Four points bending of composite pipes

Leong, Peng Chuen

2017

Leong, P. C. (2017). Four points bending of composite pipes. Master's thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/69900>

<https://doi.org/10.32657/10356/69900>

27
83

FOUR POINTS BENDING OF COMPOSITE PIPES

SUBMITTED

BY

PENG CHUEN, LEONG

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

A thesis report

presented to

Nanyang Technological University

in partial fulfilment of the

requirements for the

Degree of Master of Aerospace Engineering

Nanyang Technological University

Year 2012/2013

Abstract

The objective of this study is to identify the how pure bending will affect different materials in the view of assessing the spoolability of these materials. Experiments using four point bending were conducted on multilayered composite tubular pipes. The multilayered pipes have an external hard layer with a softer inner layer made of high density polyethylene (HDPE) thermoplastic. The external hard layer is made from either polyvinyl chloride (PVC) and glass/epoxy. The interface conditions between the hard and soft layers are either bonded or unbonded.

From the experimental results, the deflection and loading versus deflections and loading versus strains graphs show glass/epoxy has a much higher stiffness and larger deflections as compared to PVC. The experimental results also indicated that bonded and unbonded soft layer of HDPE does not affect the stiffness significantly. The minimum spool radius for PVC is 2.5 m while adding a soft layer of HDPE reduces it to 2.08 m for both bonded or unbonded cases. The corresponding increase in moment is 13.65%. For glass/epoxy fibre, the spool radius is about 2.08 m with or without the HDPE layer. There was also a large increase in the loading moment between using glass/epoxy and PVC pipes, a massive 627%. It is conclusive that spoolability performance of glass/epoxy is much lesser than that of PVC. While adding a soft inner layer for PVC leads to some increase in spoolability, it does not have any significant impact for the harder pipes such as glass/epoxy.

The study also consider the differences between measurements taken on loading movements from the bottom rollers or the top rollers. The results corroborated that the displacement from bottom rollers are more coherent and accurate to the actual displacements. Hence, measurements from loading movements of the bottom rollers should be used in 4 point bending experiments.

Acknowledgements

The student would like to tender his heartfelt and deepest appreciation to his project supervisor, Associate Professor Chai Gin Boay, for giving him the opportunity to undertake this project and his kind support given to the author. Through Prof Chai's patience, guidance and valuable suggestions offered, the author has been able to gain deep insights of the composite pipe development and capabilities which have helped the author immensely to complete the project successfully and to better understand the field of composite materials innovation for marine and offshore applications.

The author would also like offer his thanks to Research Associate, Dr Karthic Narayanan Rengarajan, for his patient advice and strong encouragement in the process of this research work. The support and assistance has helped to render the project within the schedule.

Last but not the least, the author wishes to put on record his appreciation and thanks to all staffs, lab technicians and other individuals that have provided advice and support in the entire project.

Table of Contents

Abstract i

Acknowledgements ii

Table of Contents iii

List of Figuresiv

Chapter 1: Introduction on Composites 1

 1.1 Background 1

 1.2 Objectives..... 5

 1.3 Scope 6

Chapter 2: Literature Review 6

Chapter 3: Preparations of Test Specimens and Experimental Procedure 9

 3.1 Test Specimens and their Preparations 9

 3.2 Mounting Procedure..... 11

 3. Determination of Test Materials Elastic Properties14

 3.4 Equipment and Fixtures..... 18

 3.5 Experimental procedures..... 21

Chapter 4: Results and Discussions 23

 4.1 Load-Displacement 23

 4.2 Load-Strains 29

 4.3 Moment-Curvature Relationship..... 34

Chapter 5: Some Insights into Four Point Bend Tests 38

Chapter 6: Conclusion and Future Research 43

 6.1 Conclusion 43

 6.1 Future Research..... 44

References 45

Appendix A.

Appendix B

List of Figures

Figure 1. Davy and Bessemer monopod platforms with 10% of composite materials in the topside structures operating in the North Sea (BP-Amoco)	2
Figure 2. Tendons and risers.	3
Figure 3. Composite production riser specimens prepared for qualification testing (Lincoln Composites).	4
Figure 4. Testing of an offshore composite drilling riser jointwith carbon fibre in the main structural body and titanium end flanges at the Heidrun TLP in 2001 in the Norweigen Sea. The Joint has an internal titanium liner.....	7
Figure 5. Fibre mesh wrapping around Pipe for bonding	9
Figure 6. Bonding of PVC pipe with HDPE Pipe using Adhesive.....	10
Figure 7. Layout of Strain Gauge Mounting on the PVC Pipe	11
Figure 8. Oxide layer of the terminal is removed	12
Figure 9. The Bonding terminals with Leadwires Soldered	13
Figure 10. HDPE and PVC Test Pieces with mounted strain gauges	14
Figure 11. HDPE Pipe Test Piece during the compression test.....	15
Figure 12. HDPE's Elastic Compression Region Stress-Strain Graph	16
Figure 13. PVC Experimental results of Compressive Stress vs Strain.....	17
Figure 14. PVD Compression Stress Strain Graph for the Elastic Region	17
Figure 15. Load set for PVC pipe in 4-point bending test	18
Figure 16. Graphic Illustration of Pipe Profile with local deformation	19
Figure 17. Improvised Fixtures with Rotating Loading Support	20
Figure 18. Initial Setting of the PVC Pipe	21
Figure 19. Mounting of LVDT Probe slightly depressed	22
Figure 20. Pipe with local plastic deformation	24
Figure 21. Damages and local Plastic deformation on Glass Fibre Pipe	24
Figure 22. Load-Displacement Graph of PVC pipe	26
Figure 23. Load Displacement Graph of Glass Fibre pipe	28
Figure 24. Components of Strains	29
Figure 25. Strain Graph for PVC pipe	31
Figure 26. Load-Strain Graph for PVC pipe with HDPE liner, Unbonded	31
Figure 27. Load-Strain Graph for PVC pipe with HDPE liner, Bonded.	32
Figure 28. Load-Strain Graph for Glass Fibre pipe	33
Figure 29. Load-Strain Graph for Glass Fibre pipe with HDPE Liner, Bonded	33
Figure 30. Moment-Curvature Graph for PVC pipes	36
Figure 31. Moment-Curvature Graph for Glass Fibre pipes	37
Figure 32. Two Possible displacement case scenarios	38
Figure 33. Comparison of theories with experimental data for PVC pipe	40
Figure 34. Comparison of LVDT measurements	41
Figure 35. Comparison of theories with experimental data for GRP pipe	41

Composite Tubes Subjected to Four Point Bending

Composite Tubes Subjected to Four Point Bending

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

LEONG PENG CHUEN

**SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY**

Year 2013

Chapter 1: Introduction on Composites

1.1 Background

Use of composite materials is not new. Bricks, as the most primitive known composite material, formed by straw and mud, were used by many early civilizations to construct houses. Nowadays, composites are better made and of better quality. They are widely used in aerospace construction, manufacturing of automobiles, naval construction, sports and recreation and many more industries. Industrial used composites are formed from two or more materials. For ease of manufacturing and consistency of properties, composites are made in ply form. They consist of a strong material as a filler reinforcement and a matrix film to bind the reinforcement in specific orientations, hence forming a ply. These plies are then stacked together to form composite laminates. The customization abilities of specific materials in form of laminates for their operating environment contribute much to composites popularity. Composites are mainly well-known for their lightweight, high strength-to-weight ratio and strength properties. They are generally more elastic than metal. Moreover, they are also valued for their high stiffness, ability to withstand high temperature, good fatigue endurance, high-load wear resistance and high corrosion resistance.

Since its early days, aeronautical manufacturers have been looking for light weight and robust composites to augment its metallic structure. In 1938, the Morane 406 plane (FRA) used sandwich panels with wooden core covered with light alloy skins. Later in 1943, composites made of hemp fiber and phenolic resin were used on the Spitfire (U.K.) airplane. In 1950s, glass/resin honeycombs were used in the construction of the fairings with complex forms. 1960s and 1970s saw the rapid introduction

of boron/epoxy, carbon/epoxy and Kevlar/epoxy into aerospace industry [1]. Recent examples of Boeing 787 and Airbus 350 XWB see large materials composition changes where almost 50% of the aircraft structure is composites by weight (80% by volume). At the same time, relegating metals composition to much smaller quantities, 20% aluminium, 15% titanium, 10% steel and 5% other [2]. For A350 XWB, the materials used consist of 53% composites, 19% aluminium and aluminium-lithium, 14% titanium, 6% steel, and 8% miscellaneous [3]. Composite materials provide much needed large weight savings allowing better fuel consumption and minimizes operating cost.

Figure 1: Davy and Bessemer monopod platforms with 10% of composite materials in the topside structures operating in the North Sea (BP-Amoco).

Besides aerospace industry, as mentioned earlier, composite usage is also increasing in other industries such as the offshore oil and gas exploratory

industries. Two small-scale platforms, Figure 1, deployed in shallow water by BP-Amoco are excellent examples of the use of composites in such offshore structures. The topside assemblies, which incorporated 10% by weight of composites, involved extensive use of pultruded glass/phenolic gratings for floors, walkways and handrails, along with enclosures and heat protection walls. Glass reinforced epoxy was also widely used for the pipework and tubulars.

Figure 2: Tendons and risers.

However, with increasing world demands for energy, suppliers of crude oil are looking at drilling into deeper waters. These marine oil companies operate on tension leg platforms (TLP) for drilling. TLP consists of a hull that supports the rig and production facilities and is connected to the seafloor by means of tendons and risers (See Figure 2). Rigid metallic risers are widely used on

offshore platforms in both shallow and deep waters. Risers are typically large diameter (250-550 mm) high performance tubes which undergo complex and high pressure loadings in order of 1000 bar. They may be made from high strength and duplex steels, as well as titanium, assembled from short sections into considerable lengths. For deep water drilling in excess of 1000 m, weight minimization of the platforms, tendons and risers, have become a critical design criterion. Composite tubes is the realistic alternative to metals in such situations. Moreover, where possible, these tubes may be coiled onto spools to allow for ease of storage, handling, and installation.

Development of composite rigid risers has been undertaken by a number of oil companies, including Conoco, Petrobras, Shell and Statoil. In USA, companies, like Lincoln Composites and Northrop Grumman have been involved in riser development. In Europe the Institut Français du Pétrole (IFP) has taken a leading role in research on prototype riser systems. (See C.P. Sparks et al., *Revue de l'Institut Français du Pétrole*, Jan-Feb. 1995, 50).

Figure 3: Composite production riser specimens prepared for qualification testing (Lincoln Composites).

Composite riser design and qualification is a new frontier to optimize weight-strength ratio for off-shore oil companies and the ability of spooling for such design will mark a new and significant scope for composites usage in the industry. Hence, in this respect, the objective of the investigation to identify composite spoolability and determining errors for its theoretical determination will add to the robustness of the framework of composite tubes for risers.

Despite composite wide usage, it must be noted that there are still lingering limitations in using composite materials. Notably, the main disadvantage is its high cost of fabrication but costs have been coming down in recent years. Having a part made of graphite/epoxy composite may cost 10 to 15 times the traditional material and manufacturing costs. The mechanical characterization of a composite structure is more complex than that of a metal structure as composite materials are not isotropic, which in turn means that more materials parameters are required in design and load safety considerations. Lastly, composites repair is also not a simple process and there are inherent inspection risks that critical flaws and cracks in composite structures may go undetected as non-destructive testing methodologies advancement have not fully caught up with the manufacturing of composites.

1.2 Objectives

The objective of the project is to investigate and analyse the bending response of composite pipes subjected to a constant bending moment as a result of spooling onto a drum.

1.3 Scope

The scope of the project will cover the following:

- Literature review of existing work published.
- Analyse strain response via strain gauges on pipes
- Investigate and identify the minimum spool radius without inducing damage to the tube under 4 point bending loads.
- Investigation of possible errors in theoretical development of strain measurements.

Chapter 2: Literature Review

Composite tubes provide a realistic alternative to metals in many offshore applications, offering high stiffness to weight and strength to weight ratios as well as increased corrosion resistance and flexibility. Furthermore the tubes can be coiled onto spools to allow for ease of storage, handling, and installation. Though sustaining higher initial material and manufacturing costs than that of standard materials, Fowler et al. [4] determined that the reduced installation cost, higher corrosion resistance, and reduced maintenance make composite tubulars economically attractive over their service life in many situations, especially in deep water applications. Salama et al. [5] (See Figure 4) reported on the North Sea installation of a composite drilling riser joint with a titanium liner that composites are attractive in the offshore arena due to their strength to weight advantages over standard materials.

Figure 4: Testing of an offshore composite drilling riser joint with carbon fibre in the main structural body and titanium end flanges at the Heidrun TLP in 2001 in the Norwegian Sea. The Joint has an internal titanium liner.

There are several studies of composite cylinders subjected to bending. Chan and Demirhan [6] have proposed closed-form solutions for the bending stiffness of laminated tubes based on shell theory. Utilizing finite element analysis and axisymmetric elements in ABAQUS, Judice [7] performed preliminary parametric studies to design the wall construction of a spoolable tube basing on a composite tubular with a complex wall with multiple materials of HDPE, rubber, and unidirectional and hoop-wound glass/epoxy. In their experiment, minimal matrix damage with spool radius of 14.6 m could be obtained under bending loads. Fiberspar and Conoco jointly developed a 3.8-cm outer diameter spoolable composite tube capable of being coiled on a 2.14-m core diameter reel [8]. The composite tube was specified for survival under 5000 cycles of biaxial internal pressure/bending fatigue loading. The specimens were loaded in four-point bending with a maximum bending strain of 2%, representative of the ratio of the tube to spool diameter, while simultaneously subjecting them to internal pressure of 52 MPa.

In our case, we will be investigating the interaction of two layers of varying materials in affecting the performance of tubes and our aim is to arrive at a dimensionless result for the spooling radius. These results will simulate the performance of the actual composite tube with the thermoplastic layer in real situations. All experiments are to be conducted on a 4-point bending machine to generate pure bending in the testing pipes. Pure bending occurs when the beam is only subjected equal and opposite couples acting in the same longitudinal plane such that there will only be bending stress (i.e. no shear forces).

Chapter 3: Preparations of Test Specimens and Experimental Procedure

3.1 Test Specimens and their Preparations

Bonded Pipes Preparation Procedure

Figure 5: Fibre mesh wrapping around Pipe for bonding

1. The large fibre mesh is cut into several sets of suitable length pieces such that these pieces can be sized and wrapped closely around the HDPE pipe without overlapping as they are being joined. A picture depicting the wrappings of the pieces around the HDPE pipe is shown in above Figure 5.
2. In order to stick the meshes to the pipe, adhesive glue is applied and uniformly spread out across the whole area of the smaller fibre meshes. Glue is

also applied at both ends of the pipe to ensure close fitting of the meshes into the pipe internal surface.

Figure 6: Fibre mesh wrapping around Pipe for bonding

3. The combined pieces as a rolled “rod” form of the HDPE liner is next fitted and made to slide into the inner cavity of the PVC pipe as shown in Figure 6.
4. The pipe is then cleaned and any overflowing glue are removed. Effort is also taken to ensure and check that the fibre meshes are closely stuck in the inner lining of the pipe without any protruding parts.
5. The adhering fibre meshes are then left in the pipe to be cured for 2 hours.

3.2 Mounting Procedure

Figure 7: Fibre mesh wrapping around Pipe for bonding

For the experiment, the mounting of the gauges are as in Figure 7 and the strains of the pipe under loadings are to be measured. A strain gauge is a sensor with resistance changes in response to the applied force. Measurements of the electrical resistance changes of these gauges are then converted into strain values. The procedures to mount the gauges on to the composite tube are as follows:

1. The composite pipe external surfaces are cleaned and then wiping them completely over with cotton wool that is soaked with propanol.
2. The centre of the pipe length is then measured and a mark is etched on the pipe at the centre position on its external surface.
3. To distinguish upper top half and the lower bottom half of the pipe when under loading, their correct positions are labelled at the centre position of the pipe length.

4. The tile which the gauge will be mounted is cleaned using a cotton pad soaked with propanol to ensure subsequent proper fitting of the gauge to the pipe surface.
5. The strain gauge and the bondable terminal is then placed at the tile position. A transparent tape is pasted over the strain gauge thereby holding them in position. This will also allow the strain gauge position to be seen during the entire setting up procedures.
6. A middle line across the mid position of the strain gauge is marked out over the transparent tape.

Figure 8: Oxide layer of the right terminal is removed

7. To ensure the strain gauges are clean and not affecting their measurements, their terminal points are rubbed with a sharp and hard object to ensure any remaining oxides or rust are removed as shown in Figure 8.
8. The connection of the gauge terminals and the leadwires are now to be connected. It is arranged such that the leadwires should be leading away from the gauges so as not to obstruct the observations during the loadings on the pipe.

9. The strain gauge together with the terminations are now brought to the pipe. They are then aligned and stick over the centre position of the pipe with use of the transparent tape.
10. Lift up part of the tape to enable adhesive catalyst can be applied on the adhering space between the pipe surface and the adhering surface of the tape.
11. Adhesive is also applied to the strain gauge and the termination points while at the same time press firmly on the tape down onto the pipe surface.
12. To ensure the adhesion is bonded well, press down firmly using the accessory polyethylene sheet onto the strain gauge. Hold them down in this position for at least one minute so as to ensure the complete adhesion of the contact surfaces of the gauge and the pipe surface.
13. After checking for the firmness of the gauge on the pipe surface, the accessory sheet and the tape may then be removed.

Figure 9: The bonding terminals with Leadwires Soldered

14. To set up for soldering of the terminal, a masking tape can be used to stick the connectors to the pipe. Soldering of the terminals and the leadwires can be done and the final set-up is as shown in Figure 9.

15. The data logger can then be connected to the leadwires which are connected to the gauge at the soldered connections as shown earlier in Figure 7.
16. A protective layer is coated on to the strain gauge as this will ensure the correct readings from the gauge from their adhered positions,
17. Before the gauge are used, check the resistance of the strain gauge is set correctly at 350Ω .

3.3 Determination of Test Materials Elastic Properties

In order to determine the elastic moduli of the two different material test pipes, tubular length of 37mm were cut from the HDPE pipe and PVC pipe. These pieces had their ends buffed to ensure flatness of the compression areas and also for uniform loading of the compression testing. In Figure 10, a strain gauge is axially mounted on each test piece. The test pieces, as shown in Figure 11, were then made to undergo compression tests so as to determine their respective materials' elastic modulus. During the tests, deformation occurred in the form of lateral bulging at the centre of the test piece, however there were no crack observed.

Figure 10: HDPE and PVC Test Pieces and the mounted strained gauges.

Figure 11: HDPE Pipe Test Piece during the compression test

From the compression test readings, a tabulation of the compressive stress values using $\sigma = \frac{F}{A}$ and its corresponding strains were recorded. Subsequently, a set of the respective material's compressive stress versus strain graphs was plotted.

For the HDPE test piece, measurements taken are an outer diameter of 40.3mm and an inner diameter of 32.1mm. This resulted in a compression area of 466mm². The plot of compressive force against the compressive strains for the HDPE test piece is graphed out in Figure 12. The full data set for Figure 12 can be found in Appendix A. The experimental data points are plotted in the small triangular symbol while a linear regressed trend line is plotted in a linear line. It is seen that the overlapping region of both lines is where the elastic zone deformation. Using the gradient of the linear trend line, the computation of the

elastic modulus can be evaluated. For the HDPE, its elastic modulus of $E = 1.385 \text{ GPa}$.

Figure 12: HDPE’s Elastic Compression Region Stress-Strain Graph

For the PVC test piece, its measurements are an outer diameter of 48.2mm and an inner diameter of 41.0 mm. Thus, its compression area is 504mm^2 . Figure 13 shows the experimental results of the compressive stresses versus strains during its loading. There was somewhat less linearity of the graph than the HDPE. As such, an extraction of the linear graph between strain values of 0.002 and 0.004 was made. Figure 14 is the extraction of the elastic region of Figure 13 and superimposed with the best-fit line to estimate the elastic region of the PVC pipe’s elasticity properties. Data set for Figure 14 is provided in Appendix B. From evaluation of the gradient of the linear trend line, it gives us an elastic modulus of $E = 5.781 \text{ GPa}$.

Figure 13: PVC Experimental results of Compressive Stress VS Strain

Figure 14: PVC Compression Stress-Strain Graph for the Elastic Region

There was no necessity to test the for the Elastic Modulus of Glass fibre pipe as the material properties have been supplied by the manufacturer. It is stated to have an elastic modulus of $E = 14.5\text{GPa}$.

3.4 Equipment and Fixtures

4-point Bending Machine

It is essential that pure bending be achieved in the experimental results. For this purpose, a 4-point bending set-up was used to achieve pure bending of the pipes as shown in Figure 15. The loading set up is also symmetrical. The machine has two loading rollers at 200 mm apart and two support rollers at 360 mm apart. As glass fibre has a much larger elastic modulus, the distance between the support rollers was spaced further apart, at 540mm. In the experiment, loading is done progressively such that the loading rollers move down while applying a downward force on the pipe. At the same time, the support rollers remain stationary. An illustration of the loading setup for the PVC pipe is shown in Figure 15.

Figure 15: Load set for PVC pipe in 4-point bending test

There were much local deformation on the pipe surfaces where the two top loading points act on the pipe in the first experiment, which lead to stoppage of the experiment. Figure 16 shows an illustration of the effect of local deformation at the contact regions.

Figure 16: Graphic Illustration of Pipe Profile with Local Plastic Deformation

It was deemed that the local stress points from the loading rollers may be the cause of the local deformations. Therefore, a review to improve the experiment was done. It was subsequently felt that the rollers should not be fixed but allowance for rolling to reduce the stress points. Hence, the fixture was changed to allow for the rollers to rotate and not fixated. The improvised fixture is shown in Figure 17. This change gave immediately results showing reduction of the effects of local deformation. For PVC tests, the loading rollers are of 12.5mm diameter. In the case for glass fibre tests the loading rollers with diameter of much larger diameter of 25 mm are used to reduce the effect of local deformation on glass fiber pipes.

Figure 17. Improved Fixture with Rotating Loading support

Two machines, Instron and MTS, were used for the experiments due to technical issues involving the machines. For Instron, the top jig as the loading force will move downwards while the bottom supports remain stationary. In the MTS, the bottom jig acting as the support force will move upwards to create the pure bending of the pipe, while the top jig remains stationary. Though using different machines, the same adapter set is used throughout all experiments. As such, initially, we did not expect to produce results that would require any conversions for the comparison of data. However, after the initial test results were analysed, it was deemed that there could be some differences in the results from the two different ways in which the loads were

applied. The initial test results are analysed in Chapter 4 while an analysis focusing on the possible differences in results arising from the different manners of loading are reviewed in Chapter 5.

3.5 Experimental procedures

1. Fix the pipe on the support jig and align the pipe such it is horizontal and the position of strain gauges directly at the origin point.
2. Load lightly on the pipe and ensure it is secure in position as shown in Figure 18.

Figure 18: Initial setting up of the PVC Pipe

3. Mount up the LVDT using magnetic holder such that the LVDT is slightly depressed as shown in Figure 19.

Figure 19: Mounting of LVDT Probe slightly depressed

4. Set up and connect the wires from the LVDT (Channel 0) and strain gauges (Channels 1 and 2) to the data logger.
5. Switch on computer and key in the loadings configuration.
6. Reset or initialize the data logger, the load and load cell displacement readings on the computer.
7. Switch on the data logger.
8. From the computer, start the 4-point bending machine to provide its progressive loadings on the pipe.
9. When there are plastic deformation occurrence, stop the experiment. Should there be any signs of danger, stop the machine immediately.

Chapter 4: Results and Discussions

4.1 Load-Displacement

It is important to maintain results of pure bending throughout the experiment. Hence, should there be local deformation, the experimental results thereafter are not applicable. Local plastic deformation means that any further loading would not only bend but would also contribute to indentation of the pipe as illustrated in Figure 16. Hence, contributing to the inaccuracies of the test.

For the fixture configurations, as the LVDT is in the centre, it will record a larger reading than the corresponding jig depression reading as the pipe is being bended. However, with the start of deformation, it can be observed that the magnitude of the LVDT's displacement reading and the corresponding load cell's displacement reading begins to converge and eventually the load cell registers a larger displacement reading. It is inevitable that such indentations also increase the compressive strains of the pipe.

Figure 20 (a) and Figure 20 (b) are the respective pictures of the pipe before and after the onset of local deformation on the PVC pipe. Figure 21 shows the actual damage on the pipe. The indentation by the roller pins is basically localized and has caused cracks on the pipe surface at the loading point.

(a) Before Loading (b) After Loading

Figure 20: Pipe with Local Plastic Deformation

Figure 21: Damages and Local Plastic Deformation on Glass Fibre Pipe

In Figure 22, the plotting of loads against central displacement of the PVC pipes are shown. The results show a close linear relationship between loads and displacement for the 3 pipes. The circles represent the respective loading and

displacement points when local deformation sets in for the 3 pipes. From the relative positions of the circles, our experimental data clearly show that the bonded PVC pipe and HDPE pipe give higher loadings results against local deformation when compared to the unbonded and purely PVC pipes. However, the close proximity of the results between the 3 plots indicates that the addition of the HDPE liner still has marginal increase in the load bearing capability of the PVC pipe in the initial phase. Therefore from these experimental results, it is conclusive that bonding of the two pipes gives a better load bearing result. For the following glass fibre pipe test, the unbonded experiment will thus be left out. Despite the local deformation setting in, the pipes were able to sustain increasing loads up to about additional 50% of the local deformation loads while extending the displacement. There are circles marked on the each load-displacement graph (Figure 22 to Figure 24) showing the load-displacement region where onset of local plastic deformation begins.

Figure 22: Load-Displacement Graph for PVC Pipes

The ability of the pipe to sustain almost linear relationship shows that if loading without local deformation could be done, the pipe could actually sustain higher loading and corresponding displacement. Hence, the potential of a smaller curvature radius could be explored if the loads are spread over a larger area and not acting as point loads. The earlier change from using a 12.5 mm diameter loading pin to that of the 25 mm diameter has shown that such spreading of the applied load could have a considerable impact of reducing local deformations from setting in at a lower loading.

There are also significant increase on the applied loads for the load-displacement when HDPE liner is inserted into the PVC pipe. Local deformation loadings increased to 1.8 kN (unbond) and 2.0 kN (bonded) while

respective displacements increased to 3.8 mm and 4.0 mm. In general, there were about 20% load increases with corresponding 20% of displacements increase with use of the HDPE liner.

Figure 23 shows the load-displacement relationship of the glass fibre pipe, with and without the HDPE pipe. Between the GF against PVC pipes, GF pipe shows a significant increase in load to about 5.0 kN before local plastic deformation set in at the top loading points. Moreover, the GF load increase comes with a smaller increase in displacement as both PVC and GF showed maximum displacement of about 6.0 mm and 7.0 mm respectively but GF loads is about 3.0 to 4.0 times compared with PVC. Both instances also showed about 20 % increase of loading with the use of the HDPE liner. There is a clear significant improvement of loading up to about 3 times between GF and PVC. Using HDPE liner also increase the applied load by about 20% before local deformation set in. Similar to the tests performed on the PVC pipes, HDPE liner has shown only marginal improvement in the load bearing properties of the pipe, but there was significant delay in the onset of plastic deformation.

Figure 23: Load-Displacement Graph for Glass Fibre Pipes

Comparing the trends of the PVC pipes and the glass fibre pipes, the glass fibre pipes could handle more than twice the amount of load than the PVC pipes. Beyond the local plastic deformation points, it can be seen that the HDPE liner has minimal effect on the glass fibre pipes' load carrying capacity. On the other hand, among the PVC pipes, it can be seen that beyond the plastic deformation point, the PVC pipe without the HDPE liner has shown a significant drop in load carrying capacity as compared to the other two pipes. Such phenomenon could be due to PVC being a thermoplastic pipe, which means it is relatively susceptible to bending as compared to the glass fibre pipes.

4.2 Load-Strains

From the strain gauges readings, tension and compression behaviors are graphed. In ideal pure bending by 4-point loading, the top and bottom strain gauges should only read off the same bending strains. However, due to possible inaccuracies of the setup and human error, there could arise a small membrane strain. This additional membrane strain needs to be considered for a more accurate interpretation of the displacement results. Hence, there is a need to break down the actual strain readings into membrane strains and bending strains. The comparison of using the bending strains will then give a fuller reflection of the actual spoolability of a pipe.

$$\varepsilon_{\text{Compression/Tension}} = \varepsilon_{\text{membrane}} + \varepsilon_{\text{bending}}$$

Figure 24: Components of Strain

As the membrane strain is due to inaccurate setting up, it will be consistent across the pipe cross-section and acts only in one unilateral direction, i.e. the membrane strains will be equal in magnitude and direction in the top and bottom strain readings. Evaluating, the membrane strains can be obtained using:

$$\varepsilon_{\text{membrane}} = \frac{(\varepsilon_{\text{tension}} + \varepsilon_{\text{compression}})}{2}$$

On the other hand, as bending strains equal in magnitude but act in opposite directions, the magnitude can be obtained using:

$$|\varepsilon_{bending}| = \frac{(\varepsilon_{tension} - \varepsilon_{compression})}{2}$$

With the plotting of load against strain, the stress-strain curve, where stress is given by load per unit area, can be easily evaluated.

In the following range of load-strain graphs, the absolute values of the strain readings are taken and plotted on the same axis for ease of comparison.

From Figure 25 to Figure 27, we can see that without the HDPE liner, the load carrying capability of the pipes is significantly lower. For example, for a bending strain of +0.003, the PVC pipe with the liner only carries approximately 2.2 kN of load, whereas the PVC pipes with the HDPE liner can carry approximately 2.5 kN of load. In the case of the PVC pipes with HDPE liner, the bonded and unbonded cases are almost identical in their behavior.

Using the membrane and bending strains as outlined above, it is quite evident that the graphs agree with Figure 24 predictions, where compression strain is smaller than tension strain since they have the same membrane strains. In this case, the compression provides a negative bending strain while tension provides a positive bending strain.

Figure 25: Strain Graph for PVC Pipe.

Figure 26: Load-Strain Graph for PVC Pipe with HDPE Liner, Unbonded

Figure 27: Load-Strain Graph for PVC Pipe with HDPE Liner, Bonded

Figures 28 and 29 show the Load-Strain behavior of glass fibre pipes. In both graphs, the top strain gauges that measures the compression shows a clear premature failure due to large application of compressive strains. This phenomenon is shown by the sudden cut-off of the loading graph of the compression, bending and membrane strains in both experiments at approximately 3 kN.

Figure 28: Load-Strain Graph for Glass Fibre Pipe

Figure 29: Load-Strain Graph for Glass Fibre Pipe with HDPE Liner, Bonded

4.3 Moment Curvature Relationship

The Moment-Curvature equation for pure bending of a tubular pipe is:

$$M = \langle \overline{EI} \rangle \kappa$$

where

$\langle \overline{EI} \rangle$ is the effective bending modulus;

ρ is the radius of bending, and

Pipe Moment of Inertia, I is defined by:

$$I = \frac{\pi}{64} (d_o^4 - d_i^4)$$

While the curvature, κ is defined by:

$$(\rho - \omega)^2 + \left(\frac{a}{2}\right)^2 = \rho^2$$

$$\rho^2 - 2\rho\omega + \omega^2 + \left(\frac{a}{2}\right)^2 = \rho^2$$

$$\rho = \left(\frac{\omega^2 + \left(\frac{a}{2}\right)^2}{2\omega} \right)$$

$$\kappa = \frac{1}{\rho}$$

Where ρ is the achieved storage spool radius, ω is the LVDT displacement and a is the distance between the two loading points.

Figure 30 shows the experimental Moment-Curvature graph where there is significant increase in bending moment to achieve the same amount of curvature of approximately 0.4 m^{-1} for the PVC pipes with HDPE liner as compared to the PVC pipe tested without a HDPE liner.

The higher bending moment is contributed by the larger effective bending modulus due to the contribution of the HDPE pipe's having less elastic bending properties.

The star-shaped markers, on the other hand, shows the analytical solutions based on the moment-curvature equation given above. The deviation of graph shows the inability of the analytical formula to predict the non-elastic region.

Figure 30: Moment-Curvature Graph for PVC Pipes

Figure 31 does not reflect the exact same trend as observed in Figure 30, since HDPE has a relatively insignificant elastic modulus compared to the glass fiber. The analytical results, represented by the star-shaped markers, again show a linear projection. Comparing Figure 30 and Figure 31, the glass fibre pipes require approximately eight times the amount of bending moment to achieve the same curvature. This is due to higher modulus of elasticity of the glass fibre pipes as seen in the following Table 1.

Figure 31: Moment-Curvature Graph for Glass Fibre Pipes

Material(s) of Pipe(s)	E	Outer Diamete r	Inner Diamete r	I	<EI>
HDPE	1.39E+0 9	4.03E-02	3.21E-02	7.74E- 08	1.08E+0 2
PVC	5.78E+0 9	4.82E-02	4.10E-02	1.26E- 07	7.30E+0 2
PVC with HDPE					8.37E+0 2
Glass Fibre	1.45E+1 0	4.82E-02	4.10E-02	1.26E- 07	1.83E+0 3
Glass Fibre with HDPE					1.94E+0 3

Table 1: Effective Bending Modulus

Chapter 5: Some Insights into the Four Point Bend Tests

One interesting observation that needs to be reported and then confirmed with some fundamental investigations. It was noticed that the MTS810 machine applied loads/movements through the bottom rollers while traditional testing machine like INSTRON applied loads/movements through the top rollers. Thus, there is difference in the interpretation of the test displacement results of the four point bend test for these two scenarios. The two cases are classified as CASE 1 and CASE 2 respectively as shown in Figure 32.

Figure 32: Two possible displacement case scenarios.

The theoretical development for these two cases is identical at the beginning and the end results are not exactly the same. The fundamental beam bending theory is:

$$\begin{aligned}EI \frac{d^2 y}{dx^2} &= \frac{P}{2} x - \frac{P}{2} \langle x - b \rangle \\EI \frac{dy}{dx} &= \frac{P}{4} x^2 - \frac{P}{4} \langle x - b \rangle^2 + A \\EI y &= \frac{P}{12} x^3 - \frac{P}{12} \langle x - b \rangle^3 + Ax + B\end{aligned}\tag{1}$$

CASE 1 Theory

$$\text{at } x = L/2, dy/dx = 0$$

$$\text{at } x = b, y = 0$$

$$\therefore A = \frac{Pb}{4}(b - L) \quad \dots (2)$$

$$\therefore B = \frac{Pb^2}{4} \left(L - \frac{4}{3}b \right)$$

CASE 2 Theory

$$\text{at } x = L/2, dy/dx = 0$$

$$\text{at } x = 0, y = 0$$

$$\therefore A = \frac{Pb}{4}(b - L) \quad \dots(3)$$

$$\therefore B = 0$$

The results of these two cases are then compared with those of the experimental data of both the PVC and the GRP as shown in Figures 33 and 35 respectively.

Figure 33: Comparison of theories with experimental data for PVC pipe.

PVC Case 1:

Referring to Figure 33, the full deflection of the pipe is measured based on the sum of the central deflection downwards of the pipe from the inner support pins and the upward displacement of the outer loading pins from the horizontal position of the inner support pins. Both experimental and predictions show a linear relationship of the load against the deflections until the load of 1.5 kN. However, for Case 1 total predicted deflection is a consistently smaller than the experimental results. The source of error could come from the way the LVDT is placed to measure the deflection.

See Figure 34 below on depiction of the deflection of the LVDT. The additional deflection that was measured comes from the plastic strip that acts like a cantilever as shown below. The other source of error comes from the ability of the PVC pipe to deform locally at the roller supports as discussed earlier.

Figure 34: Comparison of LVDT measurements

PVC Case 2:

Case 2 model also indicates linear relationship between the applied load and deflections, the predictions give a much higher deflection as compared to the results of Case 1 model and the experimental data. The difference in the results is logically due to the fact that the pipe is now being supported at or near the ends and the effect effective span is longer and thus more flexible to bend.

Figure 35: Comparison of theories with experimental data for GRP pipe.

GRP Case 1:

Comparing the results of Figure 35, the predicted results of Case 1 correlate closely to the experimental results with some differences. As the GRP pipe surfaces are much harder and more rigid than the PVC, the local deformation is not so obvious and hence has less contribution to the total deflection. There is however still some contribution that comes from the cantilever effect of the LVDT positioning. This could be the reason for the slightly larger experimental deflection.

GRP Case 2:

The arguments presented in the above Case 2 for PVC apply equally well here. The predicted deflection is way too high and hence the Case 2 model cannot be representative of the experimental set up.

The above comparison shows that Case 1 model should be the correct one to use for the test done with the MTS810 machine. As measurements of the central deflection is critical to the accuracy and reliability of the test results, care must be taken to ensure the experiments are properly conducted and subsequent measured deflections are correct and errors of measurement are minimized.

Chapter 6: Conclusion and Future Research

6.1 Conclusion.

From the comparison of the two materials, PVC and glass fibre, it is clear that harder materials (i.e. the material that has a higher elastic modulus) will lead to larger curvature thus lowering the spoolability performance of the pipe. The addition of HDPE liner has limited marginal increase on the stiffness of the pipes. The bonded and the unbonded interfaces in the study also did not affect the bending stiffness values. Investigating the results of minimum spool to store the tubular, the PVC shows a coiling radius of 2.5 m. With addition of HDPE, the coiling radius could be reduced to 2.08 m for both bonded and unbonded cases. However, the moment *i.e. additional effort* (force and energy) required to spool the pipe increases by **~13.65%**. Similarly, the glass fiber tubular is found to be having a spool radius of 2.08 m for both with and without HDPE inner layer. Comparing with PVC tubes, the moment required to coil increases by a whopping **627%**.

We have also considered the two different cases of the results; viz. Case 1 loads applied on bottom rollers and Case 2 loads applied on top rollers. The details of the theoretical development were also presented for these two cases. The comparison of the predicted results from each case with experimental results was elaborated and sources of errors in measurement of the deflection were also presented. It is clear that Case 1 results and predictions are more coherent and accurate.

6.2 Future Research

From the experimental results, the addition of HDPE pipe as a liner has marginal impact on the pipe's load bearing capacity. It is possible to consider that a thicker layer of the HDPE liner would improve this capacity. But, this could add to the weight and cost and so it may not be wise to use a very thick layer of the liner.

The inherent stiffness of composite tube materials may limit the range of pipe diameter and thickness for spoolability. If so, then some design change of the composite pipes may yield breakthrough in this area. A possibility for consideration is to have standard lengths of composites being joined together as in a shank of a drill head or a screw structure joint between connecting adjacent pipes. Some form of locks and sealing to cover these joints to enable risers to retain its strength and adaptability to prevent sea-water seeping into these pipes. Further experiments may consider adding stiffener rings at the loading point to delay the onset of local deformations.

Future research into new materials is also feasible. A new area of research also involves making thermoplastic composite pipes, replacing epoxy, a thermoset material, with HDPE.

The theoretical development for the Case 1 and Case 2 can be further developed to considered moment and curvature relationship. The sources of errors coming from deflection could be magnified as moment-curvature is usually a function of the second derivative of deflection.

References

- [1] Gay, Daniel and Suong, V.Hoa. 2007. "Composite Materials: Design and Applications",
- [2] Teresko, John 01 December 2007, "Boeing 787: A Matter of Materials -- Special Report: Anatomy of a Supply Chain". Retrieve from http://www.industryweek.com/articles/boeing_787_a_matter_of_materials_--_special_report_anatomy_of_a_supply_chain_15339.aspx?Page=1
- [3]Campell, Keith 11th May 2009, "Airbus to start manufacturing parts for new A350 XWB in late '09". Retrieve from <http://www.engineeringnews.co.za/article/airbus-to-start-manufacturing-parts-for-new-a350-xwb-in-late-09-2009-05-11>
- [4] Farivar-Sadri K, Structural characterization and design optimization of hybrid composite tubes for TLP riser applications, OTRC Report 5/95-B7175, Offshore Technology Research Center, Texas A&M University, 1995.
- [5] Salama M, Storhaug T, Spencer B. Recent developments of composites in the oil/gas industry. SAMPE J 2002;38(1):30–8.
- [6] Chan W, Demirhan K. A simple closed-form solution of bending stiffness for laminated composite tubes. J Reinf Plastics Compos 2000;19(4):278–91.
- [7] Judice D. Finite element analysis of a coiled composite tubular. Master's thesis, Texas A&M University, Department of Mechanical Engineering; 1999.

-
- [8] Rodriguez D. Influence of material, lay-up, and geometry on the radius of curvature of spoolable composite tubulars, Master's thesis, Texas A&M University, Department of Mechanical Engineering; 2002.

Appendix A

Compressive Stress VS Strain Table for HDPE Test Piece Compression Test

Compressive stress (Pa)	Strain (From the gauge)
1421.017	0.000665
3064.1	0.00069
5583.145	0.00073
6000.429	0.000771
7176.852	0.000801
9164.205	0.00083
12154.64	0.000868
14018.66	0.000898
17241.79	0.000936
20956.48	0.000974
26200.37	0.001009
31009.23	0.001054
37232.88	0.001099
46200.09	0.001144
54403.21	0.00119
66180.78	0.001236
78544.77	0.00129
92310.21	0.001335
109116.5	0.001385
125778.6	0.001437
150619.8	0.001484
169962.5	0.00154
193882.1	0.001587
224806.4	0.00164
252196.2	0.001687
288717.2	0.001734
322983.7	0.001792
358378.5	0.001839
401294.5	0.001894
440088.1	0.001949
494704.4	0.001997
539849.1	0.002056
593491.3	0.002108
656498.3	0.002167
710694.7	0.002217
783161.8	0.002271
851068.6	0.002337
919630.8	0.002392
1000759	0.002455
1069522	0.002518
1165382	0.002577
1235284	0.002649
1317956	0.002716
1412447	0.002789
1491494	0.002854
1589613	0.002921

1681434	0.002999
1767644	0.003065
1873130	0.00314
1960084	0.003213
2074654	0.003279
2157111	0.003358
2253032	0.003428
2366018	0.003506
2452600	0.003575
2566759	0.003645
2667688	0.003727
2766087	0.003794
2880928	0.003871
2977160	0.003948
3097915	0.004014
3188701	0.004095
3291335	0.004166
3409979	0.004247
3503385	0.004314
3623243	0.004384
3726648	0.004466
3827015	0.004532
3950556	0.004608
4048772	0.004684
4184125	0.004753
4274533	0.004834
4380564	0.004907
4507097	0.004986
4604241	0.00506
4726664	0.005134
4839345	0.00522
4940907	0.005289
5064218	0.005369
5163606	0.005448
5291613	0.005517
5382903	0.005603
5486088	0.005677
5609606	0.005764
5703461	0.005835
5826271	0.005907
5934206	0.005999
6031691	0.006067

[Type here]

Appendix B

Compressive Stress VS Strain Table for PVC Test Piece Compression Test

Compressive stress (Pa)	Strain (From the gauge)
1480624	0.002005
1889925	0.002065
2335044	0.002145
2754277	0.002231
3252646	0.002308
3717205	0.002397
4213971	0.002472
4706499	0.002551
5197954	0.002629
5773215	0.002713
6267434	0.00281
6815698	0.002891
7388700	0.002987
7910406	0.003089
8512074	0.003186
9056473	0.003302
9632405	0.003408
10173740	0.00352
10696540	0.00363
11313040	0.003739
11814170	0.003861
12372150	0.003963
12937490	0.004078
13443060	0.004201
14020520	0.004313
14559460	0.004444
15103630	0.004565
15637430	0.004692
16137200	0.004814
16723560	0.004934
17203090	0.005069
17738070	0.005185
18276180	0.00531
18755120	0.005443
19304960	0.005567
19805430	0.005708
20329370	0.005839
20816950	0.00597
21280570	0.006103
21832450	0.006232
22272060	0.006375
22771320	0.0065
23266930	0.006636
23700030	0.006775

[Type here]