plexiglas because of the stress concentration from the constraint system of the test rig. None of the composite specimen had fiber failure. Figure 10 Illustrates the failure pressure for all tested specimen. There are three specimen, A, B, and C for each wind angle. Figures 11, 12, 13 show the failure for the specimen wound at ±75, ±65, and ±55 degrees respectively. Because the hoop stress is inversely proportional to the wall thickness, it can automatically assumed that the bare Plexiglas pipe will fail at a lower pressure

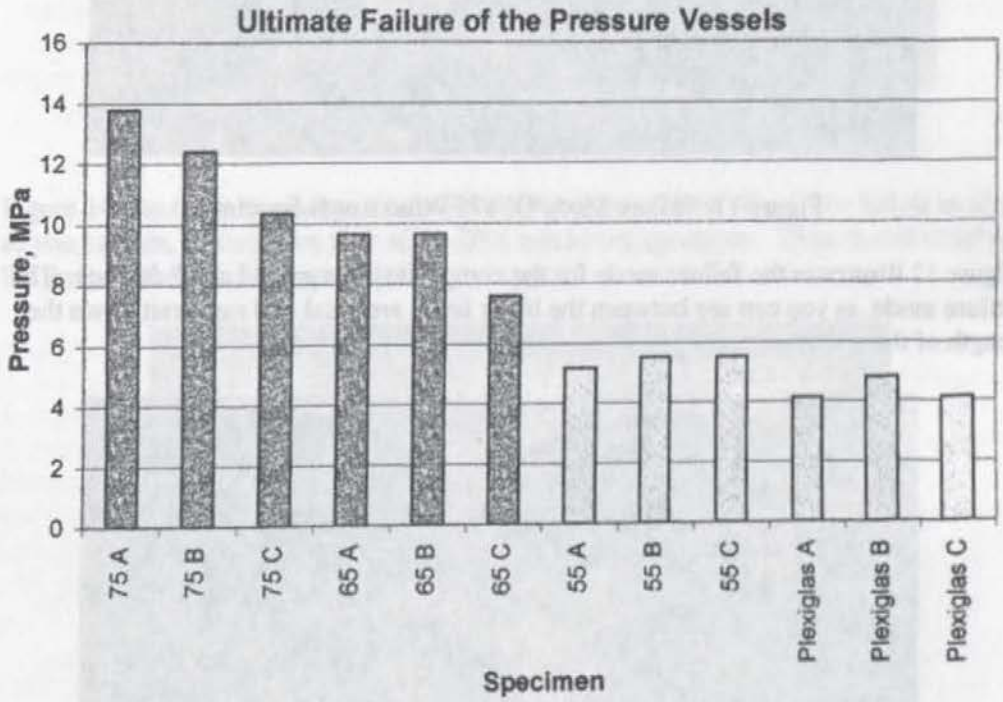

Figure 10: Composite and Plexiglas Specimen Failure Pressure

Figure 11 illustrates the failure mode for the composite fiber wound at ±75 degrees. The failure mode, as you can see between the black lines, are axial and run strait down the length of the specimen.

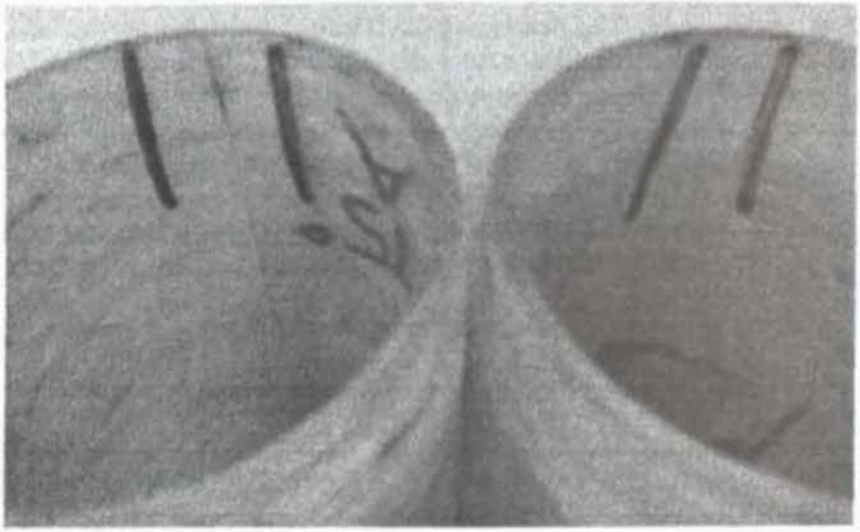

Figure 11: Failure Mode Of ±75 Wind Angle Specimen

Figure 12 illustrates the failure mode for the composite fiber wound at 65 degrees. The failure mode, as you can see between the black lines, are axial and run strait down the length of the specimen.

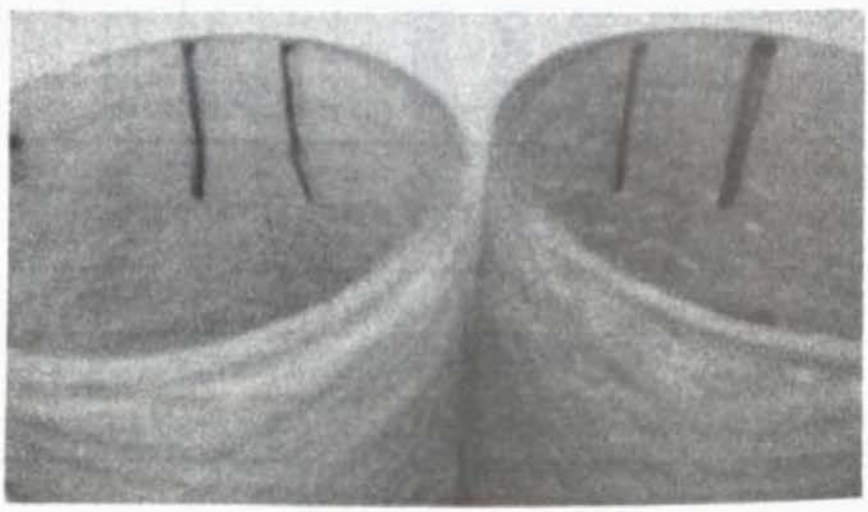

Figure 12: Failure Mode Of ±65 degree Wind Angle Specimen

Figure 13 illustrates the failure mode for the composite fiber wound at ±55 degrees. The failure mode, as you can see between the black lines, are axial and run strait down the length of the specimen.

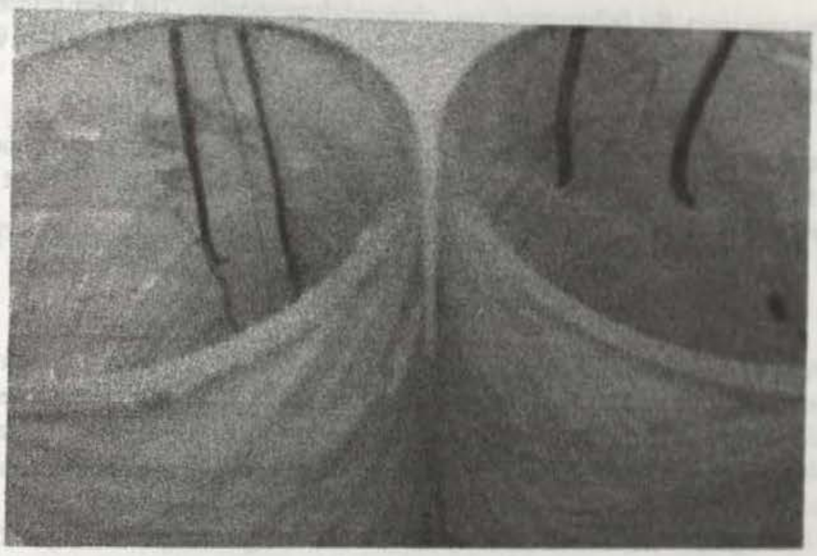

Figure 13: Failure Mode Of ±55° Wind Angle Specimen

Figure 14 illustrates the failure mode for the Plexiglas without fiber. The failure mode, as you can see, differs from that of the fiber reinforced specimen. There is catastrophic failure on the ends of the specimen.

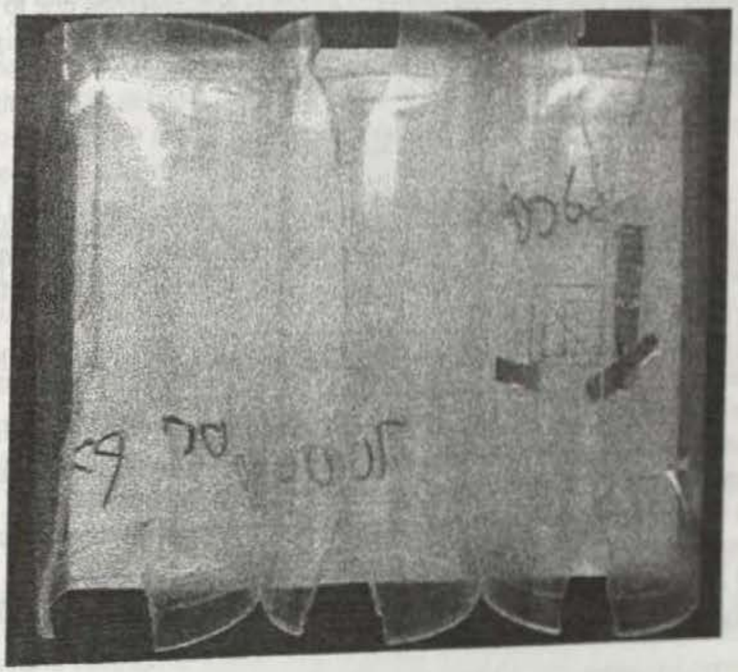

Figure 14: Failure Modes Of Bare Plexiglas Specimen

The difference in the failure modes between the composite reinforced Plexiglas pipe and the bare pipe show that the fiber reinforcement is critical. Although the there was not a dramatic increase in strength between the ±55 degree wind angle specimen and the bare

Plexiglas specimen, the failure mode was changed dramatically. The fiber reinforcement constrained the stress concentration which resulted in a less catastrophic failure in all specimens with fiber.

As seen all of the failure occurred in the axial direction of the specimen and none in the lateral direction. This is because in the constraint system the four steel bars that hold the specimen and their end caps take the majority of the axial load.

4. CONCLUSION

With the results of this experiment it can be said that the wind angle for filament wound pipes is critical. While the lower angle, ±55, did make the Plexiglas it did not have such a significant affect as the higher wind angle. There was a large gap between the strength of a ±55 degree angle wind and that of a ±65 degree angle wind. The 66 percent increase between these angle is indicative of the criticality of the wind angle with in this range. While the larger percent increase was between the ±55 degree angle wind and ±65 degree angle wind, there was also a significant increase, 36 percent, between the ±65 degree angle wind and ±75 degree angle wind.

The 179 percent increase in strength, with only a 44 percent increase in weight, between the bare Plexiglas and the ±75 degree wind angle is a perfect example of why composite materials are used. In addition to the strength increase the failure mode of the Plexiglas wound with fiberglass was less catastrophic. The stress concentration due to the constraint system did not cause a violent failure on the filament wound Plexiglas as with the bare Plexiglas pipe.

5. REFERENCES

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