QATAR UNIVERSITY

COLLEGE OF ENGINEERING

INTERNAL PRESSURE CAPACITY AND BENDING BEHAVIOR OF GLASS FIBER REINFORCED COMPOSITE OVERWRAPPING PVC PLASTIC PIPES.

BY

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ABSTRACT

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Title: Internal Pressure Capacity and Bending Behavior of Glass Fiber Reinforced Composite Overwrapping PVC Plastic Pipes.

Supervisor of Thesis: Elsadig Mahdi Saad .

The challenge associated with the use of polyvinyl chloride (PVC) plastic pipelines is to improve their structural integrity without increasing their cost. Currently, PVC pipelines are the most cost-effective method of transporting water and sewage drainage. However, the limitations of installed PVC pipelines are well known, including their low deterioration properties (which degrade their load carrying capacity), and their low fracture toughness (which causes catastrophic failure). Both poor deterioration and mechanical properties cause significant losses and sacrifice the structural integrity of pipelines. Many types of deterioration can affect PVC pipelines, including their durability and resistance to environmental effects. Meeting the increased demand for PVC pipelines, cost-effective solutions are necessary to improve their structural integrity. Therefore, this study proposes a glass fiber-reinforced polymer (GFRP) overwrapped system to strengthen the external surface of PVC pipes, which will improve pipes' pressure and flexural capacities.

Accordingly, an extensive experimental program (including five phases) is developed and performed to examine the performance of GFRP composite overwrapped onto PVC plastic pipes. These phases include the fabrication process and different types of tests for evaluating the structural integrity of the GFRP/PVC pipes. The results showed that the proposed overwrapped system significantly improved the flexural carrying capability. The initial flexural failure load increased significantly, with an improvement from 64 to 1140 N. In addition, the ultimate flexural load was improved by a factor of nine. It was also found that the pressure capacity and the flexural behavior were significantly affected by changes in the fiber orientation angle. It should also be noted that as the pipe diameter increased, the pressure capacity decreased. However, as the pipe diameter increased, the flexural carrying load capacity increased. It is also important to note that the main identified failure modes for GFRP/PVC pipes were dominated by matrix cracking, fiber debonding, and fiber breakage. For the internally pressurized GFRP/PVC pipes, the failure mode was mainly dominated by fiber breakage and fiber pullout.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Plastic pipelines are commonly used in the construction of important networks such as sewerage, water, and other drainage networks. Their widespread use can be attributed to their ability to transport large amounts of fluids. Each day, a new connection of water pipes is developed to supply water to areas that have little or no access to water. In other cases, the older pipes are replaced with modern pipes in order to improve the efficiency of delivering these utility services to customers. Plastic pipes are highly preferred over metallic pipes owing to the lower costs associated with them. They are considered for use over other superior materials in a wide range of applications in the transportation of water and sewerage (Sathishkumar, Satheeshkumar, & Naveen, 2014). Most plastic pipes are made of polyethylene and polypropylene materials.

The cost benefits of plastic pipes are mainly from the materials with which they are made. The materials are able to sustain the ground movements without cracking. They are also strong enough to prevent any kind of deformation that may occur as a result of backfill or traffic loading. According to Sathishkumar, Satheeshkumar, and Naveen (2014), the use of plastic pipes offers a wide range of advantages in terms of leak resistance compared to other materials that are used in the distribution of water or sewage disposal. Plastic materials require fewer joints when linking the pipes. Compared with concrete pipes or clay pipes, the number of joints is close to three times the number of joints in plastic pipes. In addition, the process used to join the plastic pipes provides stronger pipes, and strong leak-proof joints increase tightness.

Moreover, plastic pipes provide a better flow rate per meter compared to other materials used in water distribution and sewerage services.

1.2 Problem Statement

This study aims to determine the best mechanism for strengthening water pipes. The method proposed in this study will help to increase the pressure capacity of water pipes using a composite plastic pipe. The best approach is considered to be the use of fiber, which is integrated into the pipes to strengthen internal pressure. Plastic pipes commonly face by a number of challenges, with the main one being leakages that result in high water pressure. Each year, a number of pipes are replaced because of breakages and other damage caused by excessive pressure.

This damage has increased the cost of maintaining the plastic pipes in the provision of sewerage services and clean water, and the huge cost of maintenance is then passed to customers. Therefore, there is a need for a more optimum approach to solving the problem. The costs of maintaining the pipes are associated with treatment and supply, which is also known as the pumping of water and leakages. The replacement period for damaged pipes is quite long because of the need to lay the pipes underground, which requires fresh excavations. During this replacement period, members of the public are disconnected and cannot access the service. Another cost implication that requires labor and other related costs are the diversions of costs. The use of composite plastic with glass fiber helps to increase the internal pressure capacity of water pipes by strengthening the walls of the pipes, in effect providing high resistance to water pressure.

1.3 Objectives

The main objectives of the thesis are as follows:

1. To develop hybrid composite overwrapped plastic pipes for the construction of a strong, stiff, and strong drainage/water pipeline system.
2. To study the different fiber overwrapped orientation effects on the plastic pipes flexural resistance.
3. To evaluate the fiber wrapping effect on pressure capacity for different pipes sizes.
4. To determine the optimal fiber orientation leads to the maximum bending strength.

1.4 Outline of the Thesis

This study consists of five chapters, which are as follows:

Chapter 1: Introduction to the problem

Chapter 2: Literature review

Chapter 3: Methodology

Chapter 4: Results and discussion

Chapter 5: Conclusion and recommendations

CHAPTER 2

LITERATURE REVIEW

Composite materials have undergone extensive evolutions in recent years, especially because they have replaced conventional construction materials in various industries. Today fiber-reinforced composite materials are widely used successfully in numerous applications, particularly in applications that require materials with high strength (Sathishkumar, Naveen, & Satheeshkumar, 2014). Many custom formulations offer fiber reinforcements, such as the glass-fiber reinforcement, which strengthens different plastic products, including pipes, enabling them to hold fluids under high internal pressures. Fiber-reinforced plastic technology was developed recently with the aim of producing materials that would strengthen masonry structures (Sathishkumar, Naveen, & Satheeshkumar, 2014). Owing to its success in the construction field, experts saw the need to apply the same technology in other building and construction fields, such as piping. The main advantages associated with this technique are that it results in high corrosion resistance as well as a high strength-to-weight ratio. Compared to other traditional techniques of reinforcing materials, the use of fiber orientation as a reinforcement technique has become more popular because it uses a combination of low weight and high strength (Sathishkumar, Naveen, & Satheeshkumar, 2014). Compared to ordinary pipes, studies show that glass-fiber-reinforced plastic pipes are, on average, five times stronger, while maintaining a weight capacity that is 20% less than that of ordinary pipes (Wang, 2013). As such, fiber orientation contributes to the design and development of plastic pipes that are light in weight but strong in texture.

Fiber-reinforced plastics, which is the technology used to design plastic pipes, comprise a polymer matrix that has been reinforced using fiber, such as glass. Usually, the fibers are made from glass or carbon, although other fibers (including paper or asbestos) are applied occasionally. The plastic is commonly an epoxy or polyester thermosetting plastic (Wang, 2013). Fiber-reinforced composite materials are usually employed in industries such as the marine, construction, and automotive sectors (Wang, 2013).

2.1 Composition of Glass-Fiber Composites

Currently, glass fiber pipes have become an alternative for coated steel, concrete, and other forms of plastic pipes, because of their strength and durability. Another advantage of these pipes is that they are lightweight, which means that they are not as bulky as the traditional materials used in the production of pipes (Wu & Eamon, 2017). Moreover, they are corrosion resistant because they are made from glass fibers of veil and resin, which not only give them strength and firmness but also protect them from corrosion. The fact that glass-fiber-reinforced plastic pipes are light or weightless compared to alternative pipes means that they significantly reduce the cost of installation while at the same time increasing the speed of installation (Wu & Eamon, 2017). As such, because fiberglass-reinforced plastic pipes are made up of light materials that provide strong and durable services similar to those of their alternatives, they have become the best choice for current plumbing installations.

Glass-fiber-reinforced plastic pipes are mainly manufactured from plastic that has been reinforced with glass fibers. According to Hoa, it should also be highlighted that reinforcement is not just limited to glass fibers, but other materials such as carbon fibers and polyester fibers. However, for applications that require corrosion resistance, materials such as glass fiber are considered the most appropriate. Glass fibers are applicable to almost all thermoplastic materials. Glass-fiber-reinforced plastic pipes are used in a wide range of applications, including bathtubs, boats, and other applications that involve the emission of high-temperature water (Liu, Zhao, Li, Liu & Chen, 2014). Besides their effectiveness when used in various applications, the application of glass-fiber-reinforced plastic pipes also reduces operating costs.

Glass-fiber-reinforced plastic pipe technology is an innovation of the oil industry and dates back to 1948 (Sathishkumar, Naveen, & Satheeshkumar, 2014). The main components of this technology include glass-fiber reinforcements, which are applied to the polyester plastic matrix. In order to increase the wall thickness of these pipes while maintaining their quality and strength, a reinforced plastic mortar with silicate as its main component is used (Renard et al., 2012). Sand filler or silicate is preferred for this purpose because it is economically available and has the ability to maintain the high standards required for most modern pipes. However, in cases where only reinforced plastic mortars are used, the functionality of the pipe generated from this process is limited (Renard et al., 2012). In other words, such pipes are only appropriate for non-pressure applications, such as flow drains that rely on gravity or sewer lines.

Glass-fiber reinforcements are considered a subset of fiber-reinforced polymers or plastics, which are made up of fiber reinforcements applied to a polymer matrix (Rafiq, Merah, Boukhili, & Al-Qadhi, 2017). In this reinforcement, the fiber works to provide the tensile strength required for a plastic pipe to withstand stress, while glass fiber of resin works to provide the structural rigidity necessary to maintain a comprehensively strong pipe structure (Rafiq, Merah, Boukhili, & Al-Qadhi, 2017). Today, different types of fiber reinforcements and resins are available mainly because of their growing popularity and increasing commercial value. Because they offer better alternatives to the traditional concrete or reinforced pipes at lower costs, they are attractive in today's construction industry and other related fields.

Another component of the glass fiber used for plastic reinforcement is resin. In most cases, the resin is often used commercially with fiber-reinforced plastics. Further, polyester resin is also commonly used with fiber-reinforced plastic pipes for domestic purposes or irrigation applications (Rafiq, Merah, Boukhili, & Al-Qadhi, 2017). Epoxy and vinyl-ester are other types of resins, but the two types of glass fiber are considered to be more expensive than polyester, primarily because they are more resilient and sufficiently strong to withstand stress compared to the latter (Rafiq, Merah, Boukhili, & Al-Qadhi, 2017). In most cases, epoxy and vinyl-ester glass fibers are used to reinforce pipes carrying highly reactive or corrosive liquids or pipes because they are able to withstand extremely harsh conditions.

Reinforcing fibers are grouped into different categories, with the main ones being glass fibers, polyester fibers, and carbon fibers. Glass fibers should also be encapsulated entirely into the polymer matrix because they tend to be susceptible to different forms of attacks or corrosion by chlorides or humidity (Rafiq, Merah, Boukhili, & Al-Qadhi, 2017). To prevent the glass fiber from being corroded by chlorides or other corrosive fluids that may be flowing through the pipe, the inner walls of the pipe are lined with veil, which is also known as a surfacing mat. The aim is to provide a smooth surface that will protect the glass fiber from friction and direct contact with the corrosive fluids.

2.2 Glass-Fiber-Reinforced Plastic Pipes Layers

Fiber-reinforced plastic pipes are composite materials made up of the thermosetting polymer, which is in a family of polyesters, and reinforced with glass fiber or any other type of fiber, with the aim of providing stiffness and strength to the reinforced material (Renard et al., 2012). The type of resin used in the manufacture of glass-reinforced pipes is isophthalic resin, which is responsible for strengthening it to withstand pressure and heat from the external environment (Renard et al., 2012). For example, resin offers chemical and thermal properties (including glass transition temperature), as well as heat and chemical resistance, among others, which are required to realize a strong and solid pipe that can withstand a wide range of pressures (Renard et al., 2012). During the manufacturing process of glass-reinforced plastic pipes, their properties can be altered or varied by regulating the ratios of the raw materials used in the reinforcement process. Glass fiber-reinforced plastic pipes have three different layers that are adherent, with each of them possessing different characteristics depending on the functional requirements of the pipes involved. The first layer is the inner liner (Wu & Eamon, 2017). This layer is made up of glass materials of veil and resin, which makes it chemical-resistant, given the fact that it is usually in direct contact with the fluid flowing through the pipe. As such, it is important to have the layer reinforced with the glass fiber materials of veil and resin because it helps the pipe resist permeability by preventing chemical corrosion from taking place (Wu & Eamon, 2017). In addition, the use of these two glass materials makes the internal surface smooth, a factor that is very important because it helps reduce friction between the fluids flowing through the pipes, which can prevent fluid losses (Wu & Eamon, 2017). Moreover, a smooth inner surface prevents the growth of algae or minerals, which is very common with pipes constructed using traditional technologies.

The second layer after the inner liner is the structural wall, which is also known as the filament layer. This layer is made up of two glass materials of resin and roving. The main purpose of this layer is to provide mechanical resistance of the entire pipe from stresses that may result from external and internal pressures, such as increased thermal and physical load (Bing-can et al., 2010). For the glass-reinforced pipes, the structural wall layer can be obtained through the application of the previously cured liner with continuous riving of the glass that is already wetted with resin in very controlled tensions or conditions. In most cases, the thickness of this layer usually depends on the design conditions required for a particular pipe (Bing-can et al., 2010). Because of these specifications and the glass materials used to build this layer, it is able to acquire sufficient strength to withstand all the thermal and mechanical pressure to which it may be subjected when fluid is flowing through the pipes.

Finally, the third layer is the external liner, which is made up of glass materials of resin and veil, as with the inner layer. This layer, which is also referred to as the topcoat, is mainly made up of resin as the main reinforcing material, with a veil used to supplement its properties. In most cases, UV protectors are added to protect the whole pipe against external exposures, such as the sun (Bing-can et al., 2010). However, in areas where the pipe is likely to be exposed to very harsh external conditions, such as encountering a highly corrosive environment and aggressive soils, the topcoat is reinforced using the glass fiber of the veil because it is known to be capable of withstanding such harsh conditions (Bing-can et al., 2010).

These three layers are responsible for ensuring that the glass fiber reinforcement done on a given pipe is strong enough to withstand any form of external thermal and mechanical pressure. The glass fiber reinforcements ensure that the inner liner of the pipe is smooth enough such that it reduces the friction that may be generated by fluids flowing through the pipe (Shi, 2018). However, the glass fiber reinforcements on the structural layer are designed in such a way that it can help the pipe withstand any mechanical and thermal pressure resulting from the external environment. The thickness of this second layer is also dependent on particular specifications that are based mainly on the expected functionality of the given pipe (Shi, 2018). The glass fiber reinforcement on the topcoat layer is designed to ensure that the pipe is protected from external factors, such as heating from the sun, or corrosion from external chemicals (Shi, 2018). These three layers are responsible for reinforcing modern plastic pipes with glass fiber to enhance their tensile strength while maintaining a moderate weight.

Fiberglass composites are made up of different types of glass reinforcements, such as thermosetting resins, in order to add tenacity and help the glass reinforcements withstand any thermal pressure (Shi, 2018). Moreover, additives that are designed and processed to meet certain unique functional criteria in terms of performance are also incorporated into the glass fiber composites to produce the desired results. The amount and orientation of the glass fibers used in pipes determine the mechanical strength that is used depending on the pipe application (Shi, 2018). During this process, different types of glass reinforcements such as the surface veil, chopped roving, and woven roving corrosion-related.

2.3 Types of Fiber Orientations

Fibers used in the orientation of pipes tend to be available in two different forms: unidirectional tow sheets and woven fabric. In both of these two processes, the resin can be applied either in their original place or through the prefabrication of fiber-reinforced plastics (ISO, 2017). In the first application, the process involves laying woven fabric, but two plates are sometimes immersed in resin to produce the same results. This method is usually the most preferred because it is the more versatile of the two considering that it can be used in almost any shape (ISO, 2017).

The second method involved in the prefabrication of fiber-reinforced plastics is often preferred over others because its outcome has better quality control (Katz, 2014). During the manufacturing process of pipes using this technique, manufacturers often supply this fiber-reinforced material, such as a given package, with each method having a specific methodology that should be followed carefully (Katz, 2014). Traditionally, steel pipes have been preferred for piping services because of their ability to withstand fluid pressure flowing through them. However, the challenge with these types of pipes is that they are usually very bulky and expensive, a situation that might bring the construction budget of a given project up while the construction designs would be affected by the heavyweight of steel pipes (Katz, 2014). The use of fiber-reinforced plastics technology helped solve this challenge because it uses a combination of low weight and high strength.

The table below highlights the different property ranges for three different types of fiber-reinforced plastics in terms of weight, density, and tensile strength.

Table 2.1 Typical properties of common FRP materials and steel (Tabatabai, 2005)

Fiber Content	**Tensile strength (MPa)**	**Young's Modulus (GPA)**	**Density (kg/m3)**
CFRP (carbon)	1700-3000	140-300	1600
AFRP (aramid)	1200-2100	50-120	1300
GFRP (glass)	1500	50	2400
Steel	1860	200	7850

From the table above, it is quite evident that different types of fiber contents produce varying results in terms of weight, density, and tensile strength. In this case, glass fiber has the least percentage weight compared to the others, with carbon fiber recording the highest. With respect to the tensile strength of the two, glass fiber has a moderate strength compared to the two other fiber contents. However, glass fiber has the highest density of the three common fiber contents, which may explain why it is the preferred material for fiber orientation in glass-fiber-reinforced plastic pipes because the high density allows it to reinforce the walls of the pipe so that the pipes have a high internal pressure capacity resistance (Rafiq, Merah, Boukhili & Al-Qadhi, 2017). Glass fiber has a moderate weight and tensile strength compared with the other two materials, as well as the highest density. Therefore, it is the best material to conduct the fiber orientation on plastic pipes because it gives a combination of low weight relative to the density of the material used and relatively high strength. This can allow pipes to withstand high internal pressure from the fluids flowing through.

By using the equation shown below, it is easy to calculate the varying results in terms of weight, density, and tensile strength. In this case, glass fiber has the least percentage weight compared to the others, with carbon fiber recording the highest. With respect to their tensile strength values, glass fiber has a moderate strength compared to the two other fiber contents.

The information displayed in the table above can be represented diagrammatically, as shown in the graph below. The figure represents qualitative stress/strain curves for the three different types of fiber contents when compared with traditional reinforcing materials, such as steel.

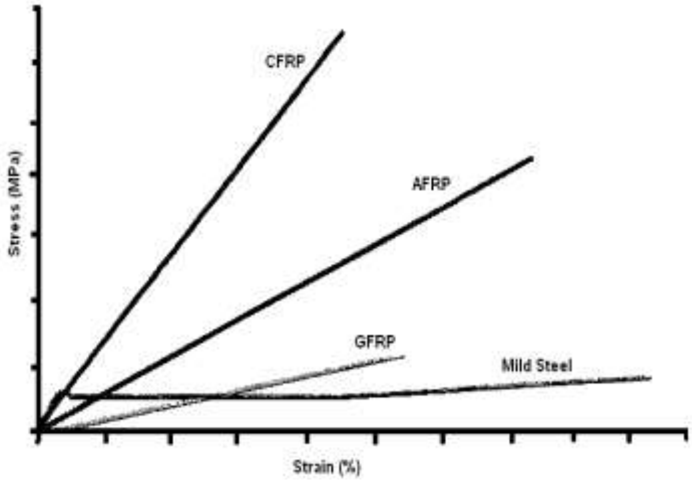


Figure 2.1 Stress-strain curve for different fiber types (Katz, 2014)

From this diagrammatic representation, it is apparent that there is a significant difference in terms of the modulus of elasticity and tensile strength for the three types of fiber contents compared to mild steel, which was the material traditionally used to reinforce pipes. The results from this graph indicate that fiber-oriented materials are more elastic, which means they can withhold more pressure when putting under stress, making them ideal for reinforcing pipes because they enable the pipe to withstand high internal pressure (Rafiq, Merah, Boukhili & Al-Qadhi, 2017). While carbon and epoxy have a higher value in terms of their ability to withstand pressure when putting under stress compared to glass fiber, they lack ductility, which makes them less suitable for reinforcing pipes. However, glass fibers are more flexible and elastic compared to the other two materials, which means that they are malleable in nature. This allows them to be molded into different shapes (Katz, 2004). As such, it is simple to come up with pipes of different shapes using glass fiber because of its flexibility and malleability.

This result explains why glass fibers are the most preferred material for today's pipe reinforcement. Because glass fiber has a moderate weight and tensile strength compared with the other two materials (and the highest density), it is the best material to conduct the fiber orientation on plastic pipes. This is clearly visible in the graph shown above.

2.4 Methods of Testing the Resistance Properties of GRP

Several methods can be applied when testing for the resistance properties of glass-fiber-reinforced plastic materials. This section discusses the most commonly used methods, such as ultra-sonication, tensile tests, impacts tests, and bending tests.

2.4.1 Tensile Test

The tensile test method mainly involves the determination of the shear and normal stresses. During the test, samples of the material are gripped at each end and then pulled apart. The resulting stress of the specimen can then be calculated using the number of forces recorded on each grip relative to the cross-section area (Alexopoulos, Bartholome, Poulin, & Marioli-Riga, 2010). By using the formula shown below, glass-fiber-reinforced pipe manufacturers are able to calculate the tensile strength of the pipe.

$$Stress = \frac{Force}{Area}$$ Equation 2.1

$$s = \frac{p}{a}$$ Equation 2. 2

$$E = \frac{1}{2} F \Delta l$$ Equation 2. 3

s: breaking strength
P: a force that can cause it to break
a: the cross-sectional area

The ultimate tensile strength of the material is the highest amount of force measured during the test. The modulus of elasticity is a function of the strain. International standards for tensile testing are set by ASTM (Faruk, Bledzki, Fink, & Sain, 2014).

As shown in the graph above, the tensile test shows the relationship between the strain and stress that a glass-fiber-reinforced plastic pipe can undergo before it can no longer withstand the internal pressure of the fluids flowing through.

Generally, it determines the plane properties of the polymer reinforced with the modulus fibers. To obtain these values, a thin flat strip that has a rectangular cross-section is used to collect the mechanical properties of the material. However, continuous reinforcement is required to ensure that adequate details are obtained. The subjection of the material to loading ensures that the forces are equally distributed throughout the surface of the material (Halpin, 2017). The material's behavior is determined mainly by the spread of the internal stresses throughout the material.

2.4.2 Bending Test

The bending test is also referred to as the mid-span loading test, and it determines the properties of a material after it has been subjected to flexural loading. The set-up of this test is as shown in the figure below.

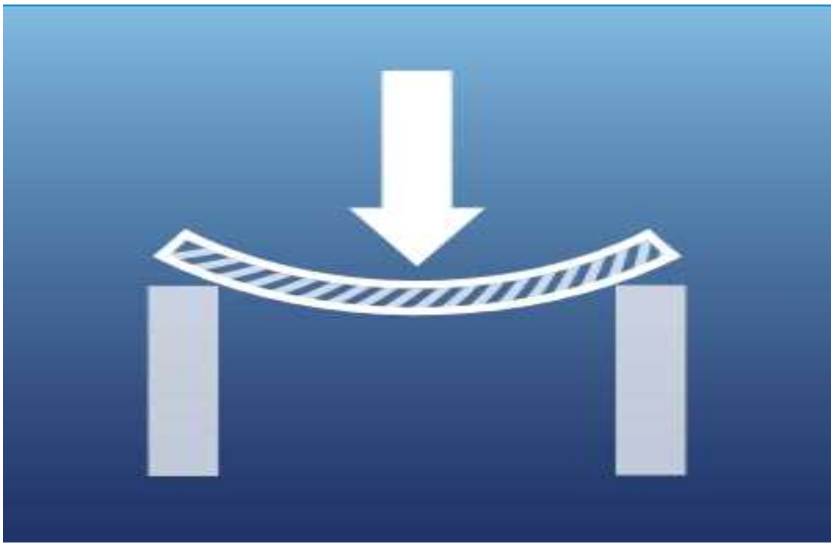


Figure 2.2 Diagrammatical representation of the bend test (Carmisciano, De Rosa, Sarasini, Tamburrano, & Valente, 2011)

The load is applied in such a manner that it produces a curvature that is used to determine the stiffness, strength, and shear modulus of the material. Tests are conducted based on tensile and compressive strengths tests (Carmisciano, De Rosa, Sarasini, Tamburrano, & Valente, 2011). For comparison, the configuration of the flexure can, however, be altered to ensure that different results are obtained.

2.5 Fabrication Methods

There are several methods that are applied to the fabrication of glass-fiber-reinforced plastic pipes. These include the hand lay-up method, the spray up method, and the filament winding method. Each of these methods is described in the sections below.

2.5.1 Hand Lay-Up Method

The hand lay-up method is one of the methods used in the fabrication of glass-fiber-reinforced plastic pipes. It is also referred to as “contact molding,” as it involves the development of molds to be used in the fabrication of thermoplastic materials. The mold is first coated using an appropriate release agent before the process of lay-up fabrication can commence (Ghanbari, Fred, & Rieke, 2011). A layer of resin of approximately 10 mm is applied to the chemical resistant glass, commonly referred to as “C-glass.” The glass is used as reinforcement and occurs in the form of a thin veil.

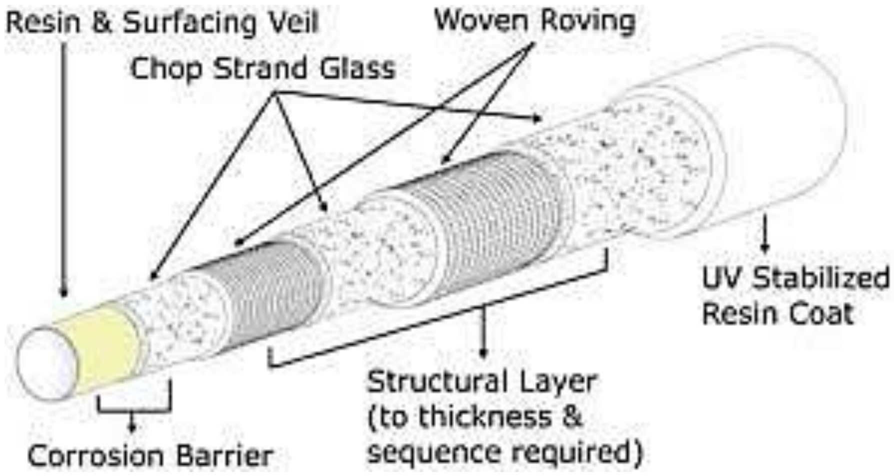


Figure 2.3 The Hand Lay-Up Method graphic (Ghanbari, Fred & Rieke, 2011)

The first layer of 10-mm reinforcement results in the formation of a corrosive barrier with low glass content and high resin content. The next step involves the formation of two fiberglass layers that take the form of a mat. According to Ramesh, Palanikumar, and Reddy (2013), the mat-like layer consists of chopped glass fibers oriented in a random manner. They have a binder that holds them in a form that can be cut or applied in any other way. By using a spray gun or a brush, the resin is then applied on the layer to act as a catalyst for the formation process (Pei, Yin, Zhu, & Hong, 2012). The incorporation of resin into the chopped glass mat is implemented through the use of rollers or similar paint rollers. The content of the resin in the mat is approximated to be between 70% and 75%. After the thickness of the walls has been ascertained to be approximately 6 mm or slightly larger, a stronger reinforcement material can be used (Stamenović et al., 2011). The reinforcement usually consists of a continuous glass filament that has been formed in a manner similar to the coarse cloth. Finally, the glass-fiber-reinforced plastic pipes are produced by rolling the chopped final layers of the thermoplastic materials.

2.5.2 Spray-Up Method

The spray-up operates under similar principles as the hand lay-up method. Both methods are classified as contact fabrication methods. The spray-up technique is simply an automated method for the deposition of the chopped glass (Emiroğlu, Beycioğlu, & Yildiz, 2011). The fabrication process starts with the surfacing of 10 mm of surface vein glass in a continuous form to form a thin rope. It is then pulled through a gun head, which reduces it into smaller lengths that are then sprayed towards the mold (Hussain, Pandurangadu, & Kumar, 2011). Simultaneously, the catalysts, resin, and glass are deposited independently, resulting in the formation of a spray lay-up that can be rolled to get good wet out of glass and eliminate any air trapped in it. For laminates that are much heavier, woven ravings can be used between various alternate layers of the fiberglass.

2.5.3 Filament Winding Method

This method is mainly applicable in the fabrication of the cylindrical and round parts of the reinforced glass fiber. Bai (2013) reports that as with the other method, it is pulled through a concentration of catalyzed resin. While being concentrated in the bath, the reinforced glass fiber is taken through a wetting process until the excess resin contained in the material has been removed (Hoa, 2017). Fibers impregnated with resin are then wrapped using a mandrel and are then continuously rotated to ensure that they remain stable. The mounting is done on a winding machine that resembles a lathe. Taheri (2013) explains the manner in which glass fiber materials traverse the rotating material to form a predetermined pattern. The diagram below gives a diagrammatic representation of this process.

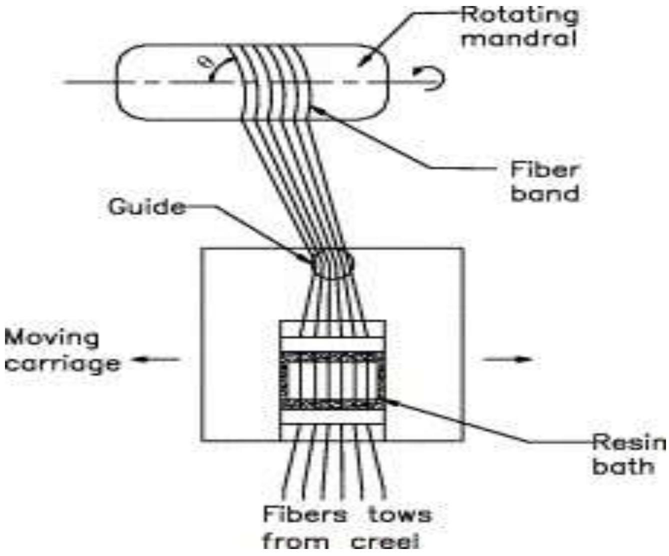


Figure 2.4 Filament winding method (Taheri, 2013)

By using this method, pipes of different lengths and diameters can be easily produced (Sathishkumar, Naveen, & Satheeshkumar, 2014). The number of layers developed on the pipes using this method is mainly dependent on the intended applications. For the composite pipe of 50mm diameter, 200-250 ml of resin is used to produce a 6m pipe with one layer of fiber.

2.6 Manufacture and Mechanics of Fiber-reinforced Polymer Composites

Reinforcing fibers are often made up of different elements, such as glass and metals (including steel or graphite, is also known as carbon fiber). The application of fibers as a reinforcing material often leads to an increased modulus of matrix material (Bakis et al., 2012). This process is possible because of the existence of strong covalent bonds within the fibers, which gives them a high modulus, and implies that for the fibers to be broken or extended, these fiber bonds have to be either moved or broken. In most cases, it is usually a very difficult process to turn fibers into composites, which is the main reason for which fiber-reinforced composites tend to be very expensive (Bakis et al., 2012). For this reason, fiber-reinforced composites tend to be applied in very advanced glass-fiber-reinforced piping, especially in areas where the reinforced pipe is expected to carry corrosive fluids moving at a very high speed and pressure. Therefore, fiber-reinforced composites, such as glass fibers, are the most preferred elements to deal with such scenarios.

The orientation of fibers relative to each other in terms of fiber distribution and concentration has a significant impact on all fiber-reinforced properties, such as strength, tenacity, and durability (Toutanji & Deng, 2012). As discussed earlier, scenarios in which the application of fiber-reinforced composite is necessary and where their application has stressors that are multidirectional imply that discontinuous fibers have to be utilized. Moreover, the nature of the stress applied to a given glass fiber-enhanced pipe determines the orientation of the fiber strength and length (Toutanji & Deng, 2012).

The modulus for this whole fiber composite, the matrix, and the reinforcement are all governed by a set of rules that are intended to strengthen the mixture. Three theories are often applied to explain the process of generating the properties for the analysis of the fiber-oriented composites. The theories are the three Youngs moduli abbreviated as (Ex,Ey,Ez), the three Poisson ratios abbreviated as (vxy, vyz,vxz), and the three shear moduli represented as (Gxy, Gyz, Gx). A combination of these theories can be explained using the figure below.

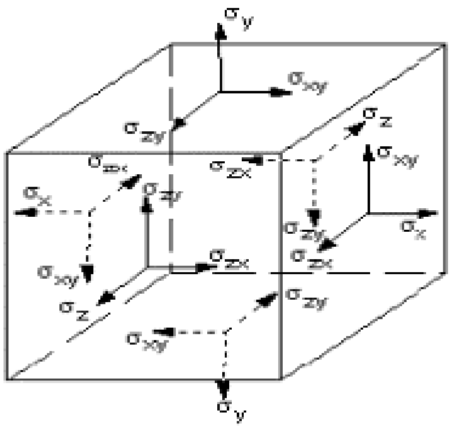


Figure 2.5 (Mutasher et al., 2012)

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{xz} \end{Bmatrix} = \begin{bmatrix} 1/E_x & & & & \text{symm} & \\ -\nu_{yx}/E_y & 1/E_y & & & & \\ -\nu_{zx}/E_z & -\nu_{zy}/E_z & 1/E_z & & & \\ 0 & 0 & 0 & 1/G_{xy} & & \\ 0 & 0 & 0 & 0 & 1/G_{yz} & \\ 0 & 0 & 0 & 0 & 0 & 1/G_{xz} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{Bmatrix}$$

Equation 2. 4

By applying this formula, it is then easy to determine that the application of the required fiber-reinforced composite and their application have stressors that are multidirectional implies that discontinuous fibers have to be utilized. In addition, from this formula, plumbers are able to determine the nature of stress applied to a given glass fiber-enhanced pipe, thus determining the orientation of the fiber as well as its strength and length.

The properties of various products can be altered through the adjustment of the winding patterns adopted during the fabrication. Davoodi et al. (2010) reported that commonly used winding patterns include hoop, helical, and polar windings. The fibers have the tendency to pass through a resin bath and to wet out and feed on the mandrel. Other components of the bath during the fabrication process include the eyes and the rollers, and they are all important in ensuring that the excess resin is removed from the thermoplastic.

Once the wetted fiber has been formed, it is taken through a pre-set carriage and eventually a mandrel. By determining the number of fiber bundles, it becomes possible to determine the width of the band. According to Mutasher et al., (2012), if the lead screw is moved in a rotary motion, the carriage moves along the length of the mandrel. By coordinating the movement of the mandrel, it is possible to coordinate the angle as desired. There is a close relationship between the winding angle and the speed of the carriage (Mutasher, Mir-Nasiri, & Lin, 2012). This relationship is presented in the equation below.

$$tan\theta = \frac{r^2 \pi Nm}{LNs} \qquad \text{Equation 2. 5}$$

tan θ: winding angle
r: radius
N_m: speed of rotation
N_s: speed of the carriage N_m
L: speed of the lead screw

Mutasher et al. (2012) present all of the delivery units used in the past. These units ensure that the wetted fibers are delivered on the rotating mandrel as well as on the entire rotating unit. However, it is important to ensure that the fiber is kept constant during the whole machining process. Rollers help to ensure that this is achieved.

One of the most critical properties of the lamination process is ensuring that the tension of the fiber is maintained at a constant value. Other important properties include the accuracy of the winding process, the arrangement of the mold handling, as well as the repeatability of the layers (Devendra & Rangaswamy, 2013). This helps to minimize the wastage of the materials at both ends of the pipe, where the wind direction is likely to change. According to Mutasher et al. (2012), there is no limit to the size of the filament. Currently, used pipes range in diameter from 6 to 7 m, while the vertical length may exceed 20 m.

2.7 Raw Materials

The properties of glass-fiber-reinforced plastic vary through the selection of certain resin types and other reinforcements owing to the existence of some specific properties. According to Mutasher et al. (2012), some of the most commonly preferred reinforcement materials are E-glass and S-glass fibers. The resistance to corrosion results mainly from the various properties of the resin, which include both weather and chemical resistance, thus making the product more resilient to corrosion. Polyesters are the most commonly used types of resins (Ramesh, Palanikumar, & Reddy, 2013), and under special circumstances only, phenolic resins can be used. It is important to ensure that the resins used have a low viscosity in order to support fast wetting and longer working time for the products.

It is a common requirement that the resin systems with longer working times are provided with elevated temperatures in order to enable curing. Through the use of infra-red lamps, the products can be heated to improve their fabrication (Deogonda & Chalwa, 2013). At this stage, the woven mats or cut molds can be used, and they can be applied between different layers before subjecting them to winding. It is also important to point out that some of the products based on thermoset resin can also be wound into pre-pegs, and these are mainly semi-cured products that have been treated with resin. The main advantage of the development of pre-pegs is that it eliminates the need for external baths (Bhattacharyya & Fakirov, 2012). The end products are also cleaner and of much higher quality. This method is highly applicable in the manufacture of thermoplastics, such as glass-fiber-reinforced plastics.

Other raw materials are used together to form a strong plastic pipeline so that they can attain the required properties of a specific fiberglass product. Additives such as a catalyst, which is an organic product that must be added together with resin, act as an accelerator for the mixture between the resin and the plastic being reinforced (Belarbi & Wang, 2011). A chemical compound referred to as an accelerator is often added together with the resin to catalyze polymerization at ambient temperatures in order to obtain a strong and well-reinforced plastic pipe. An inhibitor is usually added to reduce the reactivity of this mixture during ambient temperatures (Belarbi & Wang, 2011). These steps are required for plastic pipe manufacture before they are reinforced with different glass fiber components.

2.8 Properties of Glass-Fiber-Reinforced Plastic Products

The properties of the materials are mainly dependent on the fabrication method that is adopted. For instance, glass-fiber-reinforced plastics manufactured using the filament wound method are superior because the reinforcements tend to be continuous and directional. The achievement of a high-volume fraction of fibers is quite possible (Moorthy & Manonmani, 2013). This will ensure that the quality is as high as that attained in the pre-peg lamination process. The fabrication methods used also affect the geometry of the products. For instance, the use of spray-up methods results in the formation of products with pre-determined patterns. The product geometry should be done in such a manner that the fibers enable continuous tensile loading throughout the entire process (Khan et al., 2010). After the winding process has been completed successfully, the post-processing of the products can be done separately. Post-processing operations are conducted using various compression methods.

From an economic perspective, the use of glass-fiber-reinforced plastic provides low-cost solutions with high productivity. The properties of glass-fiber-reinforced plastic pipes make them quite competitive in the market (Jawaid, Khalil, Bakar, & Khanam, 2011). These pipes tend to have high mechanical strength, high resistance to fatigue, and resilience to higher temperatures. Compared to steel, glass-fiber-reinforced plastic pipes have better and more improved properties. The inner surface of the pipes also has a lower coefficient of friction, which makes the flow of the fluids easier and more efficient (Ku, Wang, Pattarachaiyakoop, & Trada, 2011). In addition, the lightweight properties of steel make it easier to handle.

2.9 Textile Fiber Glass

This material is mainly used for the reinforcement of various matrix composites. They consist of SiO2, Al2O3, B2O3, CaO, or MgO, mostly in powder form. The mixture is then heated to a temperature of 1600°C, resulting in the formation of liquid glass (Mobasher, 2011). The hot liquid is then passed through very small bushings and then cooled to produce glass fiber with a diameter of 5–24 μm. The filaments are closely knit together to enable the cohesion and protection of the glass from abrasion.

There are different types of glass fibers that are available, the most common of which are soda-lime glass, electric-type glass fibers, and chemical resistant types of fiberglass. S-glass-type fiberglass usually has a much higher tensile strength and modulus of elasticity compared to the E type (Zimniewska et al., 2012). They are therefore considered expensive.

Figure 2.6 Textile Fiber Glass (Source: Fradelou, 2013)

2.10 Applications of Glass-Fiber-Reinforced Plastic Pipes

There are several applications of glass-fiber-reinforced plastic, especially in the construction industry. First, they are commonly used as the primary structural elements (Hussain, Pandurangadu, & Kumar, 2011), and are critical in load-bearing as well as supporting the profile of a structure. One of the most notable applications of glass-fiber-reinforced plastic is the construction of facades. It is also used in the manufacturing industry to develop embedded grits that help to ensure that slip resistance is reduced (Dhand et al., 2015). Glass-fiber-reinforced plastic pipes are also used in the automotive industry to develop some of the key automotive components. Generally, these materials are applied in areas where low-weight and high-strength materials are required in the development of various products.

2.11 Strength Characteristics of Glass-Fiber-Reinforced Plastic Pipes

When considering both the structural and strength properties of glass-fiber-reinforced plastic pipes, three main rules of thumb should be considered. According to Kim et al., (2011), the first consideration is that the strength of the material is directly proportional to the glass content in the pipe. This means that materials with a higher percentage of reinforced glass are likely to be stronger — secondly, the more continuous the glass filament, the higher the strength properties of the materials. For instance, by using the filament wound construction method, the glass that is formed has higher strength compared to the other methods. Rafiee (2013) explains that the woven glass will have much higher strength compared with chopped glass. Finally, the third rule is that the tensile strength of the material is dependent mainly on the direction of orientation of the glass fibers.

These rules can be explained in the formula demonstrated below.

$$\varepsilon_c W_c = \varepsilon_f W_f + \varepsilon_m W_m \qquad \text{Equation 2. 6}$$

$$V_f = \frac{W_f}{W_c} \text{ and } V_m = \frac{W_m}{W_c}, \qquad \text{Equation 2. 7}$$

$$\varepsilon_c = \varepsilon_f V_f + \varepsilon_m V_m \qquad \text{Equation 2. 8}$$

$$\varepsilon_c = \frac{\sigma_c}{E_t}, \varepsilon_f = \frac{\sigma_f}{E_f} \text{ and } \varepsilon_m = \frac{\sigma_m}{E_m} \qquad \text{Equation 2. 9}$$

The equation becomes:

$$\frac{1}{E_t} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \qquad \text{Equation 2. 10}$$

For instance, pipes that are manufactured using the filament approach have the fiber filaments oriented at an angle of 90°. For the chopped mat glass, they are flat and hence equal in both directions. At right angles, the strength of the fiberglass is minimal.

2.12 Effects of Using Glass-Fiber-Reinforced Plastic Pipes

The use of glass fibers as the preferred material for orientation purposes in glass-fiber-reinforced plastic pipes has numerous benefits, and there are a number of advantages associated with the use of glass-fiber-reinforced plastic in the manufacture of pipes. First, the material is highly resistant to corrosion. In some cases, this is the only material that can be used effectively in a particular service environment (Jain & Lee, 2012). In other cases, it is the most economically feasible solution. Resistance to corrosion is determined mainly by the resin that is applied to the glass. The greater the amount of resin available on the glass, the lower the vulnerability of the pipes to corrosion (Wang, Wu, Wu, Dong, & Xie, 2014). Therefore, during the fabrication process, the layer of the material consists of 90% resin and 10% glass. Hota and Liang (2011) report that materials with a high glass component are mainly used in high-service applications, where it is important to eliminate any form of corrosion.

Another advantage of glass-fiber-reinforced plastic is its low weight as it has a very low weight-to-strength ratio. Studies show that compared to steel, for the same weight, glass-fiber-reinforced plastic will weigh at least 1/7th of the total weight (Belarbi & Wang, 2011). Arikan (2010) shows that materials with lightweight properties are very important, especially when considering the cost of construction and installation. This is valid, especially for pipes and tanks. The weight advantage of glass-fiber-reinforced plastic is realized when mounting the equipment on existing structures, rooftops, and scrubbers.

Thirdly, glass-fiber-reinforced plastic also has major advantages with respect to its high strength. This property plays a very critical role in the design of various shapes using the pipes (Hensher, 2016). Pipes fabricated using the filament wound methods in the presence of high strength ensures that the material has a lower weight.

Glass-fiber-reinforced plastic is also an economical solution, and lower costs are incurred when using these materials. They are also applicable to major solutions for corrosion-related problems, and hence cost-related issues (Teng, Yu, & Fernando, 2012). While there is no particular rule of thumb with respect to the application of glass-fiber-reinforced plastic, the costs are mainly dependent on the applications and the availability of the materials.

Another benefit is that the material is corrosion-resistant. In other words, when used for pipes, glass fiber material will not rust, as was the case with steel-reinforced pipes (Belarbi & Wang, 2011). Glass fibers are able to withstand the action produced by salt ions or other chemicals that pass through the pipes being reinforced. For this reason, glass fibers are suitable for reinforcing pipes as they are able to withstand challenges that are very common with traditional pipe manufacturing methods (Belarbi & Wang, 2011).

Glass fibers are considered to be a light-weight material compared to other fiber contents that can be used for pipe reinforcement purposes. For example, glass-fiber-reinforced pipes are estimated to weigh, on average, a quarter of the weight of equivalent steel-reinforced pipes (Shi, 2018). As a result, it is an effective material for ensuring that piping services in any construction design do not take up a lot of space while reducing the overall weight of the construction material using lighter piping material (Shi, 2018).

Moreover, the use of glass fiber in piping is preferred because it is electromagnetically neutral as the glass fiber material contains no metal. As a result, the material is preferred for reinforcing pipes, especially those that are used in different types of construction because it will not interfere with electronic devices that may be affected by metals or magnetism in general (Belarbi & Wang, 2011). Other than being electromagnetically neutral, glass fiber-oriented piping is thermal neutral, which means that it has a high resistance to heat transfer (Belarbi & Wang, 2011). Thus, plastic pipes reinforced with glass fiber are able to withstand high temperatures, a factor that would allow them to remain strong even during harsh thermal conditions.

2.13 Failure Analysis of Glass-Fiber-Reinforced Plastic Pipes

According to Arikan (2010), glass-fiber-reinforced plastic pipes have seen increasing demand in the water and sewage industries because they have been proven to have excellent properties such as corrosion resistance, high tensile strength, and light-weight. In addition, the maintenance costs are very low. Although glass-fiber-reinforced plastic pipes have many advantages, their applications are still limited by the absence of adequate information or knowledge about the failure mechanisms or some of the unsatisfactory results that can occur in case of any failure (Eslami, Honarbakhsh-Raouf, & Eslami, 2015). In most cases, incidences resulting from the failure of glass-reinforced plastic pipes can sometimes lead to adverse consequences, which may result in a loss of resources or accidents. As such, it is very important to conduct thorough failure analysis on glass fiber-reinforced pipes because it will help to understand this technology better, and future research can be conducted with the aim of addressing the existing risks.

Fiber-reinforced plastic pipes can be described as being a composite material that is made up of the thermosetting polymer, which is in the family of polyesters and is reinforced with glass fiber or other types of fiber with the aim of providing stiffness and strength to the reinforced material (Rafiee & Reshadi, 2014). The type of resins used in the manufacture of glass-reinforced pipes is the Isophthalic resin. The presence of this resin property in the glass-reinforced pipes strengthens it such that it can withstand pressure and heat from the external environment. For example, resin offers chemical and thermal properties such as glass transition temperature, heat, and chemical resistance, among others, which are required to have a strong and solid pipe that can withstand all types of pressure (Lee et al., 2015). During the manufacturing process of glass-reinforced plastic pipes, their properties can be altered or varied by varying the ratios of the raw materials used in the reinforcement process.

Before any project can be undertaken, one of the main issues to be considered by engineers and other experts and planners of this project is related to its durability. This question has been asked many times with respect to glass-reinforced plastic pipes, particularly when applied to high-risk industries such as the gas and oil industry (Guedes, Sá, & Faria, 2010). However, although the risks associated with the water and sewage industry may not be as high as those in the gas and oil industry, the quality and durability of the glass-reinforced plastic pipes used are equally important because organizations will be able to cut down on maintenance costs (Guedes, Sá & Faria, 2010). In addition, the dangers associated with the failure of these pipes are also minimized significantly, which ensures that there is minimal loss of resource wastage and that the required operations are executed efficiently.

According to Rodriguez, Alvarez, and Montemartini (2013), the failures associated with glass-reinforced plastic pipes should be considered from both short- and long-term perspectives. Keshavamurthy, Sharma, and Kulkarni (2011) clearly indicate that most failures are likely to occur during the manufacturing process of these glass-reinforced plastic pipes and during the installation of these pipes. The common failures that occur there include air bubbles that form between the various layers of the pipes, which occurs mostly during the manufacture and installation of these pipes (Rodriguez, Alvarez, and Montemartini, 2013). Studies show that when glass-reinforced plastic pipes with air bubbles between their layers are exposed to high thermal conditions, these air bubbles expand, exerting more pressure on the pipes; this is a condition that can result in the development of cracks. These cracks reduce the overall strength of the pipe, making it unable to sustain high internal pressure, especially when the fluid flowing through the pipes is under high pressure (Diniz Melo et al., 2011). Such situations often lead to pipes bursting, which wastes resources, while the applications of such pipes become unstable and unreliable.

Another failure of the glass-reinforced plastic pipes can result from bulging, which often occurs when a pipe is resting on a sub-grade that is very hard. According to Hawa et al., (2016), poor compaction below the pipe launch leads to inverse flattening or the formation of a bulge. A situation where there is over compaction can often result in the pipe bulging from any location. The occurrence of these bulges often results in a situation where there is a strain concentration within the pipe, owing to a prolonged period of high stress. To address this challenge, new techniques that involve the use of photogrammetry should be applied because they help identify bulges quickly by assessing the condition of the pipe’s shape during the inspection phase (Hawa et al., 2016). Moreover, other techniques may involve the use of numerical methods in order to calculate strain and stress levels using the shape of the pipes.

Another challenge affecting the design and failure criteria of glass fiber pipes is deflection. The design of fiberglass has an effect on the allowable long-term deflection in the sense that it limits it to just a 5% maximum of its long-term stability (Wu & Eamon, 2017). Wu and Eamon argue that by limiting the long-term maximum deflection to just 5%, the short-term deflection cannot exceed 3%. However, the current techniques for determining deflection are not sufficiently precise because these methods are not accurate enough. In the future, experts in this field should employ more advanced technologies to take better deflection measurements, such as the use of photographic methods to obtain precise measurements (Wang, 2013). Having the right deflection measurements in place will be crucial for fiberglass-reinforced pipeline manufacturers and users because they would be able to develop their designs accordingly.

Finally, pipe stiffness has also been identified as one of the reasons that can result in the failure of glass fiber-oriented plastic pipes. Davis et al., (2010) show that the reinforced plastic mortar pipes that were used in the 1970s had an approximate pipe stiffness of 10 psi, but the current generation of reinforced plastic mortar pipes is somewhat stiffer, with a pipe stiffness reading measuring between 18 psi and 72 psi. Abdul Majid et al., (2015) indicate that the increased stiffness in modern pipes owing to the application of modern glass fiber plastic pipe reinforcements implies that although these pipes are strong in texture and capable of handling more internal pressure, the associated breakage risk is very high (Sayman, Deniz, Dogan, & Yaylagan, 2011). In the future, developers of glass fiber-oriented plastic pipes should consider the development of more advanced technology that can handle these challenges.

2.14 Summary

From the foregoing, compared with other traditional techniques of reinforcing materials, the use of fiber orientation as a reinforcement technique has become more popular because it employs a combination of low weight and high strength. Studies show that glass-fiber-reinforced plastic pipes are, on average, five times stronger, while maintaining a weight capacity that is 20% less than that of ordinary pipes. Among the advantages associated with the technique of glass-reinforced plastic pipes is that it results in high corrosion resistance, while it also has a high strength-to-weight ratio. However, although there are many advantages associated with glass-fiber-reinforced plastic pipes, there are numerous challenges that can result in the failure of glass-reinforced plastic pipes, leading to adverse consequences such as loss of resources or catastrophic accident. This study develops a set of recommendations that can help the piping industry avoid catastrophic incidences resulting from the failure of glass-reinforced plastic pipes.

First, current manufacturing techniques have to be assessed and improved so that they are able to detect any factor defects in good time, preferably during the production process. The implementation of this measure will ensure that the quality of glass fiber-reinforced pipes that are available in the market are of high-quality and overcome the challenges identified, such as bulging and stiffness. Secondly, the current inspection and criteria for determining quality standards should also be upgraded because it will help address the current challenges facing glass fiber-reinforced pipes. Another study is required to verify the impact resistance and strength retention of the glass-reinforced plastic pipes in order to establish their ability to overcome the internal pressure of the fluids flowing through them. The study should also address the remedies or actions that should be taken in situations where the glass-enhanced plastic pipes fail to achieve their objectives. This will involve developing techniques that assess any potential areas of weaknesses and recommend the best measure that can be taken to address such challenges. Deflection has been identified as one of the main challenges facing glass-reinforced plastic pipes, and as such, it is important to have techniques that can help to address this evolving challenge.

CHAPTER 3

METHODOLOGY

This chapter describes the methods used to carry out the research, including the fabrication process and preparation for different types of tests. The flow chart for this investigation is shown in Figure 3.1, which also describes the outline plan of the study. The implemented methodology has been divided into five phases, as described below:

Methodology Phases

3.1 Phase 1: Fabrication Process of Composite Overwrapped Plastic Pipes

It is well known that the filament winding technique is the most appropriate manufacturing technique in the fabrication of composite pipes or applying the overwrapping system over the plastic or metallic pipes. In this study, five-axis filament winding machines were used to apply the overwrapping system to strengthen the plastic pipes. The resin used is slow curing resin (EL2 epoxy laminating resin) blended with AT30 Fast epoxy hardener, which has an initial curing time of 5–6 hand full dryness after about 48 h at 25°C. The mixing ratio for the resin and hardener is 10 to 3 per weight. The number of layers was selected such that they have the same thickness as the thickness of the plastic pipe. After being warped, the glass fiber composite layers were left overnight for complete curing. In this phase, polyvinyl chloride (PVC) pipes and E-glass fiber-reinforced polymer (GFRP) were employed. Table 3.1 list the typical mechanical properties of glass fiber/epoxy. Figure 3.2 shows the five-axis machine and the ongoing fabrication of overwrapped PVC plastic pipe. Table 3.2 summarize the values selected for the winding process.

Table 3.1 Typical Engineering Properties of GFRP

	GFRP
E_{11}(GPa)	40.0
E_{22}(GPa)	11.9
E_{33}(GPa)	11.9
G_{12}(GPa)	3.52
G_{13}(GPa)	3.52
G_{23}(GPa)	3.28
ν_{12}	0.28
ν_{13}	0.66
ν_{23}	0.28

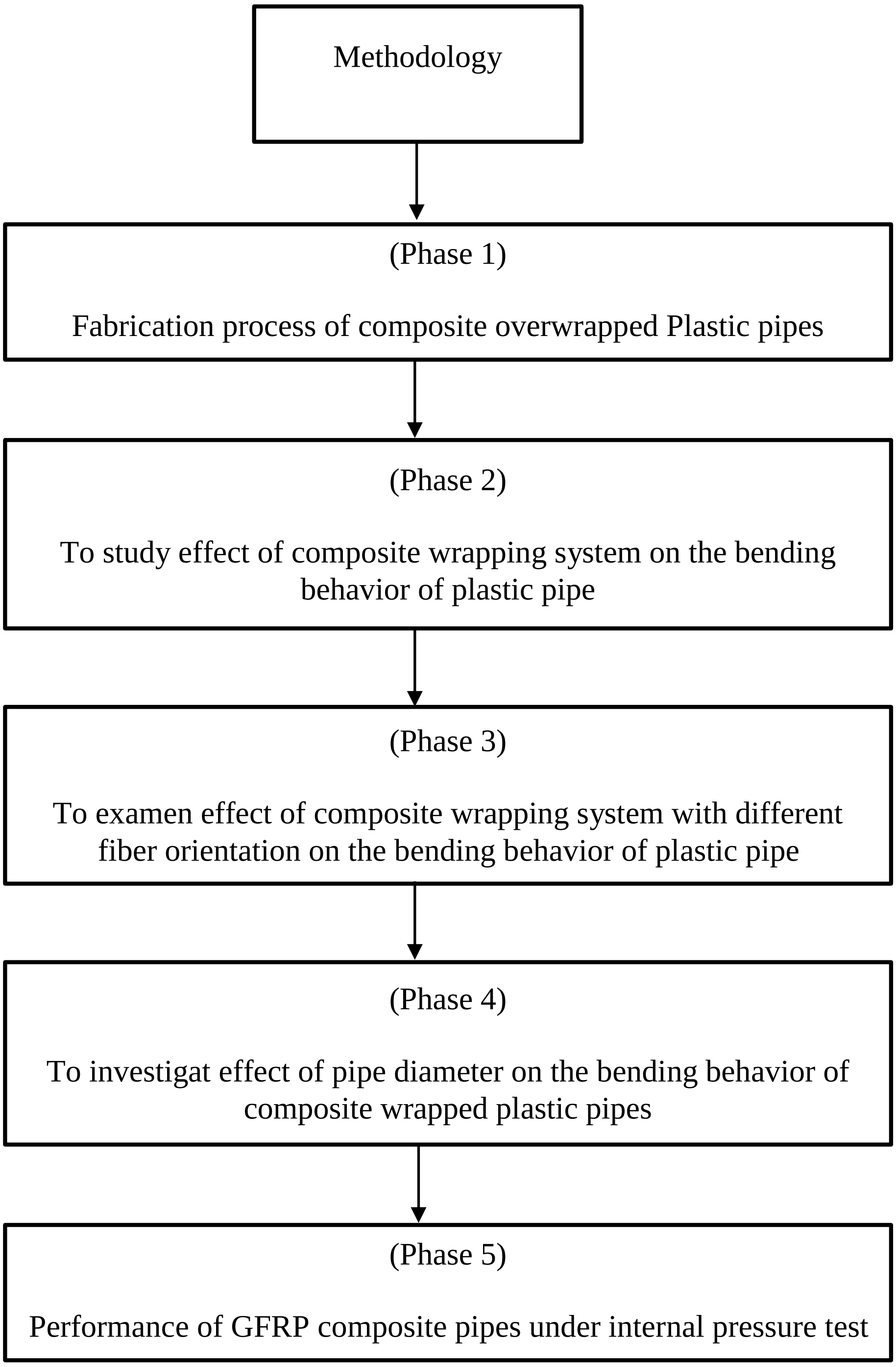
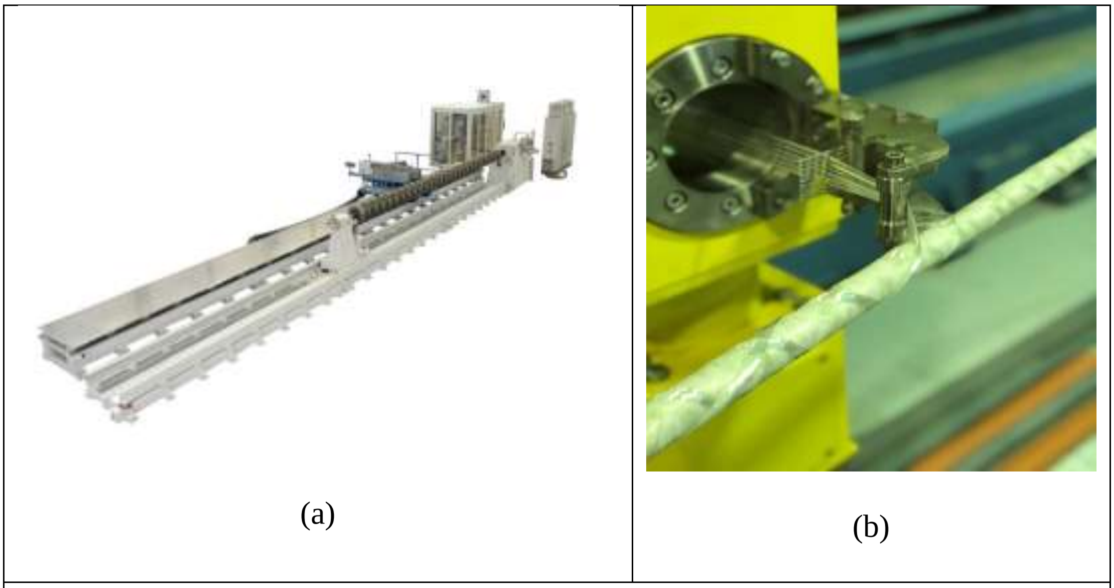


Figure 3.1 Flow chart showing the phases of this study methodology.

Table 3.2 Summary of the winding values in the fabrication process

Winding angle (degree)	Fiber speed (m/min)	Feed (m/min)	Spindle speed (RPM)
90	7.8	9.56	27
65	25	9.92	27
55	25	10.2	27
45	25	10.6	27


(a)

(b)

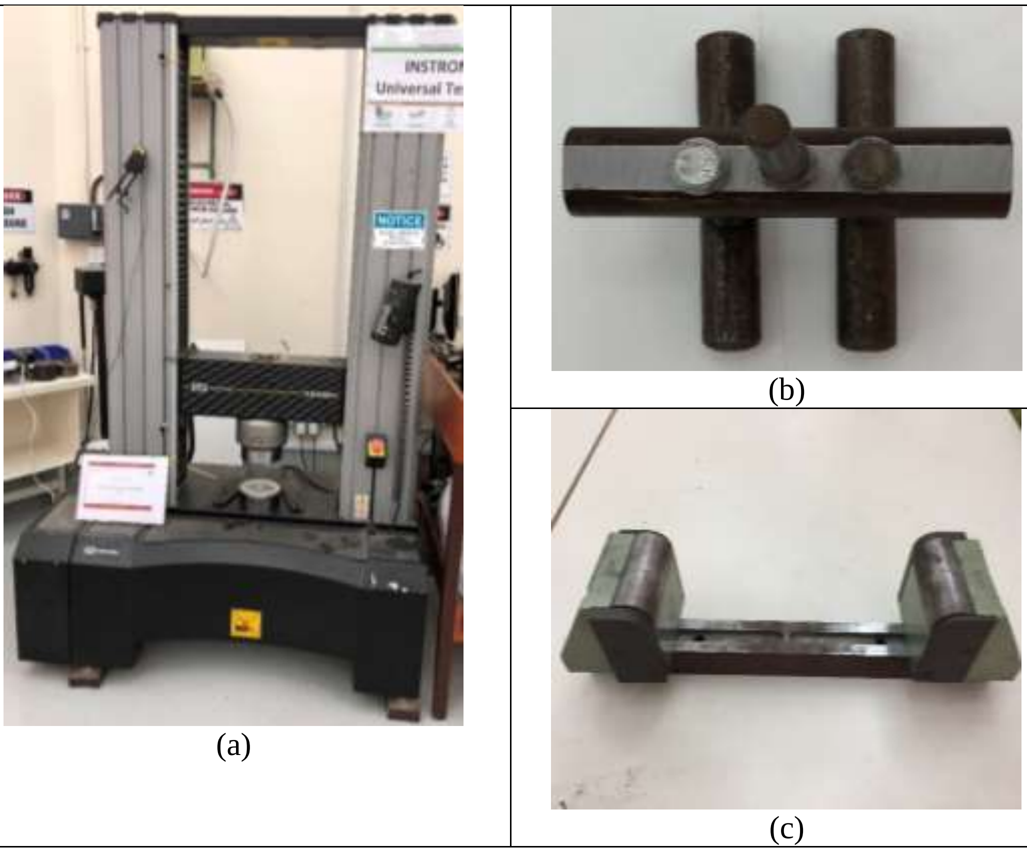
Figure 3.2 (a) 5-axis Filament Winding Machine, (b) Ongoing Fabrication of GFRP Composite Overwrapped Plastic Pipe

3.2 Phase 2: Effect of Composite Wrapping System on the Bending Behavior of Plastic Pipe

In this section, the effect of composite overwrapped on the plastic pipe bending behavior is examined. To this end, a plastic pipe with a diameter of 25 mm is used as a control specimen, as shown in Figure 3.3. Accordingly, a GFRP composite with a fiber orientation of 55° is wound on the top of the plastic pipe to produce the overwrapped specimens for a four-point bending testing. It should be noted that the Instron machine was used to perform a four-point bending test throughout the study. The machine was programmed to perform a flexural test at 5 mm/min, and the maximum deflection was determined to be 60 mm, as shown in Figure 3.4.

(a) (b)

Figure 3.3 Prepared and fabricated specimens for examining the effect of the composite wrapping system on the bending behavior of plastic pipe (a) plastic pipe with 25 mm diameter (b) GFRP overwrapped plastic pipe with 25 mm diameter and fiber orientation of 55°.

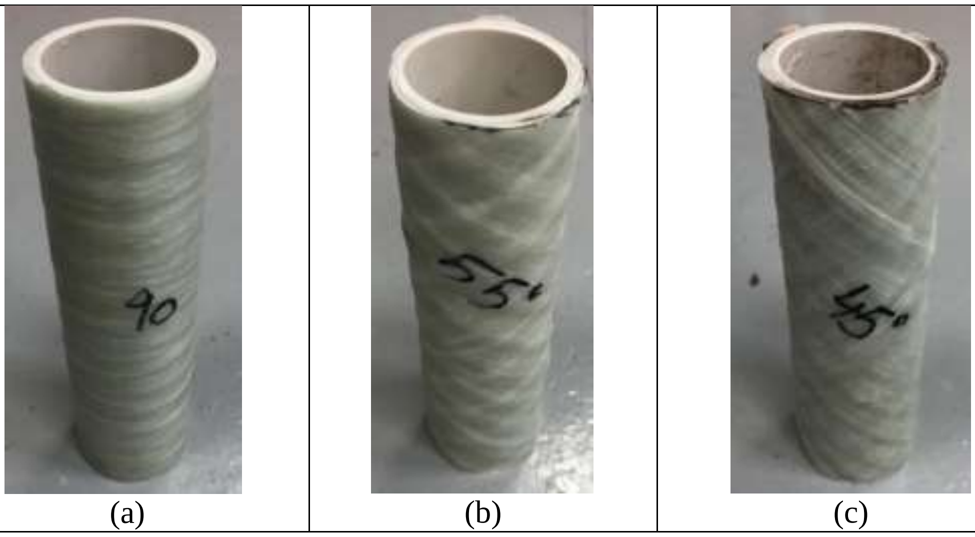


(a) (b) (c)

Figure 3.4 (a):Instron machine with 250 Ton capacity, (b): Support, (c): Mandrel-tool.

3.3 Phase 3: Effect of Composite Wrapping System with Different Fiber Orientation on the Bending Behavior of Plastic Pipe

Based on classical lamination theory, the fiber orientation angle was found to have a significant effect on the behavior of composite overwrapped systems. Accordingly, glass fiber composite overwrapping systems with four different orientations 0°, 45°, 55°, and 90°, were used to examine their effect on the bending behavior of glass fiber composite overwrapped plastic pipes. Figure 3.5 shows the fabricated specimens employed to investigate the effect of fiber orientation on the bending behavior of GFRP overwrapped plastic pipes.



(a) (b) (c)

Figure 3.5 Fabricated specimens for investigating the effect of fiber orientation on the bending behavior of GFRP overwrapped plastic pipes. Sample of specimens with 50 mm diameter (a) GFRP pipe with 90°, (b) GFRP pipe with 55° (c) GFRP pipe with 45°

3.4 Phase 4: Effect of Pipe Diameter on the Bending Behavior of Composite Wrapped Plastic Pipes

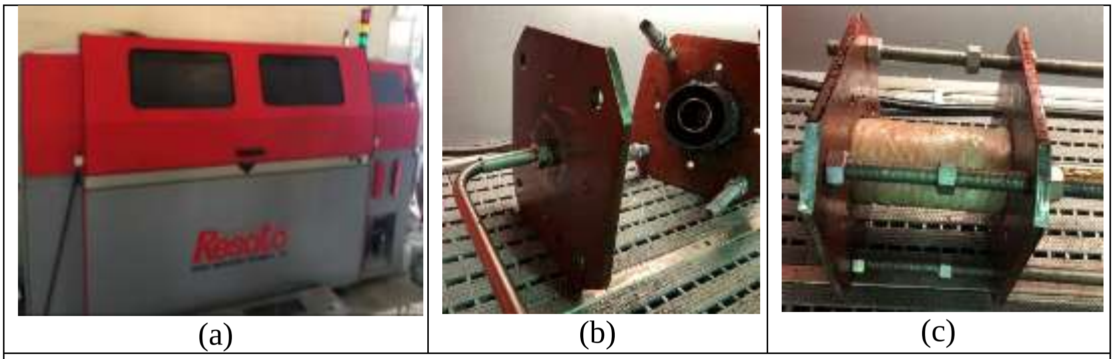
An effect of plastic pipe diameter on the bending behavior of composite wrapped plastic pipes is investigated in this phase. Plastic pipes with different diameters were overwrapped with GFRP composites to examine their flexural behavior under four-point bending. The three diameters were chosen as 25, 50, and 100 mm, as shown in Figure 3.6.

(a) (b)

Figure 3.6 (a) plastic pipes with different diameters (b) GFRP overwrapped plastic pipes with a fiber orientation of 55° and different diameters.

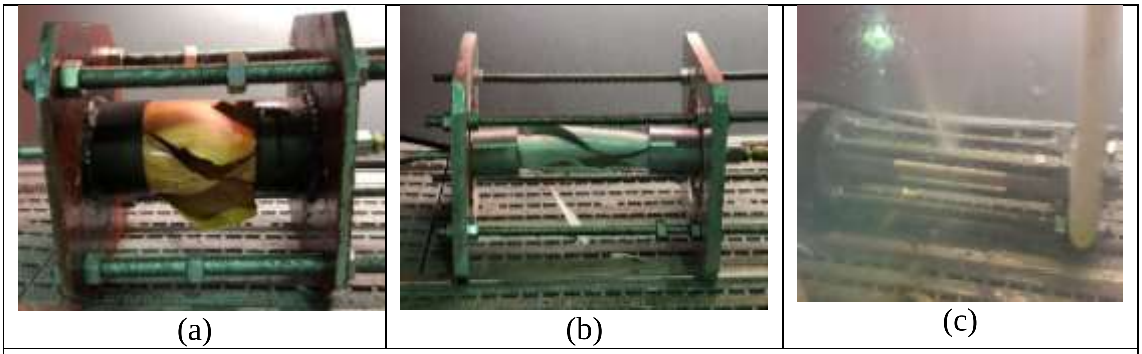
3.5 Phase 5: Performance of GFRP Composite Pipes under Internal Pressure Test

As the main aim of the plastic pipe is to handle the internal fluid pressure, overwrapped plastic pipes were tested under internal pressure until failure. Figure 3.7a shows the high-pressure machine used to conduct the pressure test. The machine brand was a Resato model SPU-CC-2000. The machine pressure had a capacity up to 2000 bar using hydraulic oil by the air pump. The test idea is to fix the pipe from two ends and to have thread, which allows the hydraulic hose to connect with the fixture. The Resato technique involves filling the pipe with oil, then applying low pressure to confirm that there is no leakage after a gradual pressure increase until bursting. Fixtures made customized with a 30-mm thickness of aluminum plate are threaded from four corners to allow keeping the threaded rod in which tight the cylinder both ends. However, this leads to failing and bulking of the aluminum plate. This, therefore, led to the need for a stronger material, after which the decision was made to employ steel with the same dimensions, but with higher resistance to bulking. The same fixture was used to test different pipes with different diameter sizes by manufacturing them with different cup groove sizes. Additional to the groove rubber sealing used. Then Four threaded rods were fixed with 16 nuts to tighten the pipe in order to prevent it from moving. Figure 3.8 shows the set-up and tested tubes.



(a) (b) (c)

Figure 3.7 (a) Resato high-pressure testing machine. (b) The designed end closer for pipe internally pressurized. (c) Internal pressure setup.



(a) (b) (c)

Figure 3.8 (a) 100mm PVC plastic pipes after the internal pressure test (b) 50mm PVC plastic pipes after the internal pressure test (c) 25mm PVC plastic pipes after the internal pressure test

3.6 Summary

Chapter 3 focuses on the methodology and phases, which have been implemented to conduct the present study. It is important to consider these methods in detail in order to understand the experimental program, results, and discussion, which will be presented in the following chapter.

CHAPTER 4

RESULTS & DISCUSSION

In this chapter, the responses of the unwrapped PVC plastic pipe and glass fiber composite overwrapped plastic pipe to the internal pressure and a four-point bending test are presented and discussed in detail. The four-point flexural and internal pressure tests were performed for three pipes for each type of unwrapped PVC plastic pipe, and glass fiber overwrapped plastic pipes. Furthermore, GFRP composite overwrapped plastic pipes with four fiber orientation angles were used to examine their effect on bending behavior. Finally, the responses of plastic pipes and composite overwrapped plastic pipes subjected to internal pressure tests are presented and discussed.

4.1 Effect of GFRP Composite Overwrapping System on the Bending Behavior of Plastic PVC Pipe

In this section, the flexural behavior of the plastic pipe and GFRP overwrapped plastic pipe is investigated, presented, and discussed in detail. The bending behavior of the unwrapped PVC plastic pipe is used as a control in order to evaluate the performance of the GFRP overwrapped plastic pipe.

4.1.1 Unwrapped PVC Plastic Pipe with 25-mm Diameter

Figure 4.1 shows the flexural load-deflection curve for the plastic pipe with 25 mm diameter and 400 mm length that was subjected to a four-point bending test. The flexural behavior of the PVC pipe can be categorized into six stages. In the first stage

(Stage I), the initial flexural failure occurred at (1.21 mm) the deflection point, and the flexural load was 64.24 N. This initial failure stage was followed by stage II, where the flexural load is sustained for a very short duration for a 0.5-mm deflection. This post-initial failure process is continued in the next stage (Stage III), where the flexural load increases in a non-linear manner until it reaches its maximum flexural load capacity value of 225.5 N at a deflection of 17.5 mm. Subsequently, the flexural load starts to decrease gradually until it reaches its first lowest value of 169.83 N at 32.78 mm (Stage IV). At end (Stage IV) the top surface become in contact with bottom surface which made the load recovers gradually to reach its highest peak at a value of 516 N and deflection of 50 mm, as labeled by Stage V. After it attains its maximum peak, Stage VI starts, in which the flexural load starts to decrease gradually, reaching 452 N at a deflection of 60 mm.

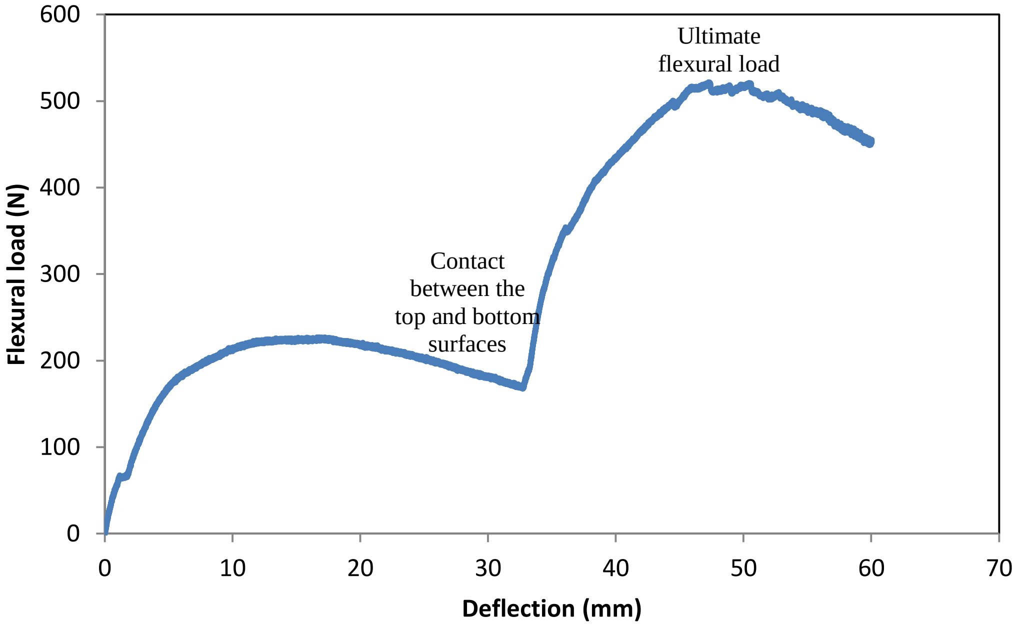


Figure 4.1 Flexural load-deflection curve of PVC plastic pipe under a four-point bending test.

Figure 4.2 Undeformed and deformed unwrapped 25mm PVC plastic pipe under a four-point bending test.(a) undeformed pipe (b) deformed

4.1.2 GFRP Composite Overwrapped PVC Plastic Pipe with 25-mm Diameter

Figure 4.3 shows the flexural load-deflection of the GFRP composite overwrapped using the plastic pipe with 25 mm diameter and 400 mm length having one layer of the overwrapped fiber orientation angle of 55°. The orientation angle is measured with respect to the axial direction of the pipe and subjected to four-point bending. The flexural bending behavior of the test pipe can be seen to have four stages. The first stage represents the elastic stage behavior, where the relationship between the load and deflection is linear, and the deflection at this stage is about 4.07 mm and the load is 1140 N. Beyond the first stage, there is the second stage, where it can be seen that there was a deflection in the sample without any increase in the flexural load. A gradual change was exhibited in the behavior of the specimen from elastic to plastic. It noticed the contribution of plastic is very low; as we increase the radius, the contribution of plastic increases. The deflection that was seen in the second stage of plastic deformation was about 27 mm. In the next stage, the load necessary to continue with plastic deformation in the specimen was found to increase, and the ultimate pipe load was about 4800 N, with the corresponding deflection at the point being 38 mm. After the ultimate stage of loading, fractural failure caused by fiber pulls out the load started to decrease steadily to 2200 N at a deflection of 60 mm. The flexural load-deflection of the GFRP composite overwrapped the PVC plastic pipe by 25 mm and fiber orientation of 55°as shown in Figure 4.3. The response of the GFRP composite overwrapping the

PVC plastic pipe can be classified into four stages. In the first stage, the elastic deflection was found to be 0.63 mm. As the pipe deflected beyond this point, the flexural load was no longer proportional to the deflection, and the curve deviates from linearity. The change in pipe behavior from linear elastic to nonlinear elastic was observed to be a gradual process, which results in the onset of matrix cracks at four locations, two at the loading points, and the other two at the reaction points, as shown in Figure 4.5. The initiation of cracks was found to be due to the onset of matrix cracking on both the tension and compression surfaces, as shown in Figures 4.5 (1, 2) and 4.6 (1, 2). The evolution of matrix cracking was found to occur at a flexural load of 1140 N and a vertical deflection of 4 mm. The attained load was observed to continue without any significant increase in the pipe flexural load carrying capacity until a deflection of 26 mm, where the pipe’s load-carrying capacity starts to increase significantly in order to reach its maximum capacity of 4800 N at a vertical deflection of 38 mm. After that, the pipe starts to experience major cracks at the four locations owing to the tensile stress at the outermost bottom surface. The crack was found to be dominated by the debonding failure node, which was followed by fiber breakage, as shown in Figures 4.5 (3, 4) and 4.6 (3, 4). This major fracturing failure mode results in the gradual decrease of the pipe load-carrying capacity. The pipe’s load-carrying capacity was found to be 2201 N at a vertical deflection of 55 mm.

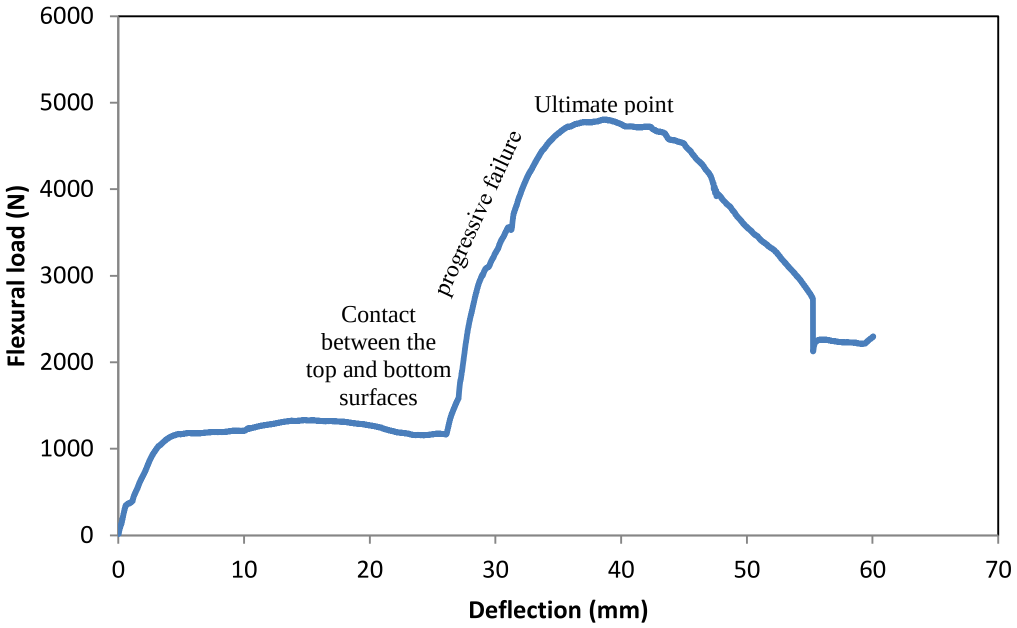
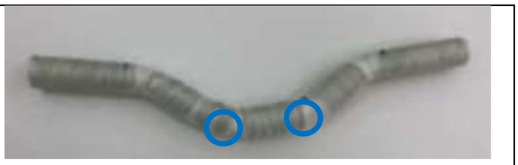


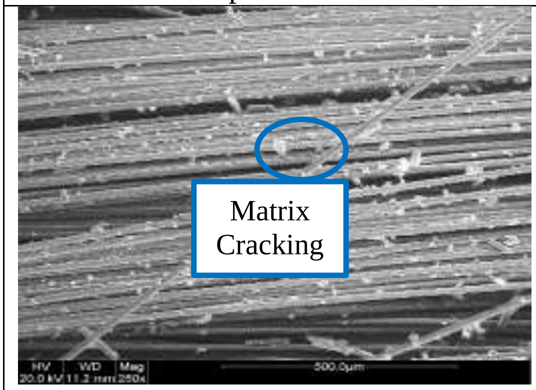
Figure 4.3 Flexural load-deflection curve of GFRP overwrapped PVC plastic pipe under a four-point bending test.

(a)

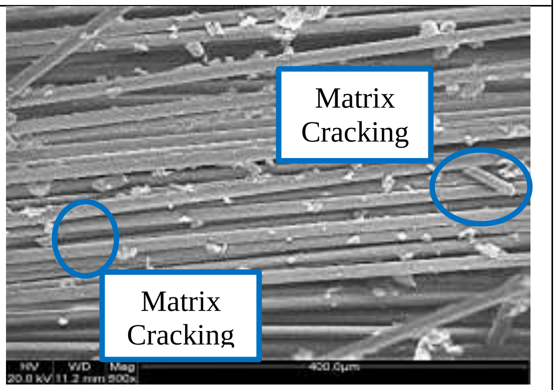


(b)

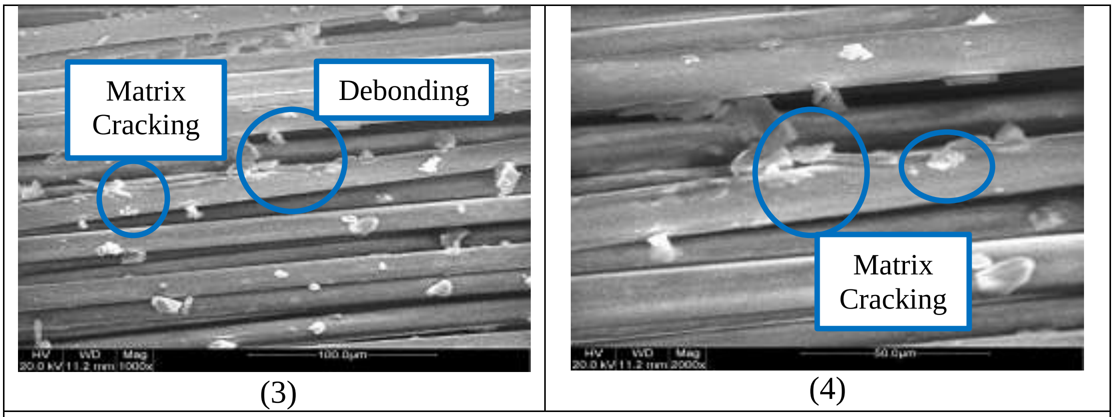
Figure 4.4 Overwrapped GFRP composite 25mm PVC plastic pipe under a four-point bending test. (a) undeformed pipe (b) deformed pipe with matrix cracking on the load contact point



(1)

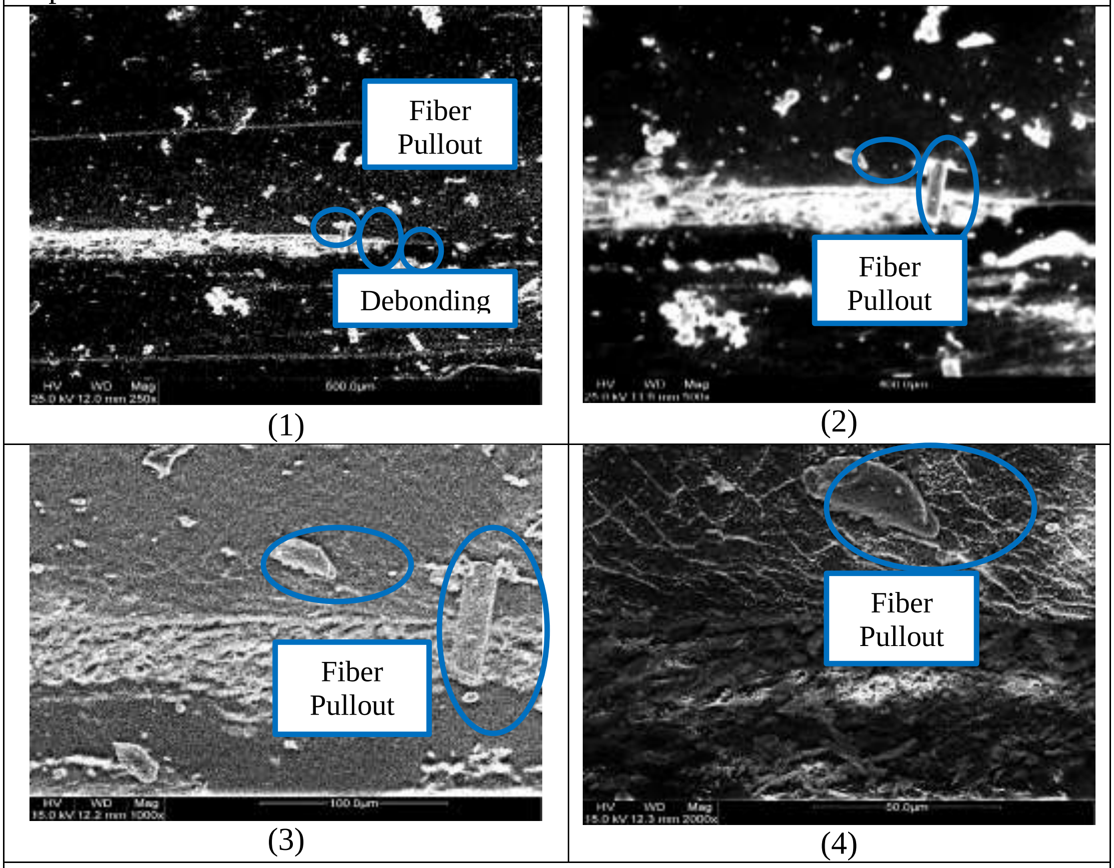


(2)



(3) (4)

Figure 4.5 SEM of the fractured specimen, which is taken from the surface that experienced tension.



(1) (2)

(3) (4)

Figure 4.6 SEM of the fractured specimen, which is taken from the surface that experienced compression.

4.1.3 GFRP Composite Overwrapped the Plastic Pipe vs. Plastic PVC Pipe

Glass fiber with a fiber orientation of 55° has been used to examine the effect of the composite overwrapped system on the bending behavior of the PVC plastic pipe. The initial failure is found to be dissimilar to wrapped and unwrapped, in which the lower

CFRP is shown as in Figure 4.7 and Table 4.1. In the second stage (Stage II) (post-failure), the load-deflection curves were had almost the same trend, where the load is found to be constant. However, in stage III, the GFRP composite wrapped pipe was found to have a very high load-carrying capacity compared to the unwrapped pipe.

Table 4.1 Summary of the effect of the GFRP composite overwrapping system

Test pipe	**Initial flexural failure**		**Ultimate flexural**	
	Load (N)	**Deflection (mm)**	**Load (N)**	**Deflection (mm)**
Unwrapped PVC plastic pipe	64 ± 0.798	1.21 ± 0.001	516 ± 3.5	50 ± 1.849
wrapped PVC plastic pipe	1140 ± 6.722	4.07 ± 0.015	4800 ± 70	38 ± 2.118

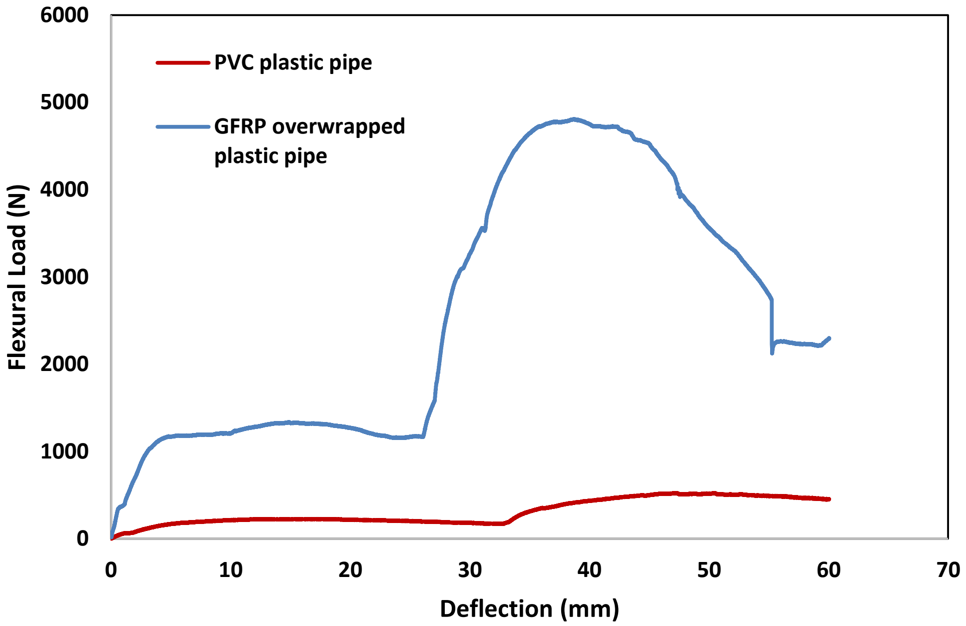


Figure 4.7 Flexural load vs.. deflection curves for the GFRP composite overwrapped the plastic pipe and the plastic PVC pipe.

4.2 Effect of Different Fiber Orientation on the Bending Behavior of the GFRP Overwrapped PVC Plastic Pipe

In this section, we present the results of a four bending test for a GFRP composite plastic pipe. The plastic pipes used in the test were all 50 mm in diameter, 400 mm in length, and had one layer of fiber. The variation in the four pipes resulted from the use of different orientations of the one layers of fibers. The orientation angle is measured with respect to the axial direction of the pipe. The four orientations that were tested and discussed in this section were: 45° GFRP fiber orientation composite plastic pipe joined; 55° GFRP fiber orientation composite plastic pipe joined; 65° GFRP fiber orientation composite plastic pipe joined, and 90° GFRP fiber orientation composite plastic pipe joined.

4.2.1 GFRP Composite Overwrapped PVC Plastic Pipe with 90°

In this test, a 0/90°GFRP fiber orientation composite plastic pipe was used, and the results were as shown in Figure 4.8. The response of the 90° GFRP fiber orientation composite plastic pipe can be approximately placed into three stages. The first stage is where the specimen exhibits behavior that is very close to elastic, and this can be seen just at the onset of loading. At this stage, the flexural load increases to 8035 N, while the corresponding deflection is at about 3 mm. From 8035 N, there are some temporal fluctuations where the load drops to about 5600 N while the deflection remains the same at about 3 mm. This is the stage yield, which is assumed to take place as, beyond this point, we have plastic deformation, where it can be seen clearly that the flexural load is no longer proportional to the deflection. The change in the behavior of specimens from elastic to plastic could be considered to have been gradual. In the plastic deformation stage, the load that keeps the process going is observed to increase up to the point when the test pipe reaches its ultimate load-carrying capacity at 17055 N with corresponding at the point is 22 mm. From the ultimate load point, we transition to the failure stage, where we have a general pattern of reduction in the load as the deflection increases up to the point of failure. On the path to failure, the load at one point dropped to a minimum of about 5600 N, with a corresponding deflection of about 48 mm before starting to rise again, and finally failing at a flexural load of 8800 N with a corresponding deflection of 60 mm.

By considering the figure, it can be seen that from the ultimate strength level, the pipe deflection increased by a further 28 mm from the peak point to failure. This is an indication that the pipe was not brittle.

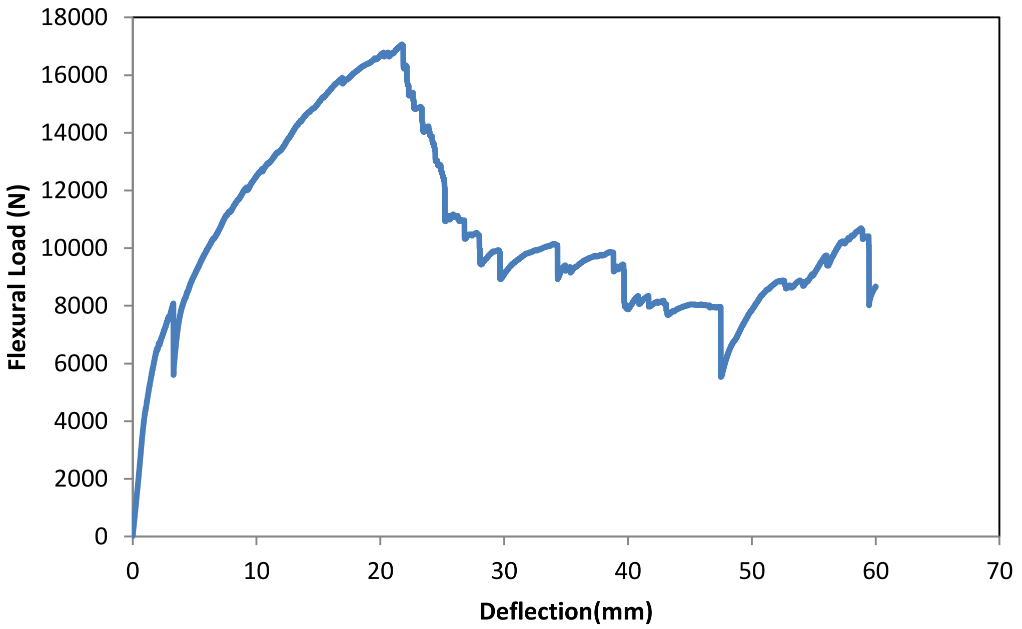


Figure 4.8 Flexural load vs.. deflection curve for 90° GFRP fiber orientation composite plastic pipe.

4.2.2 GFRP Composite Overwrapped PVC Plastic Pipe with 65°

In this experiment, the 65° GFRP fiber orientation composite plastic pipe joined was used, and the results are as shown in Figure 4.9. The response of the 65° GFRP fiber orientation composite plastic pipe can also be roughly allocated to three stages, just as in the case of the 90° GFRP fiber orientation composite plastic pipe. The first stage is where the specimen exhibits behavior that is very close to elastic, and this can be seen just at the onset of loading. At these stages, the flexural load increases to 3428 N, while the corresponding deflection is slightly below 1 mm. From 3428 N, the load drops to about 2800 N momentarily, while the deflection increases to slightly above 1 mm. This is the stage yield that can be assumed to take place, as, beyond this point, there is plastic deformation, where it can be seen that the flexural load is no longer proportional to the deflection. It can also be said that the change in behavior of specimens from elastic to plastic is gradual. In the plastic deformation stage, the load that keeps the process going on and is seen to increase to the first peak value of 14800 with a deflection of 23 mm; then, the load level decreases to about 12000 N. Then, the load is maintained roughly at this level while the plastic deflection persists. The load is then increased to the maximum level of 16876 N at a deflection of 58 mm, and it finally collapses as the load drops to almost zero at a deflection of 60 mm. From the ultimate strength level, the load dropped sharply, as can be seen from the figure, and this is the point at which the test pipe failed. This is a clear indication that the material was highly brittle at this point.

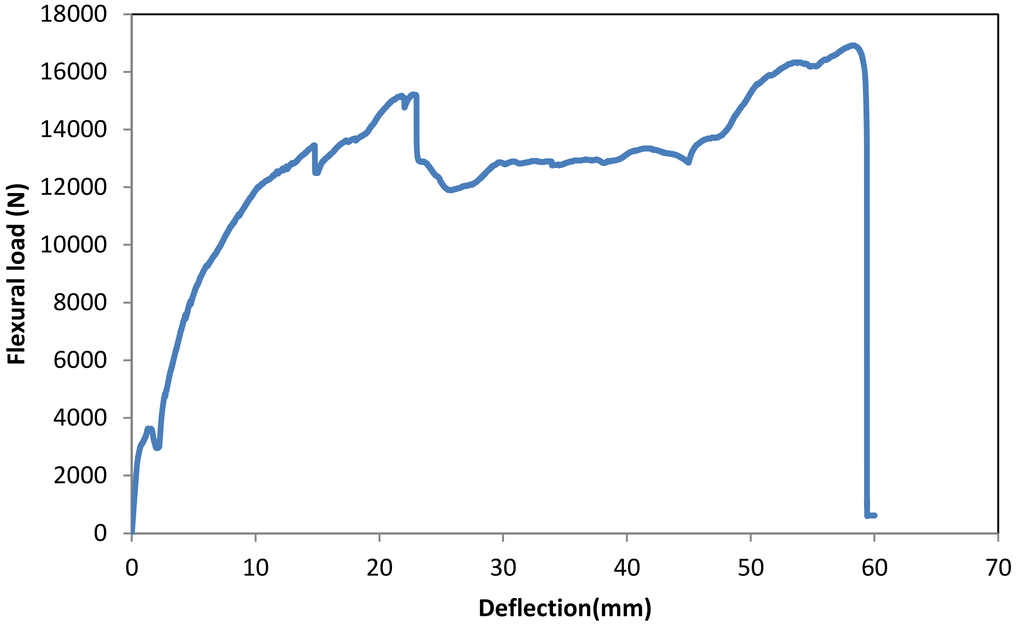


Figure 4.9 Flexural load vs.. deflection curve for 65° GFRP fiber orientation composite plastic pipe.

4.2.3 GFRP Composite Overwrapped PVC plastic pipe with 55°

In this test, the 55° GFRP fiber orientation composite plastic pipe joined used, and the results were as shown in Figure 4.10. The response of the 65° GFRP fiber orientation composite plastic pipe can be roughly allocated to three stages, just as in the case of the 90° and 65° GFRP fiber orientation composite plastic pipe. The first stage is where the specimen is exhibiting behavior that is very close to elastic, and this can be seen just at the onset of loading. At this stage, the flexural load increases to 4011 N, while the corresponding deflection is slightly below 2 mm. It is clear that in this specimen, the transition from elastic to plastic deformation is quite vague. The 4011 N point is where it is assumed beyond the point that we have plastic deformation, where it appears more clearly that the flexural load is no longer proportional to the deflection. In the plastic deformation stage, the load that keeps the process going is seen to increase to the ultimate strength level of 10933 N, with a corresponding deflection of 16 mm, at which point the loading goes to the last stage where failure takes place. In this last stage where the specimen is heading to inevitable failure, we first have a sudden drop in the flexural load to about 8200 N. Then, there is another slight increase in the load, accompanied by a deflection to the flexural load level of 9200 N with a deflection of 21 mm. There is then a further drop in flexural loading 4100 N at a deflection of 35 mm. Next, the flexural load started to increase again, passing through a constant-load period, and finally, failure occurred at a flexural load of 9000 N, with the corresponding deflection being 60 mm.

The figure shows that from the ultimate strength level, the pipe deflection increased by about 44 mm, which is a clear indication that the ultimate load the pipe was not brittle. However, with further loading, we observe the final failure occurring at a load level of 9000 N, which is an indication that at this point, the pipe exhibited brittle properties.

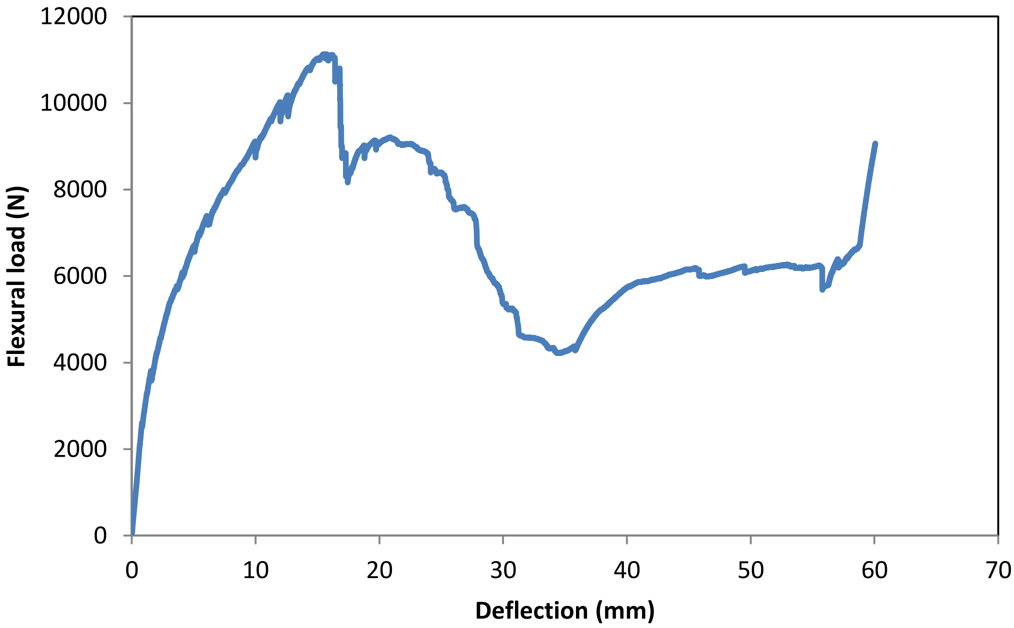


Figure 4.10 Flexural load vs.. deflection curve for 55°GFRP fiber orientation composite plastic pipe

4.2.4 GFRP Composite Overwrapped PVC Plastic Pipe with 45°

In this test, a 45° GFRP fiber orientation composite plastic pipe joined used, and the results are as shown in Figure 4.11. The response of the 45° GFRP fiber orientation composite plastic pipe corresponds to 3 stages. The first stage is where the specimen exhibits behavior that is very close to elastic, and this can be seen just at the onset of loading. At this stage, we have the flexural load increasing to 4078 N, while the corresponding deflection is at about 1 mm. The 4078-N point is where it is assumed that beyond the point, we have plastic deformation, where it can appear more clearly that the flexural load is no longer proportional to the deflection. In the plastic deformation stage, the load that keeps the process going on is seen to increase to the ultimate strength level of 16702 N with a corresponding deflection of 14 mm, at which point the loading goes to the last stage where failure takes place. From the ultimate load, the specimen undergoes deflection while the flexural load decreases to the point of failure, where the flexural load is almost zero, and the deflection is 30 mm. The figure shows that there was a continuous deflection of the pipe as it headed to failure, and indicated that at this point, the pipe exhibited plastic behavior.

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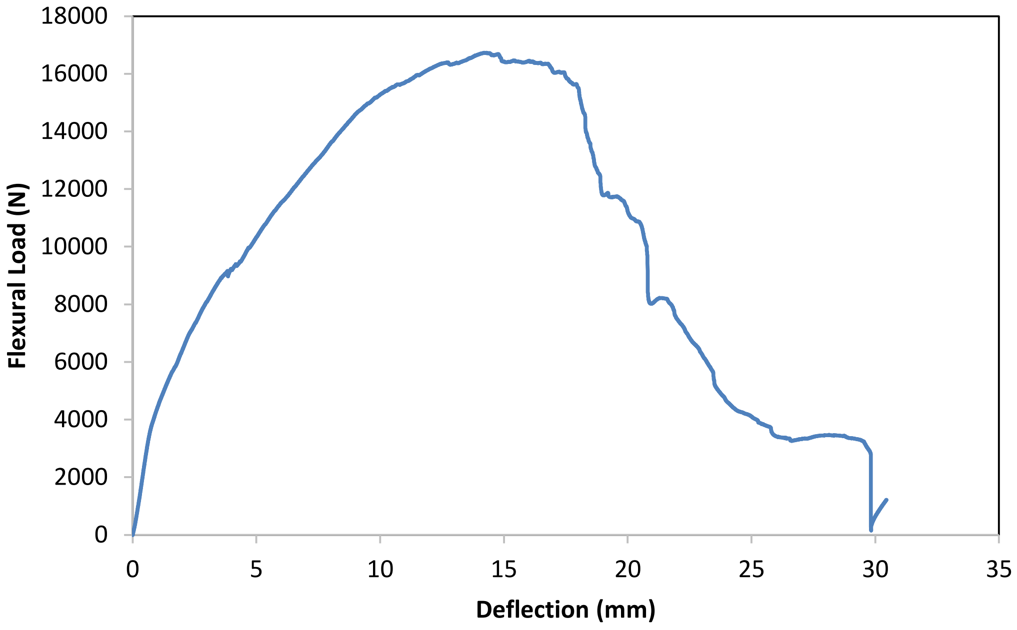


Figure 4.11 Flexural load vs.. deflection curve for 45°GFRP fiber orientation composite plastic pipe

4.2.5 Summary of the Four-Point Bending Test for Pipes with Different GFRP Fiber Orientation

The summary of the major findings of this section is shown in Figure 4.12 and Table 4.3. It can be seen that the ultimate strength that the highest ultimate strength was for the 90° GFRP fiber orientation, where the ultimate strength was 17200 N; in the second position was 45° GFRP fiber orientation and 65° GFRP fiber orientation with both having ultimate strength of 16800. The least ultimate strength was for the 55° GFRP fiber orientation with an ultimate strength of 11200 N. It was expected that the GFRP of 0º/90º orientation would register high flexural load values above that of the ±45º and ±55º and 65º orientations. This is because, at the 0º/90º orientation, it is possible to have the maximum tension loads as the uni-axial load in both tension directions in pipes subjected to bending. At ±45º, ±55º, and ±65º, as well as all other angles with the exception of 0º/90º, the shear forces will always occur in both directions of tension.

Indeed, Kim et al. (2011) reported that with respect to the strength of GFRP, the orientation is one of the three important factors, with the other two being the proportion of glass content (high glass content high strength) and the continuousness of glass filament, where possessing more continuous strength properties indicates a greater strength. As observed by Rafiee (2013), the woven glass will have superior strength than in the case where chopped glass is used.

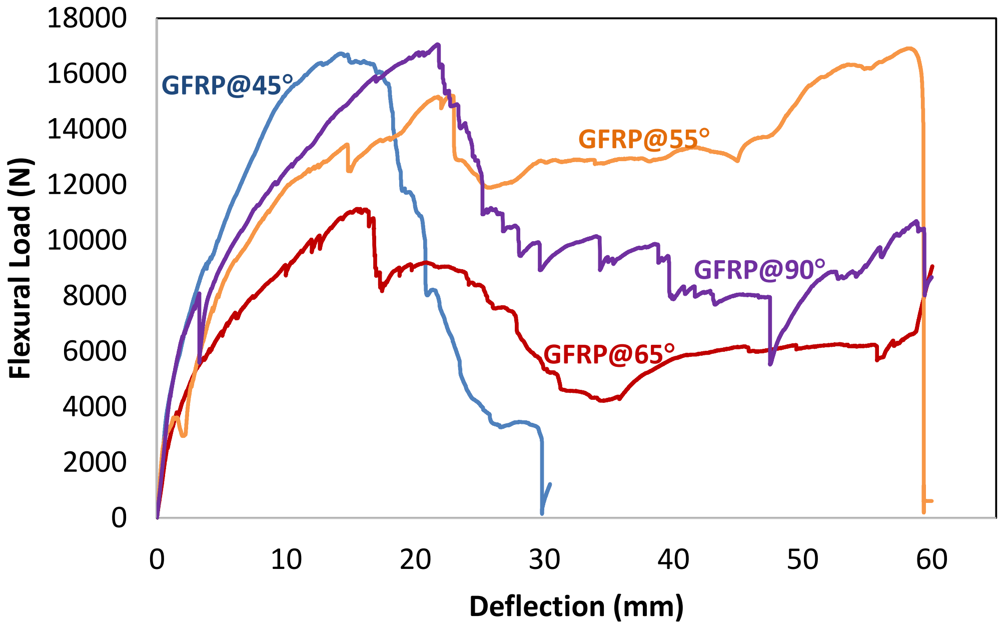


Figure 4.12 Combined curves for a four-point bending test for pipes with different GFRP fiber orientation

Table 4.2 Initial flexural failure, ultimate flexural and corresponding deflection values in test pipes

Test pipe	Initial flexural failure		Ultimate flexural	
	Load (N)	Deflection(mm)	Load (N)	Deflection(mm)
90° GFRP	8035 ± 49	3 ± 0.033	17055 ± 17	22 ± 0.067
65° GFRP	3428 ± 244	1 ± 0.187	16876 ± 47	58 ± 0.308
55° GFRP	4011 ± 45	2 ± 0.027	10933 ± 246	16 ± 0.305
45° GFRP	4078 ± 107	1 ± 0.039	16702 ± 26	14 ± 0.148

(a) (b) (c) (d)

Figure 4.13 (a) GFRP overlapped plastic pipes with 90° (b) GFRP overlapped plastic pipes with 65° (c) GFRP overlapped plastic pipes with 55° (d) GFRP overlapped plastic pipes with 45°

4.3 Effect of Pipe Diameter on the Bending Behavior of PVC Plastic Pipes

In this section, the four-point bending test results for different pipes are presented, analyzed, and discussed. The tested pipes are 25 mm, 50 mm, and 100 mm plastic pipes, and also GFRP composite plastic pipes with one layer of fiber, with a length of 400 mm and a 55-degree orientation. The pipes include three plastic pipes and three single layers of GFRP fiber at a 55-degree orientation, with diameters of 25, 50, and 100 mm. The results of the unwrapped PVC plastic pipe with a 25-mm diameter have been discussed earlier in Section 4.1. Therefore, only the results for the 50- and 100-mm plastic pipes will be discussed in detail in the following section.

4.3.1 Unwrapped PVC Plastic Pipes with 50-mm Diameter

Figure 4.14 shows the results obtained when the 50-mm plastic pipe is subjected to flexural loading. From the figure, it can be seen that there was an approximately linear relationship between the flexural load and deflection till 800, with the deflection at this point being 11 mm. The normal high flexural load due to the material reality since PVC has very low material reality. Beyond the flexural load of 800 N, it can be seen that the curve is nonlinear, which is an indication that the rate of deflection increased, with the initial maximum point being obtained with a flexural load of 1180 N and with a corresponding deflection of 30 mm. The flexural load then dropped to about 880 N for a deflection of 43 mm. The flexural load increased to the ultimate limit of 17600 N, with a corresponding deflection of 60 mm, at which point we have a failure.

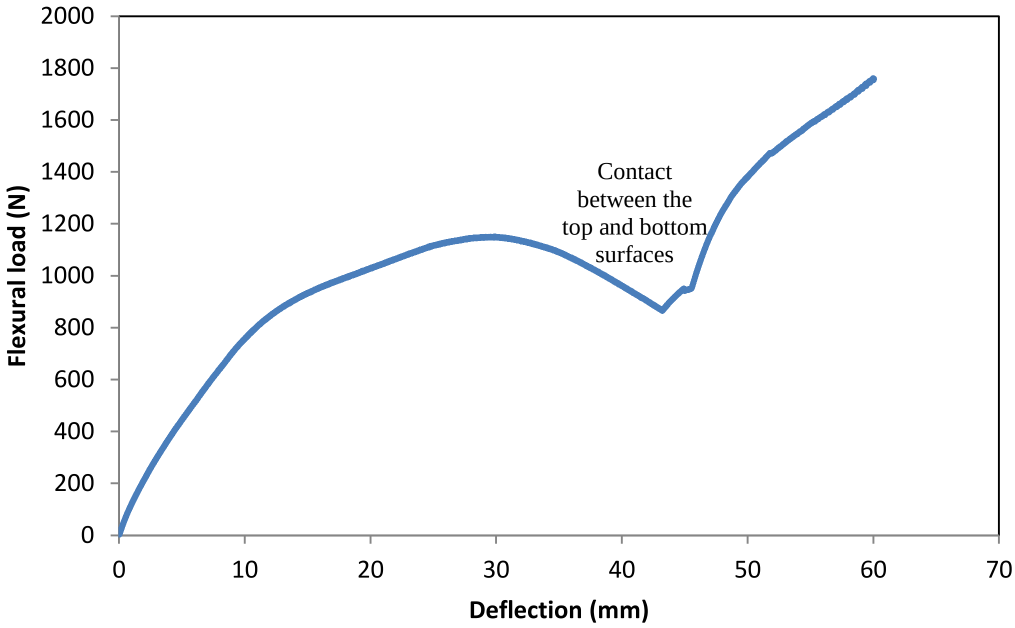


Figure 4. 14 Flexural loads vs.. deflection curve for 50-mm-diameter plastic pipe.

Figure 4.15 Undeformed and deformed unwrapped 50mm PVC plastic pipe under a four-point bending test.(a) undeformed pipe (b) deformed

4.3.2 Unwrapped PVC Plastic Pipes with 100-mm Diameter

Figure 4.16 shows the results obtained when the 100-mm plastic pipe was subjected to flexural loading. From the figure, it can be seen that there was a steady increase in the deflection as the load was increased, with the relationship between the flexural load and deflection being very close to linear from the start of loading to the point when the specimen pipe reached the ultimate strength of about 1017 N, with a deflection at which point was 83 mm. From the figure, the initial failure was realized at a flexural load of about 200 N, where the deflection was approximately 11 mm. From the peak flexural load, there was an increase in deflection as the flexural load was reduced. Finally, the pipe failed at a deflection of 120 mm, with the flexural reading at this point is 520N.

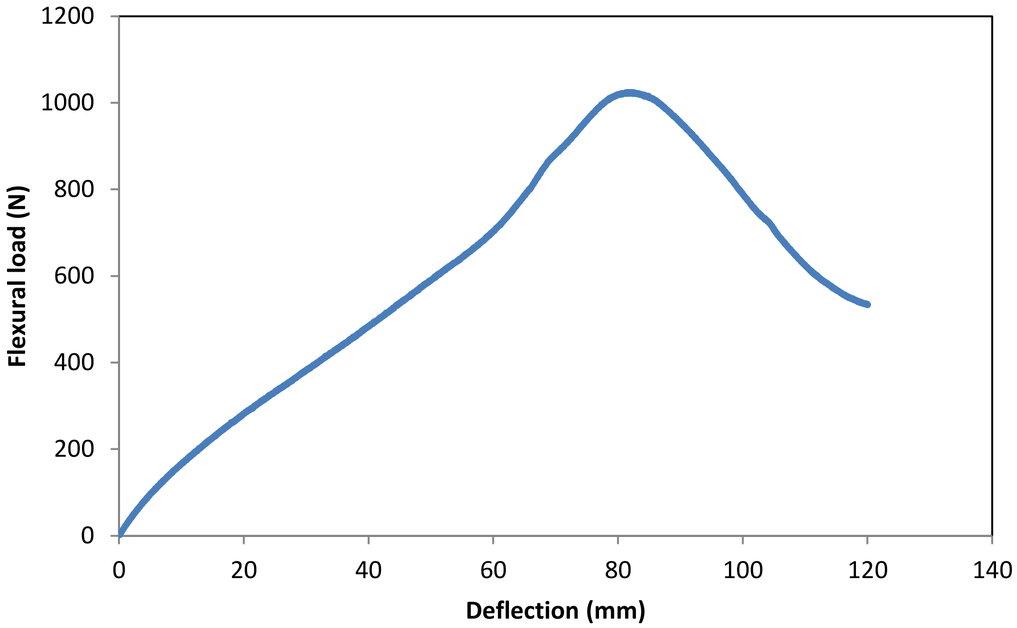
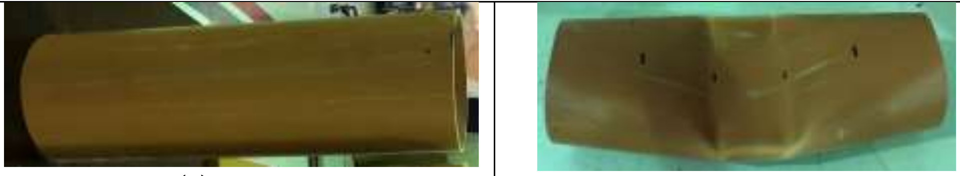


Figure 4.16 Flexural load vs.. deflection curve for 100-mm-diameter plastic pipe.



(a)

(b)

Figure 4.17 Undeformed and deformed unwrapped 100mm PVC plastic pipe under a four-point bending test.(a) undeformed pipe (b) deformed

4.4 Effect of Pipe Diameter on the Bending Behavior of GFRP Composite Overwrapped PVC Plastic Pipes

4.4.1 GFRP Composite Overwrapped PVC Plastic Pipe 50-mm Diameter

Figure 4.18 shows the results obtained when the GFRP composite plastic 50-mm pipe is subjected to flexural loading. From the figure, it can be seen that there is an approximately linear relationship between the flexural load and deflection up to the point when the flexural load was 1034 N, with the corresponding deflection being 1.69 mm. Beyond the flexural load of 1034 N, it can be seen that the curve is flatter, which as an indication that the rate of deflection has increased, with the initial maximum point being with a flexural load of 4600 N and a corresponding deflection of 30 mm. The flexural load then drops to about 3200 N at a deflection of about 45 mm. Then, the flexural load increased rapidly due to the contact between the upper and bottom surface of the pipe, which reached the ultimate limit of 7800 N with a corresponding deflection of 60 mm, at which point we have a failure. The cracks started to occur in both the tension and compression surfaces, as shown in Figures 4.20 and 4.21, respectively. The flexural load is 1000N. The matrix starts to crack with a vertical deflection of 2 mm. The pipe continued to deflect until it reached its maximum capacity of 7800 N with a 60-mm deflection. As shown in Figures 4.20 and 4.21, the fiber breakage occurred as a result of the cracking that occurred during the test. One of the major results is that the breaking outcome continuous decreasing of the pipe load-carrying capacity.

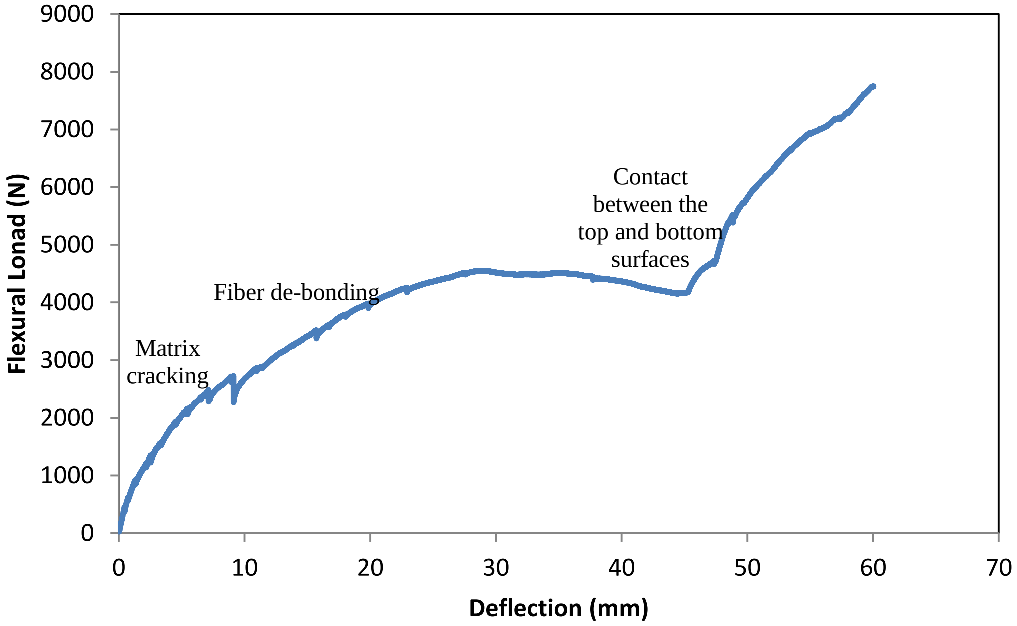


Figure 4.18 Flexural load vs.. deflection curve for GFRP composite 50-mm-diameter PVC plastic pipe 50-mm diameter.

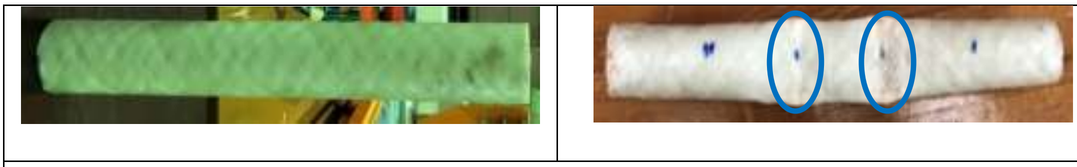
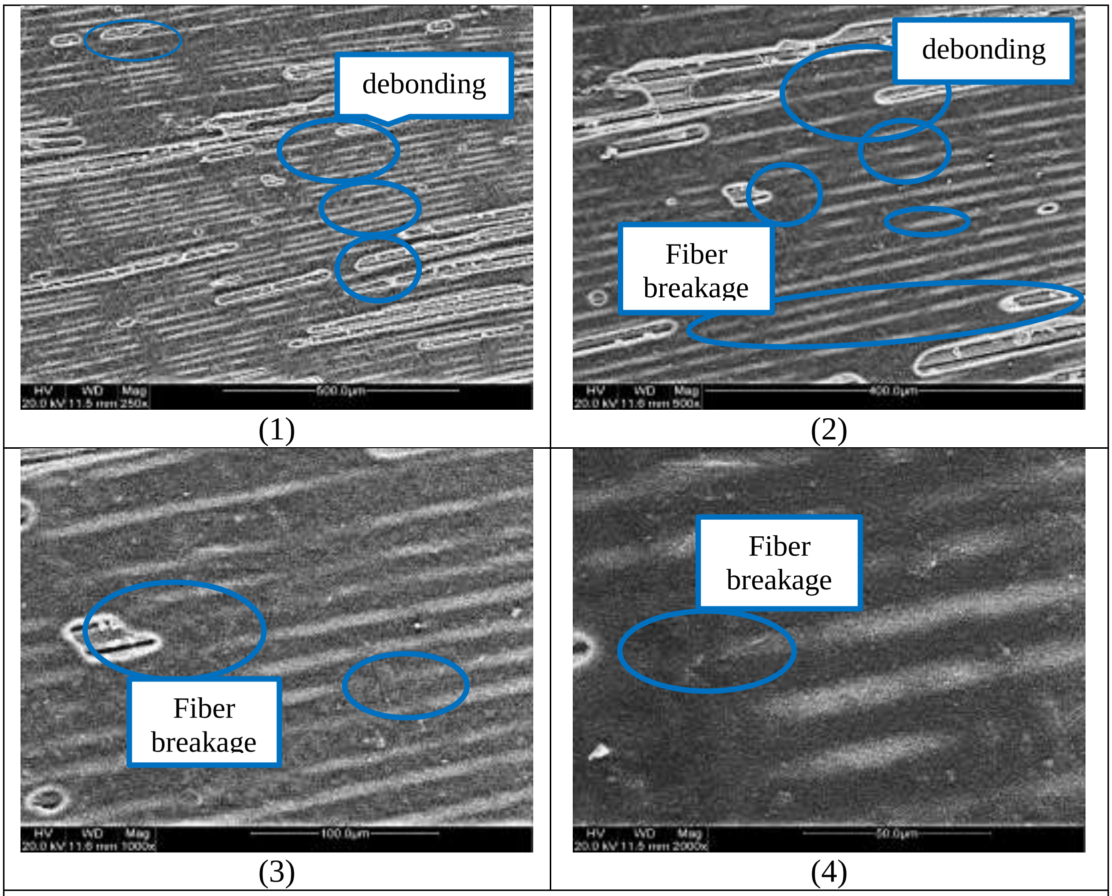
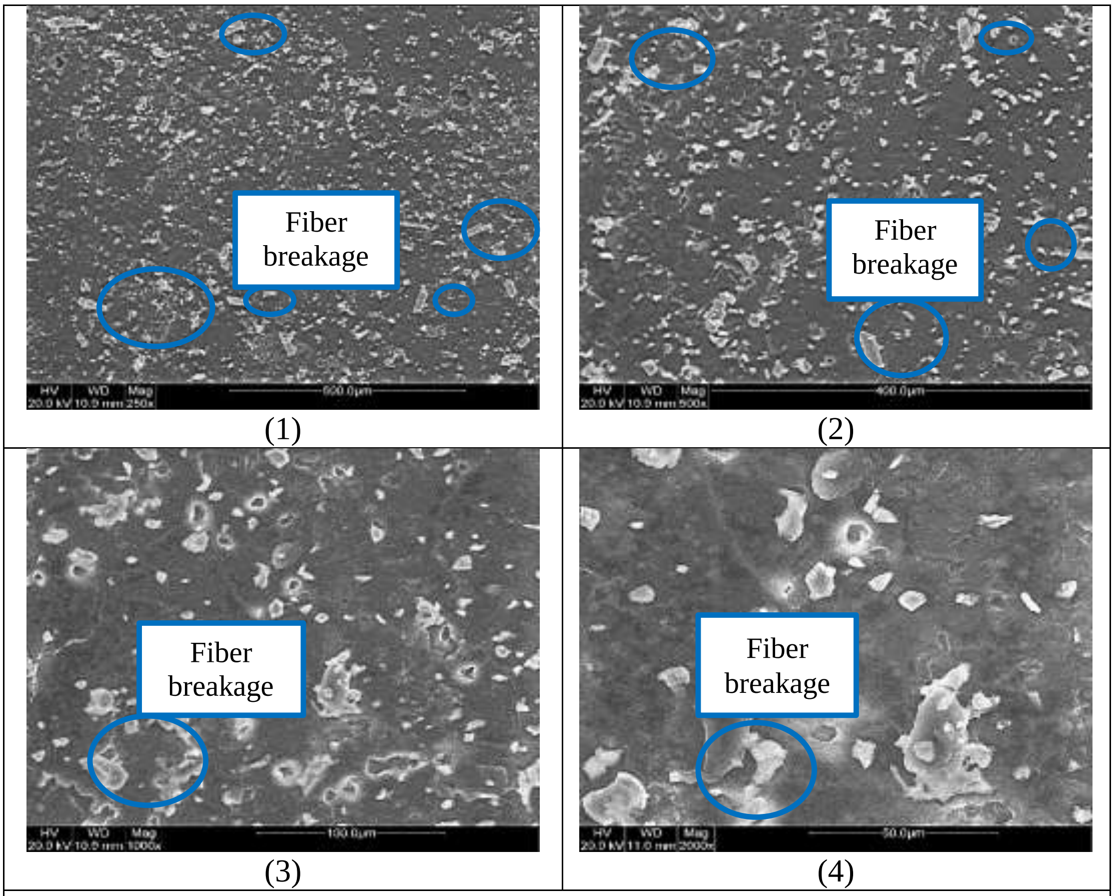


Figure 4.19 Overwrapped GFRP composite 50mm PVC plastic pipe under a four-point bending test. (a) undeformed pipe (b) deformed pipe with matrix cracking on the load contact point.



(1) (2) (3) (4)

Figure 4.20 SEM of the fractured specimen, which is taken from the surface that experienced tension.



(1) (2)

(3) (4)

Figure 4.21 SEM of the fractured specimen, which is taken from the surface that experienced compression.

4.4.2 GFRP Composite Overwrapped 100-mm-Diameter PVC Plastic Pipe

Figure 4.22 shows the results obtained when the 100-mm plastic pipe was subjected to flexural loading. The flexural bending behavior was seen to have three stages. In the first stage, we have the test pipe, which exhibits behavior that is very close to elastic, where the variation between the load and deflection is linear, and the flexural load at the initial failure is 1200 N with a corresponding deflection of 13.2 mm. After the first stage, we have the second stage, where it can be seen there was an increased rate of deflection compared to the first stage. The change in the behavior exhibited in the specimen from elastic to plastic was gradual. At this second stage, the flexural load kept increasing non linearly due to the matrix cracking and depending happening during the test. Moreover, the flexural load increased to the first peak level, where the fiber breakage occurs at a load of 3700 N, with a corresponding deflection of about 80 mm. After the ultimate stage of loading, the failure stage set in, where the load decreased steadily as the specimen deflected, and the top surface contacted with the bottom surface and then culminated to failure where the flexural load was 3200 N and the deflection was 120 mm. As experienced from the other tests, the load for the 100-mm pipe diameter will increase after the 120mm deflection where it reached the contact surface at 100mm deflection, and the pipe flexural load capacity started to increase again. Figures 4.24 and 4.25 present the tension and compressing matrix cracking. This begins to appear at a flexural load of 1400 N, with a 1-mm deflection. The pipe experienced cracks in four areas owing to the tensile stress at the outermost bottom surface. This leads to a reduction in the pipe load-carrying capacity.

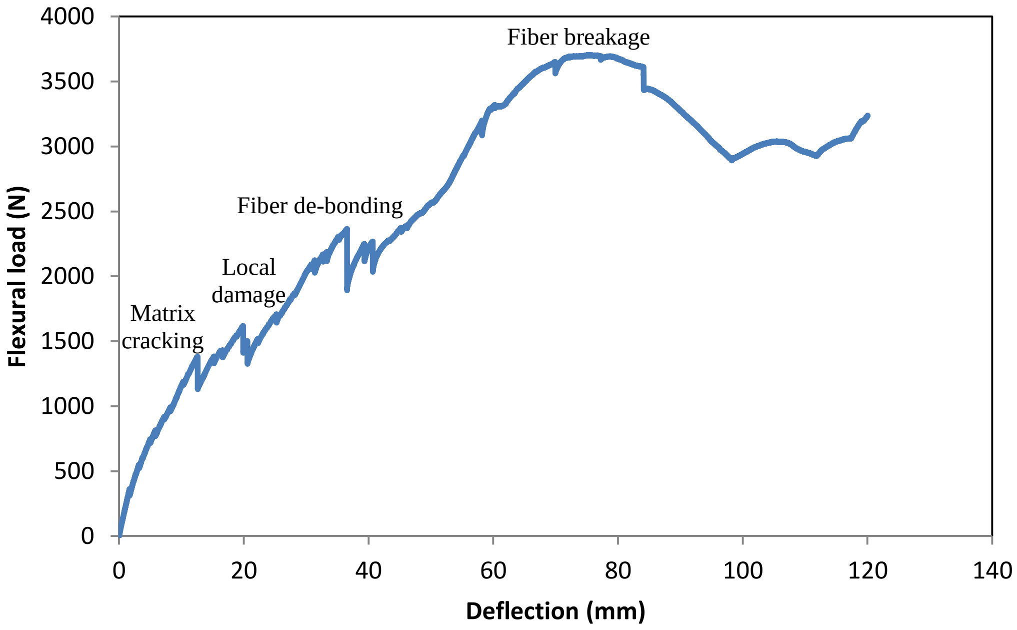


Figure 4.22 Flexural load vs.. deflection curve for 100-mm-diameter GFRP composite PVC plastic pipe.

Figure 4.23 Overwrapped GFRP composite 100mm PVC plastic pipe under a four-point bending test. (a) undeformed pipe (b) deformed pipe with matrix cracking on the load contact point

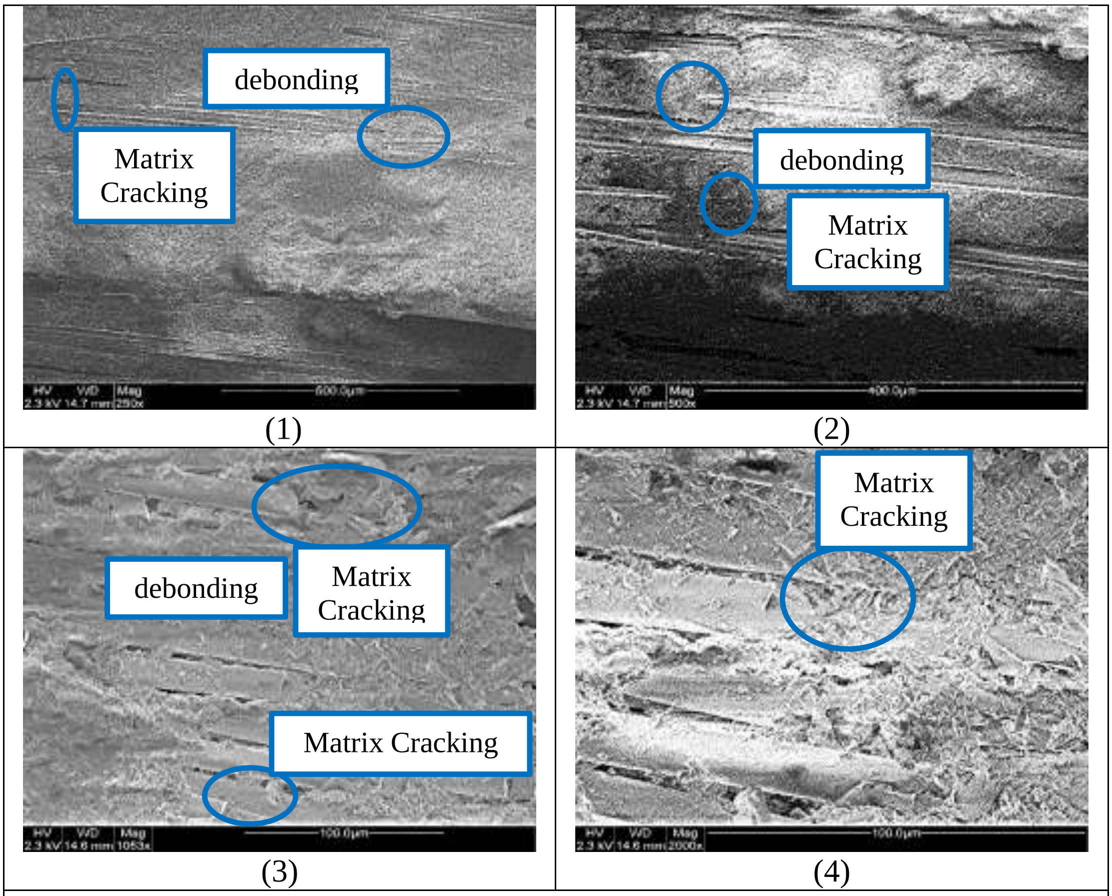
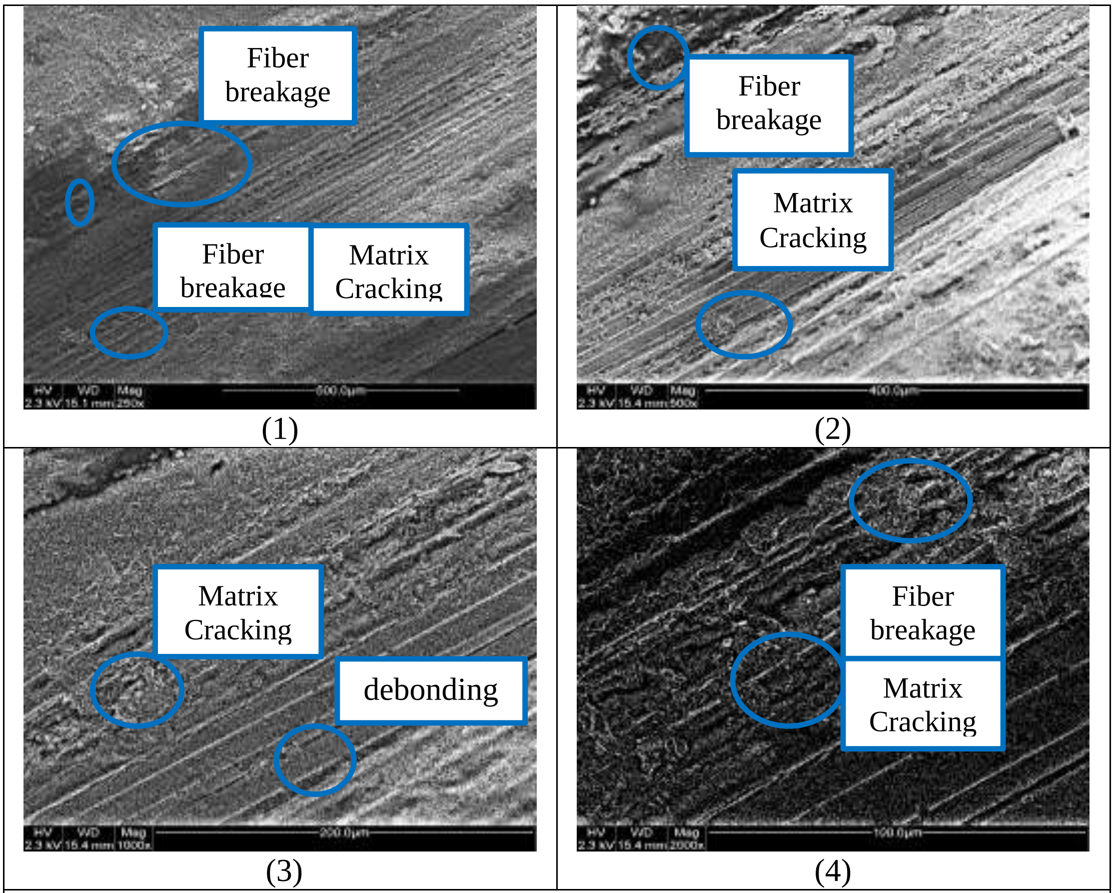


Figure 4.24 SEM of the fractured specimen, which is taken from the surface that experienced tension.



(1) (2)

(3) (4)

Figure 4.25 SEM of the fractured specimen, which is taken from the surface that experienced compression.

4.5 Summary of the Four-Point Bending Test

The summary of the major finding of this section is shown in Table 4.2 and Figure 4.26. The elastic load and their corresponding deflection, then the ultimate flexural load with the corresponding deflection too. It can be seen that the maximum deflection at the failure point was the same in four of the pipes at 60 mm. With respect to the ultimate strength, it clearly shows that the GFRP composite plastic pipes generally had higher strength, as can be seen from the figure. In the GFRP pipes, the highest strength was 7800 N in the GFRP 50-mm pipe; the next highest strength was the GFRP 25-mm pipe, with an ultimate strength of 4800 N, while GFRP 100 mm had a strength of 3700 N. The corresponding deflection at the ultimate strength was 60, 38, and 80 mm, respectively.

However, for the plastic pipes, the highest ultimate strength recorded was 1760 N for the 50 mm pipe, followed by the 100 mm pipe with an ultimate strength of 1000 N, while the 25 mm pipe had the least ultimate strength of 522 N. The corresponding deflections at the ultimate strength of the pipes were 60 mm, 83 mm, and 48 mm, respectively. The strength of the GFRP is one of the characteristics that cause the material to find several applications. As observed in the literature, the material is usually employed as a primary structural element that supports the profile of a structure (Hussain, Pandurangadu, & Kumar, 2011). This result is a clear manifestation that the GFRP pipe can serve as a primary structural element. This means that with their high strength, the GFRP pipes used in the supply of water can cross over barriers such as railways over rivers supported on columns a considerable distance apart. It is also observed that GFRP is applied in the construction of facades, which shows the strength of the material. In addition to the strength, the weight comes into play when GFRP is the material of choice for pipes in that GFRP pipes are lighter, which reduces the cost of construction.

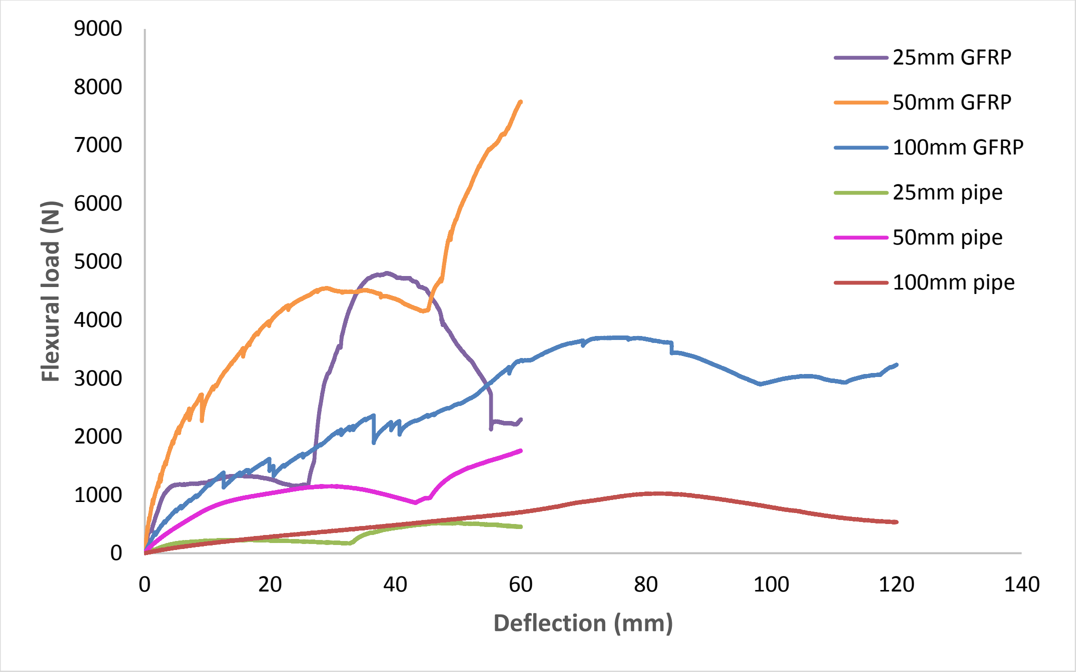


Figure 4.26 Summary of flexural load vs. Deflection

Table 4. 3 Initial Failure, ultimate load and corresponding deflection values in test pipes

	Initial Failure (N)	**Deflection (mm)**	**Ultimate Failure (N)**	**Deflection (mm)**
Unwrapped PVC plastic pipe				
25mm pipe	64 ± 0.798	1.21 ± 0.001	516 ± 3.5	50 ± 1.849
50mm pipe	800 ± 4.600	11 ± 0.090	17600 ± 28.9	60 ± 0.044
100mm pipe	200 ± 12.752	11 ± 0.018	1017 ± 1.07	83 ± 0.140
GFRP composite overwrapped PVC plastic pipe				
GFRP 25mm pipe	1140 ± 6.722	4.07 ± 0.015	4800 ± 70	38 ± 2.118
GFRP 50mm pipe	1034 ± 0.969	1.69 ± 0.002	7800 ± 33	60 ± 0.012
GFRP 100mm pipe	1200 ± 7.2	13.2 ± 0.070	3700 ± 96	80 ± 0.493

4.6 Performance of GFRP Composite Pipes under Internal Pressure Test

In this section, the internal pressure test results for unwrapped PVC plastic pipes and GFRP composites overwrapped plastic pipes are presented and discussed in detail. Accordingly, three plastic pipes with the same length of 200 mm and three different diameters are internally pressurized until they burst, and were used as a control. To examine the effect of GFRP composites overwrapped on the internal pressure capacity of PVC plastic pipes, plastic pipes with different diameters that were wound with three GFRP layers at 55° were employed unsuccessfully. However, the test failed because the end closure experienced buckling. Finally, plastic pipes wound with one GFRP layer at 55° were successfully employed because the pipes experienced burst failure without any observation for end closure buckling failure. Two pressure tests conducted for unwrapped and wrapped PVC plastic pipe.

4.6.1 Unwrapped PVC Plastic Pipe with 25-mm Diameter

When the 25-mm plastic pipe was subjected to internal pressure, the result was as represented in Figure 4.27. From the figure, it can be seen that there increase in pressure with respect to time this because the pipe is full of oil and started to get pressurized. The pressure kept increasing nonlinear increase till it reached the peak pressure of 7 bar breakage appears, and the drop in pressure occurred.

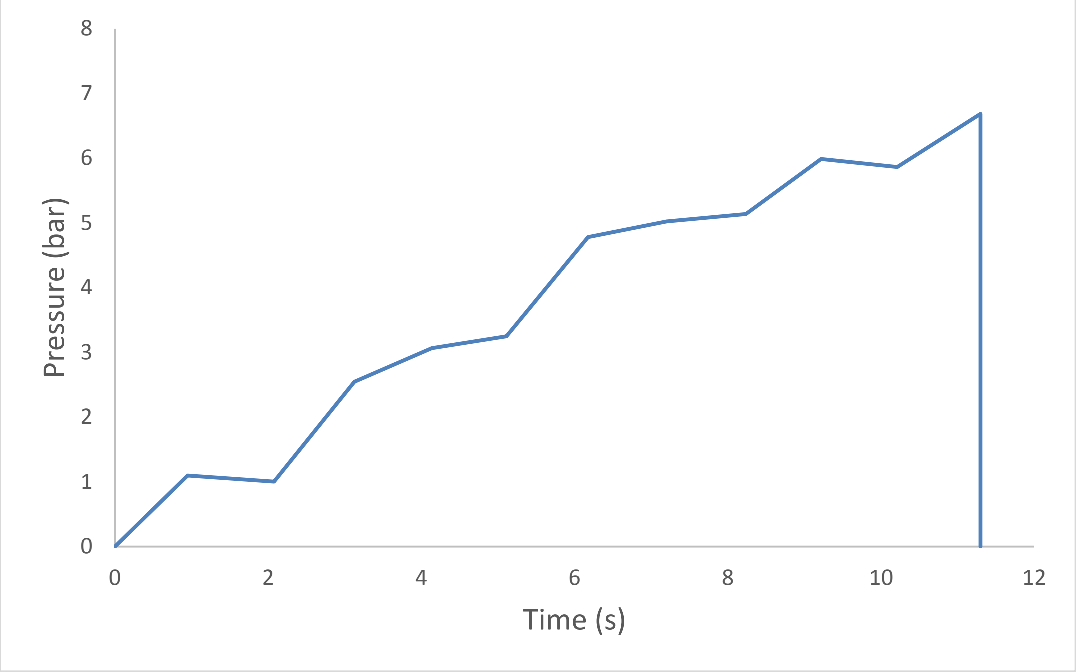


Figure 4.27 Pressure vs. time curve for plastic pipe with 25-mm diameter.

4.6.2 Unwrapped PVC Plastic Pipe with 50-mm Diameter

The pressure test result when the 50-mm diameter pipe was subjected to the pressure test is as shown in Figure 4.28. From the figure, it can be seen that there was a very small increase in the pressure from zero seconds up to about 1 s. the slight increase for one second just to ensure there is no leak. After 1 s, there was a sharp increase in the pressure up to a maximum of 42.2 bar at 3.8 s. The pressure then started to decrease until it reached almost 0 bar gradually.

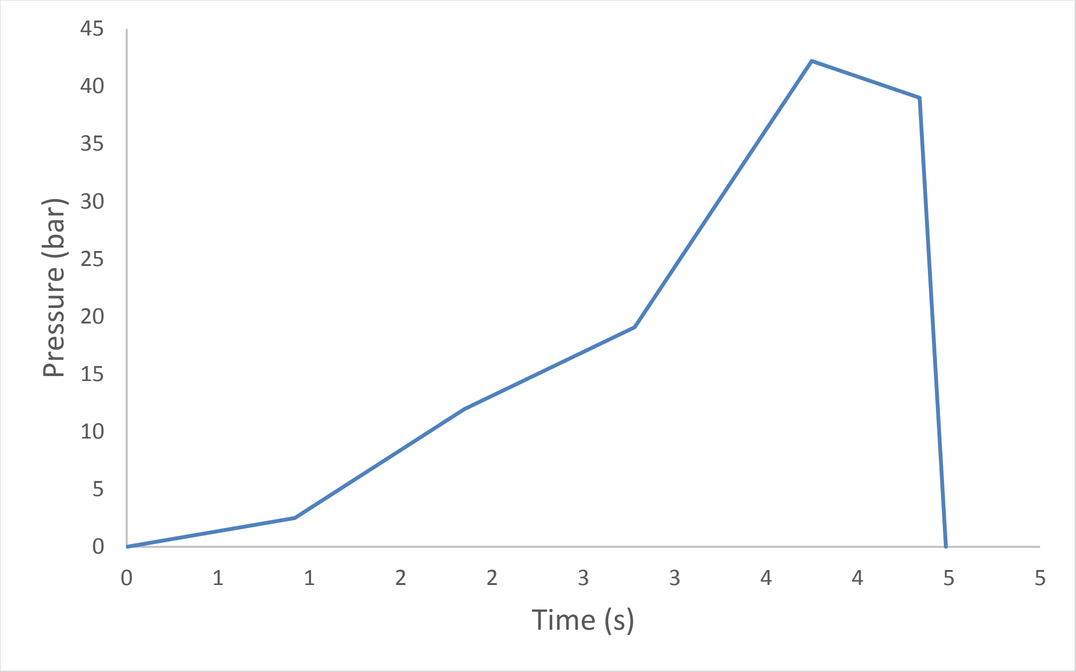


Figure 4.28 Pressure vs. time curve for plastic pipe with 50-mm diameter.

4.6.3 Unwrapped PVC Plastic pipe with 100-mm diameter

When the 100-mm plastic pipe was subjected to internal pressure, the result was as represented in Figure 4.29. From the figure, it can be seen that there was a sharp increase in pressure from zero seconds up to about 1 s, where the pressure had risen to 3.7 bar. Within this 1 s, the pipe has observed to start experience burst. It noticed as the pipe size increases, the internal pressure capacity decrease.

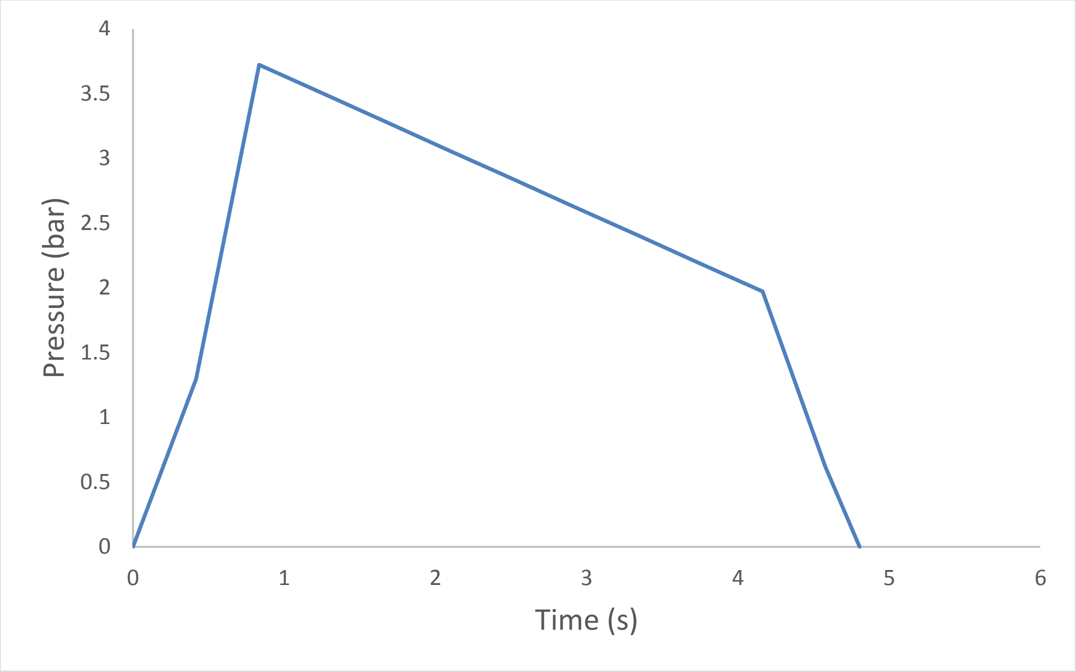


Figure 4.29 Pressure vs. time curve for plastic pipe with 100-mm diameter.

4.6.4 GFRP Composite Overwrapped 25-mm-Diameter Plastic PVC Pipe

The results when the 25-mm GFRP composite plastic pipe was subjected to internal pressure was shown in Figure 4.30. From the figure, it can be seen that there was an almost steady increase in pressure for around 1.5 s, and it had risen to the maximum level of 250 bar from 0 bar after 15.2 s. After the 15.2 s, the pressure then started to drop sharply, and it was recorded to be 221 bar at the 16 s mark. Electronic microscope Figure 4.32 and Figure 4.33 shows the fiber breakage in the destroyed specimen due to the high pressure applied.

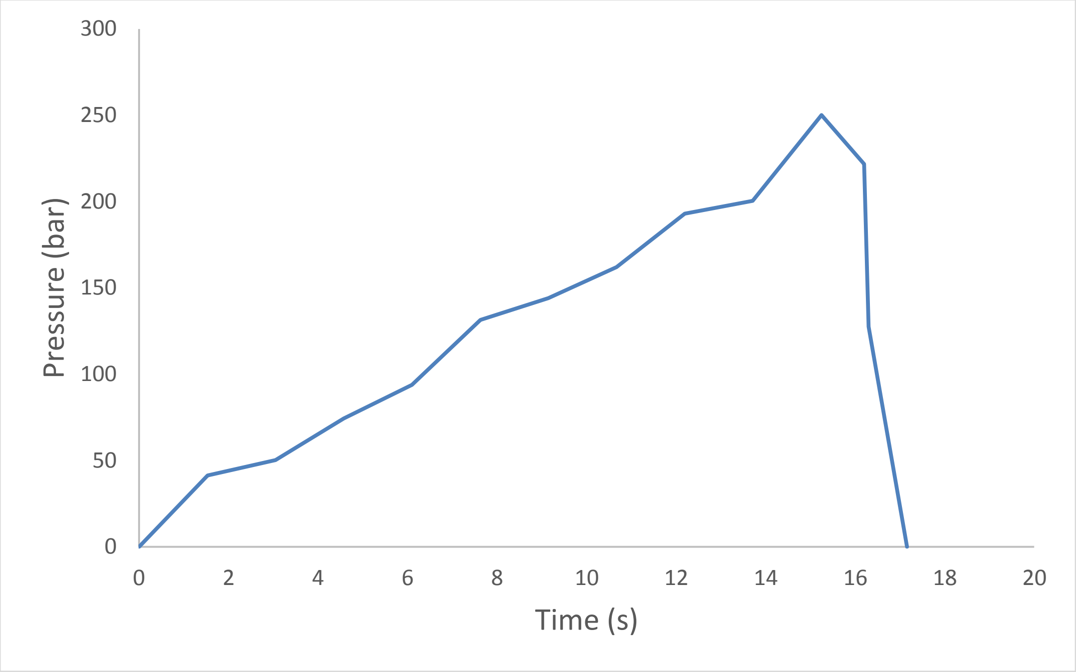
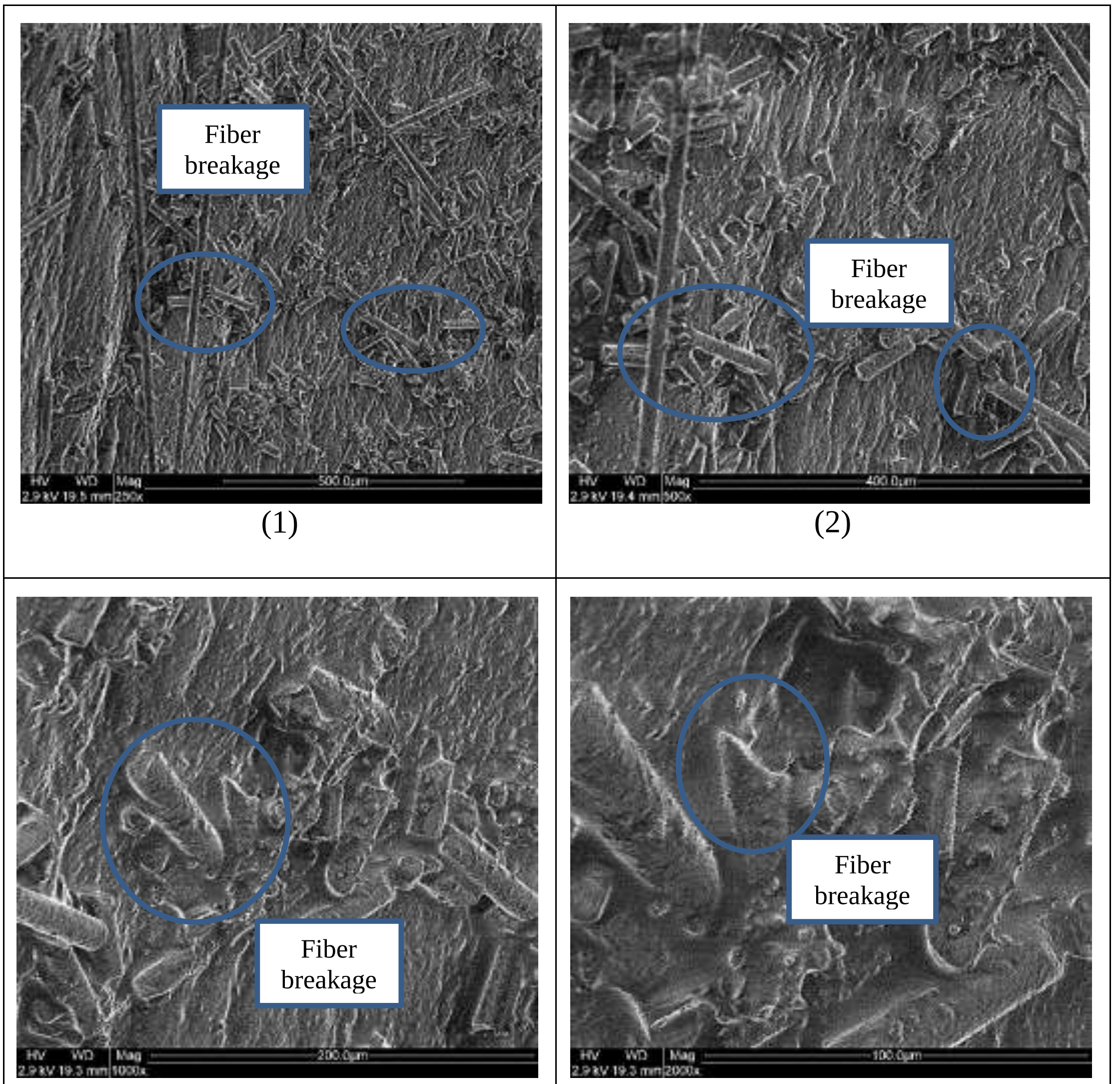


Figure 4.30 Pressure vs. time curve of internally pressurized GFRP composite overwrapped PVC plastic pipe with 25-mm diameter.

Figure 4.31 Deformed of internally pressurized GFRP Composite overwrapped PVC plastic pipe with 25mm.



(1) (2)

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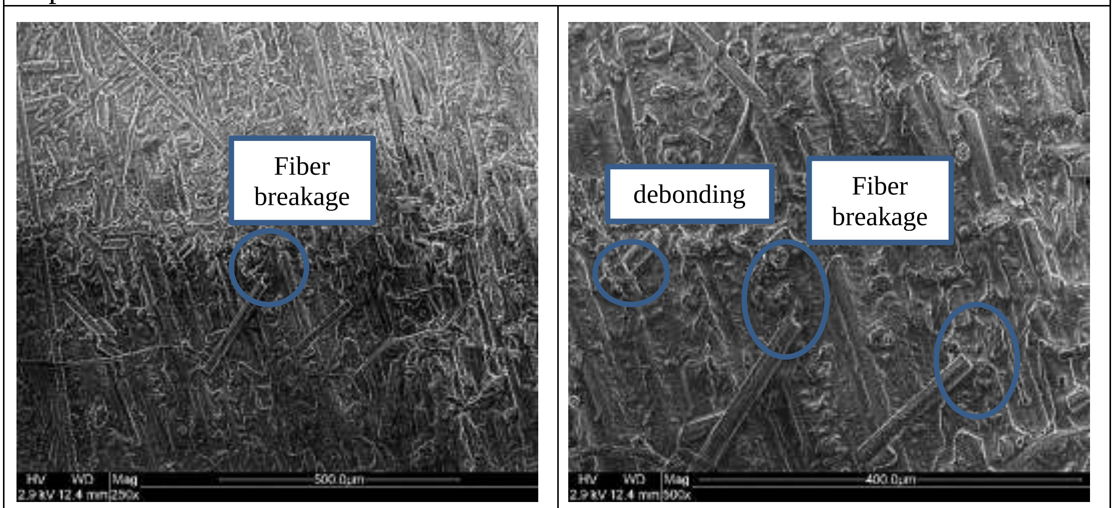
Figure 4.32 SEM of the fractured specimen, which is taken from the surface that experienced tension.



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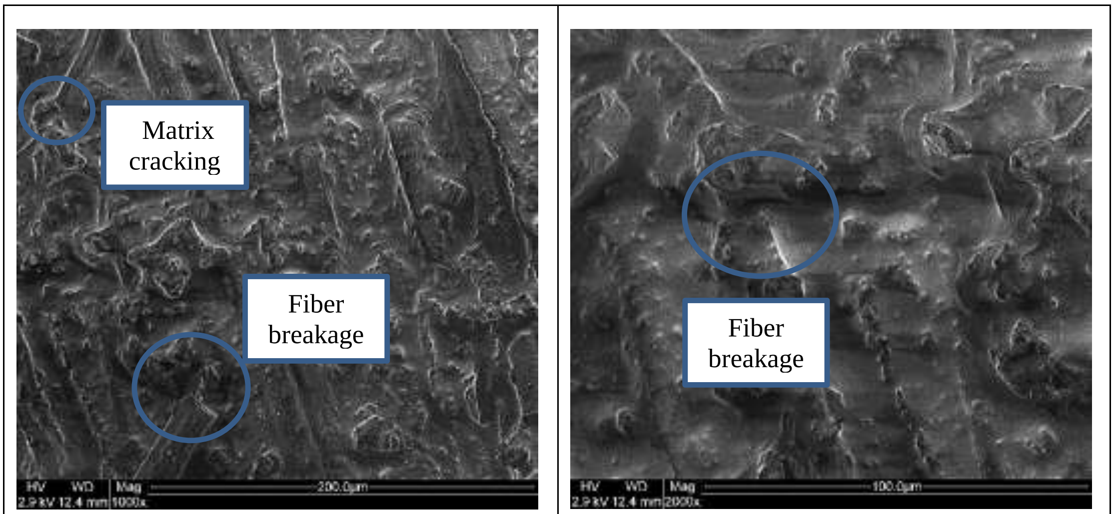


(3) (4)

Figure 4.33 SEM of the fractured specimen, which is taken from the surface that experienced compression.

4.6.5 GFRP Composite Overwrapped 50-mm-Diameter PVC Plastic Pipe

When the 50-mm GFRP composite plastic pipe was subjected to internal pressure, the result was as shown in Figure 4.34. The figure shows that there was first a gradual increase to 12.3 bar from 0 bar after 7.3 s. After 7.3 s, there was a sharp increase in pressure up to a maximum of 155.5 bar after 12.6 s. The sharp increase due to the glass fiber polymers became under tension in which the strength increase and required more pressure to burst the pipe. After bursting at 155.5 bar, the pressure then started to drop sharply. Figure 4.36 and Figure 4.37 shows the fiber breakage and debonding that occurred due to the high pressure applied.

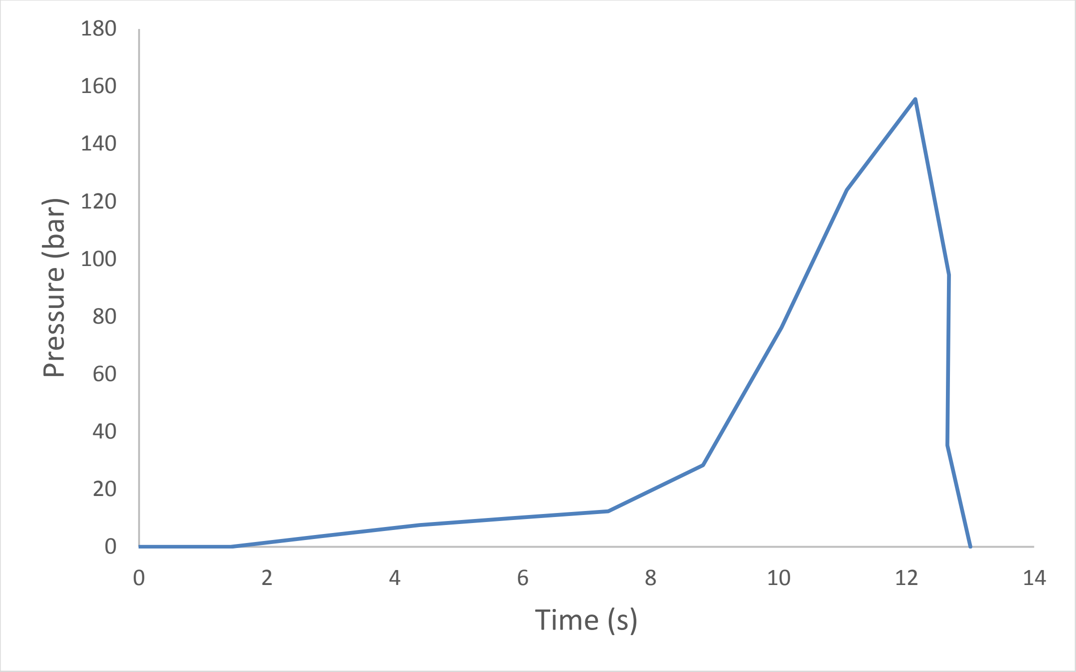


Figure 4.34 Pressure vs. time curve of internally pressurized GFRP composite overwrapped PVC plastic pipe with 50-mm diameter.

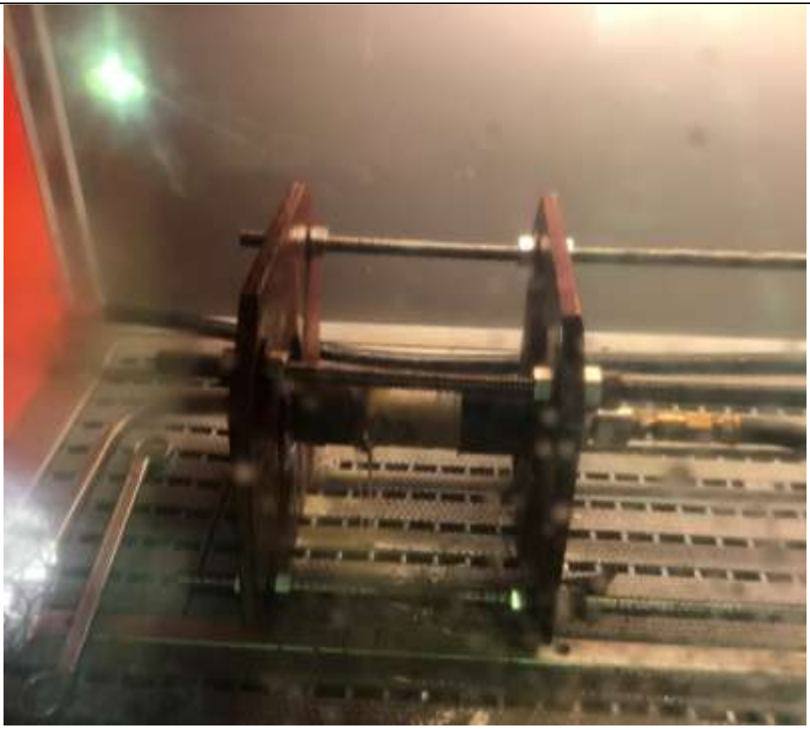
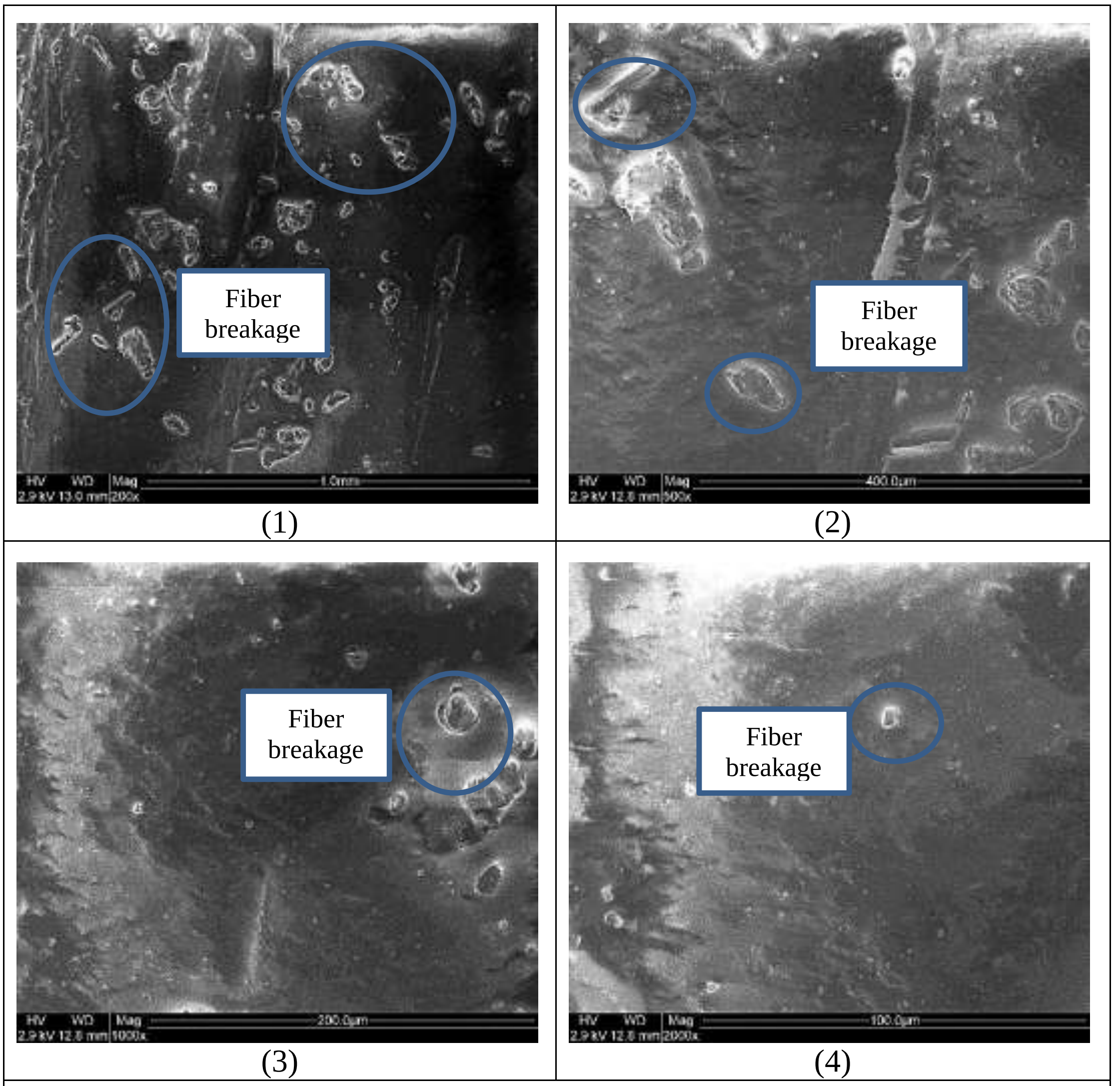


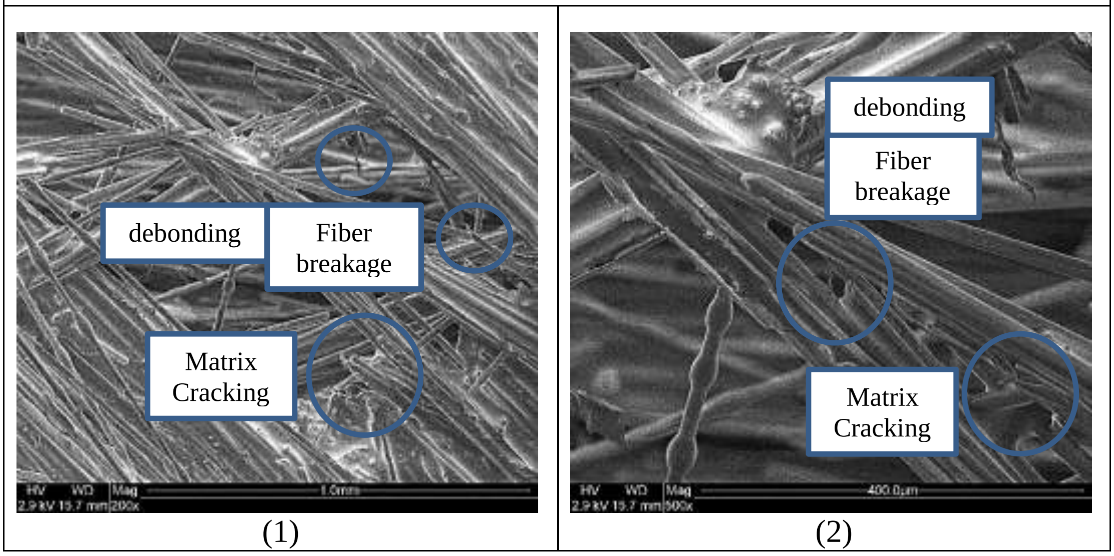
Figure 4.35 Deformed of internally pressurized GFRP Composite overwrapped PVC plastic pipe with 50mm.



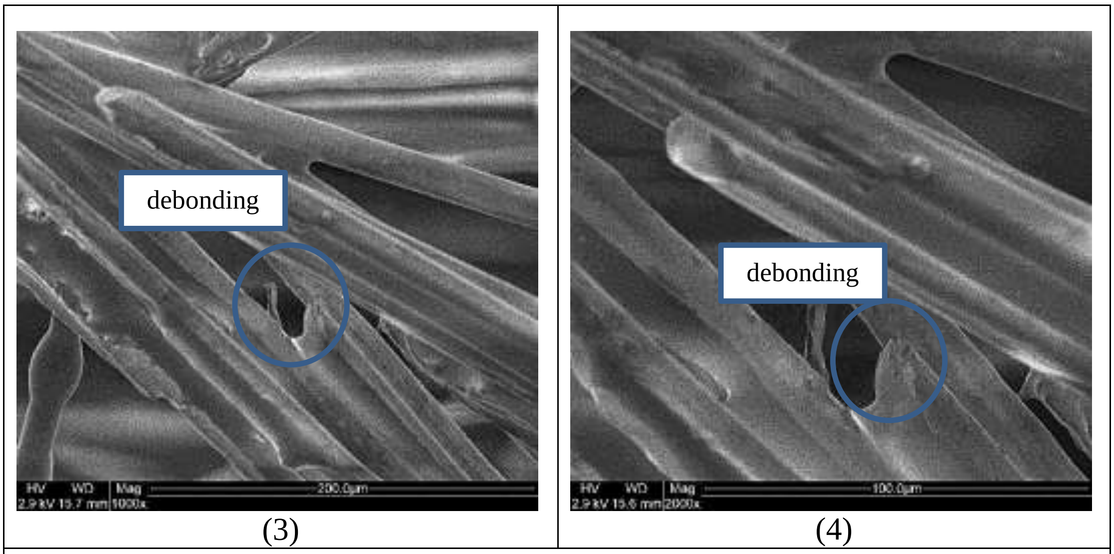
(1) (2)

(3) (4)

Figure 4.36 SEM of the fractured specimen, which is taken from the surface that experienced tension.



(1) (2)



(3) (4)

Figure 4.37 SEM of the fractured specimen, which is taken from the surface that experienced compression.

4.6.6 GFRP Composite Overwrapped 100-mm-Diameter PVC Plastic Pipe

When the 100-mm GFRP composite plastic pipe was subjected to internal pressure, the result was as shown in Figure 4.38. From the figure, it can be seen that there was an increase from 0 bar to a maximum pressure of 80 bar within 9 s. After 9 s, the pressure started to drop sharply. Having a sharp decrease in big diameters due to the heavy oil leakage after the burst of the pipe. Figure 4.40 and Figure 4.41, respectively represent the cracking and fiber pullout that occurred after the pipe explosion. In Figure 4.41, the scanning electron microscope (SEM) images show fiber breakage.

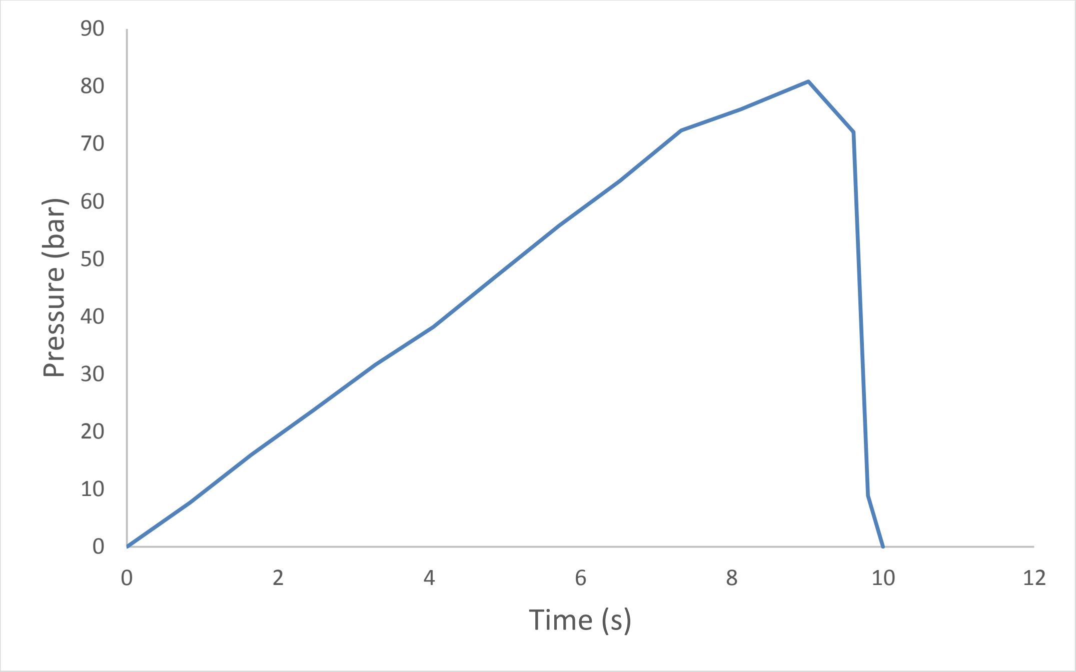


Figure 4. 38 Pressure vs. time curve of internally pressurized GFRP composite overwrapped PVC plastic pipe with 100-mm diameter.

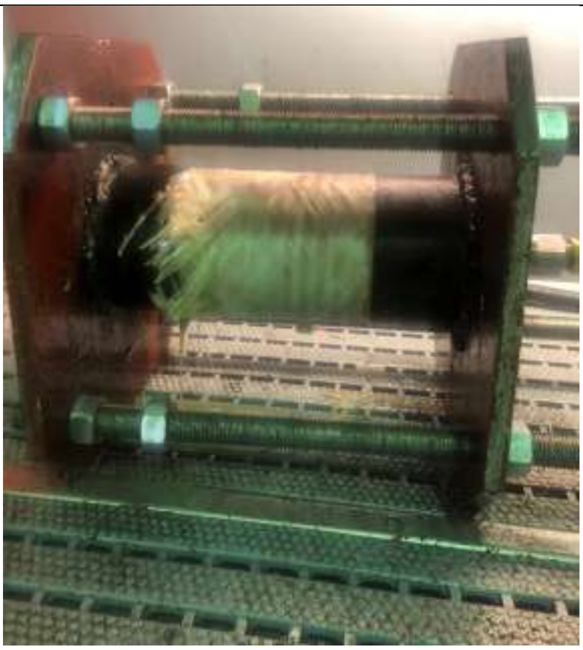
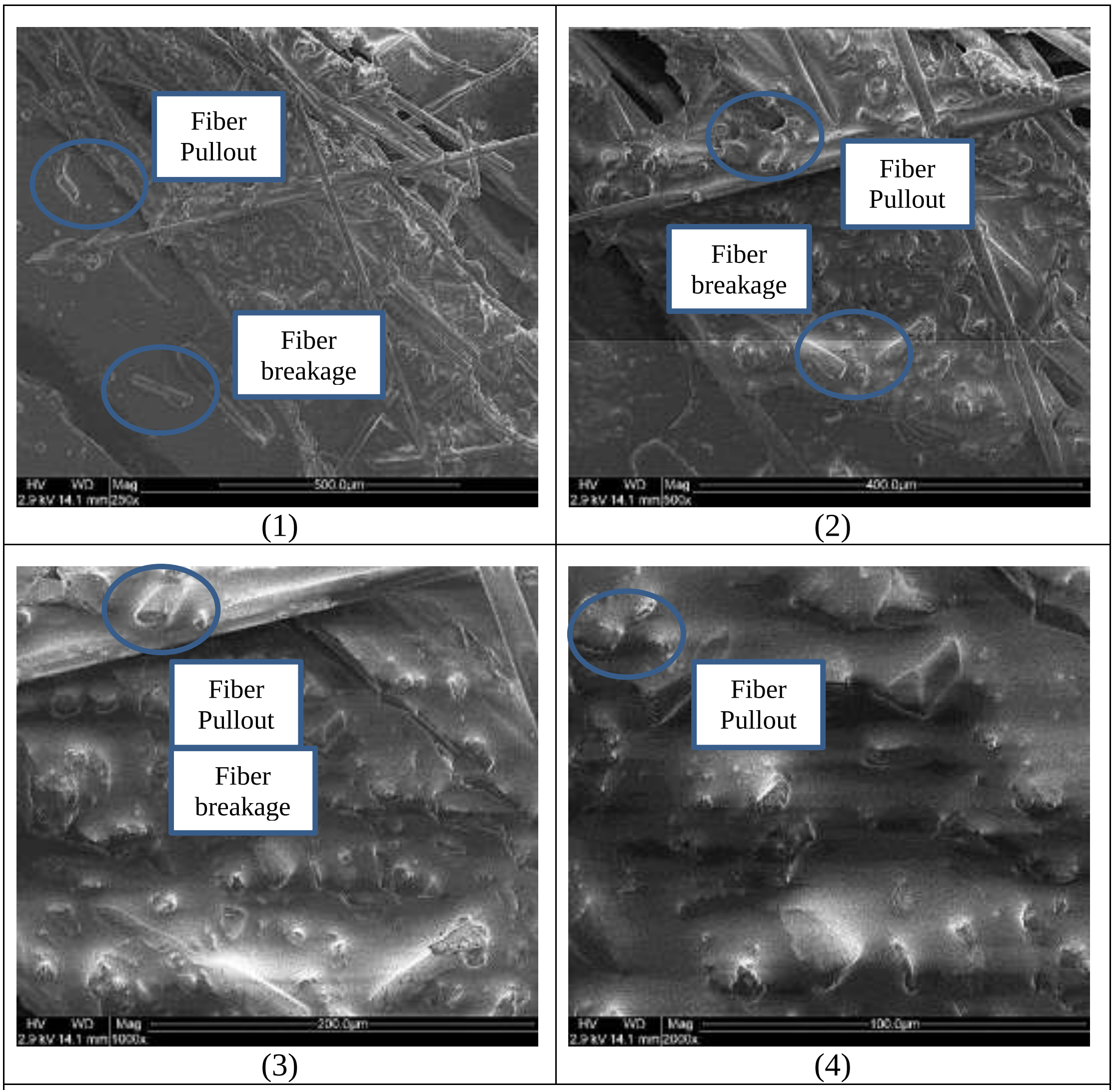


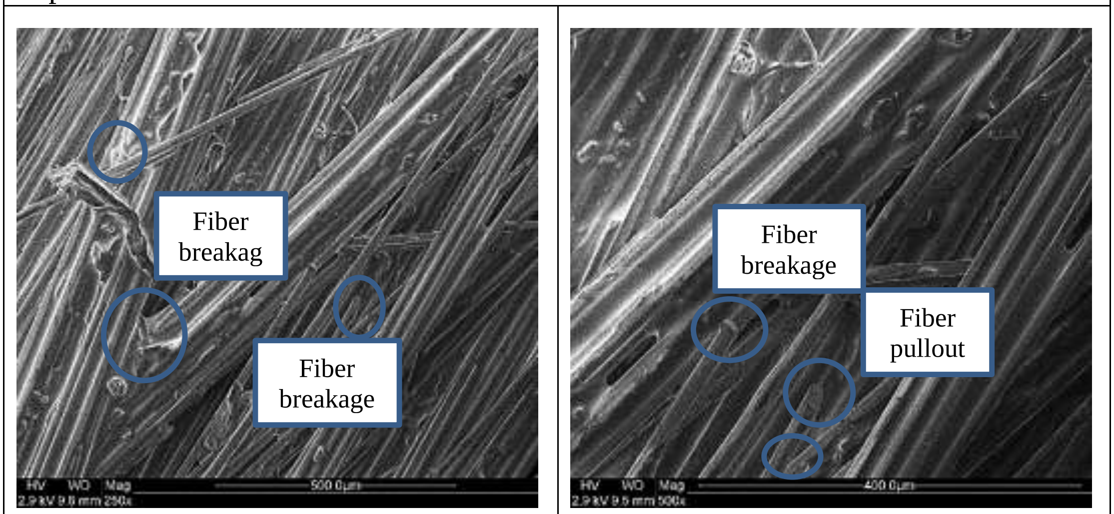
Figure 4.39 Deformed of internally pressurized GFRP Composite overwrapped PVC plastic pipe with 100mm.



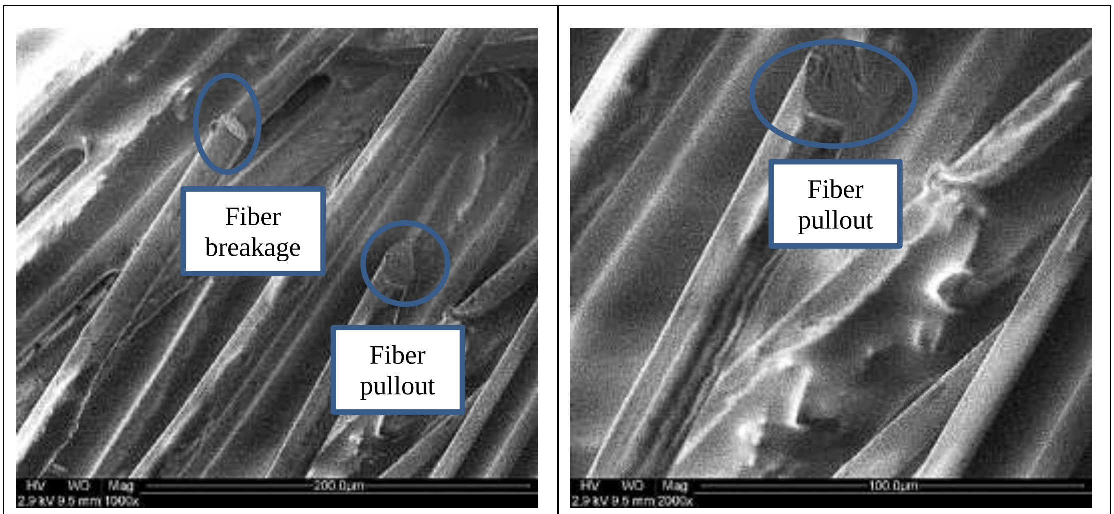
(1) (2)

(3) (4)

Figure 4.40 SEM of the fractured specimen, which is taken from the surface that experienced tension.



(1) (2)



(3) (4)

Figure 4.41 SEM of the fractured specimen, which is taken from the surface that experienced compression.

4.6.7 Comparison of Results in all Pipes

Figure 4.20 shows the variation of the internal pressure with time at their respective maximum levels. From the figure, it can be seen clearly that the GFRP is able to sustain a much higher internal pressure before failing. From Figure 4.20, it can be seen that the response of 25-mm GFRP to pressure was the fastest, and it reached the highest pressure point compared to the others. The filter reaching the peak GFRP took the shortest time to fail. When compared with the others, the 100-mm plastic pipe can be seen to have had a very low peak, after which it failed. The peaks for 50-mm GFRP and 100-mm GFRP were reached at almost the same time between 9s to 12s. Figure 4.20 shows the maximum internal pressure attained for each pipe before failure. It can be seen that a higher diameter is associated with low-pressure failure. This observation was recorded for both types of tubes (i.e., unwrapped and wrapped PVC pipes). This is because the pressure that can be sustained by a pipe is inversely proportional to the internal diameter of the pipe, as can be seen in equation

$$P = \frac{2t\sigma}{d} \qquad \text{Equation 4. 1}$$

where

P: pressure
t: pipe thickness
σ: stress in the pipe
d: pipe diameter.

The introduction of extra layers on all the pipes means that the thickness will be increased by the same margin in all of the pipes, but for a smaller diameter increase in the thickness, there is a greater implication with regard to the increasing pressure. This is because of the ratio t/d, which is the proportion by which the pressure to failure will increase.

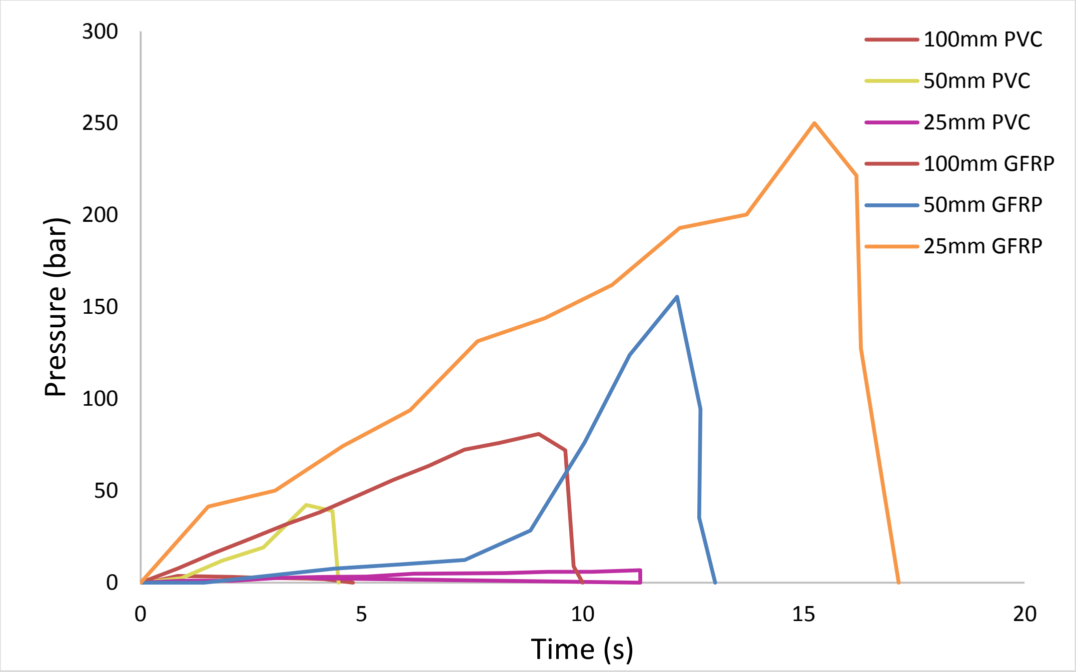


Figure 4.42 Pressure vs. time curves of internally pressurized GFRP composite overwrapped and unwrapped PVC plastic pipe with different diameters.

4.7 Summary

The results of the experimental program for unwrapped PVC plastic pipe and glass fiber composite overwrapped plastic pipe subjected to the internal pressure, and a four-point bending test has been presented and discussed in detail. Tests were performed for three pipes with different diameters for each type of unwrapped PVC plastic pipe and glass fiber overwrapped plastic pipe. The bending behavior for four fiber orientation angles was examined. The results showed that the introduction of the overwrapped system significantly improved flexural capability.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

1. The use of GFRP composite overwrapped PVC plastic pipes resulted in a significant improvement of flexural carrying capacity compared to unwrapped PVC plastic pipes.
2. GFRP composite overwrapped PVC with a fiber orientation of 90º demonstrated the highest flexural load carrying capacity.
3. GFRP composite overwrapped PVC plastic pipes with a large diameter showed the highest ultimate flexural load compared to other diameters.
4. The effect of one layer of GFRP on the load-carrying capacity was found to be significant compared to unwrapped pipes, the significant found to be more than 10 times.
5. The GFRP composite overwrapped PVC plastic pipes were found to sustain much higher than unwrapped PVC plastic pipes.
6. The smallest diameter 25-mm GFRP composite overwrapped PVC plastic pipe was found to be the fastest, reaching the highest pressure point of all the other overwrapped pipes.
7. GFRP composite overwrapped PVC plastic pipe as far as the pipe with a bigger diameter the peak reached almost at the same time.
8. It was observed that the introduction of extra layers on all the pipes caused the thickness to be increased by the same margin in all the pipes, but for a smaller

diameter, the increase in thickness had a greater implication with respect to increasing pressure.

5.2 Recommendations for Future Work

1. The need to study the effect of different types of thermosetting resin on the GFRP composite overwrapped PVC plastic pipe.
2. To test the manufactured GFRP composite overwrapped PVC plastic pipe’s performance under different operating conditions, such as high temperature.
3. Examine the fatigue behavior of GFRP composite overwrapped PVC plastic pipe.
4. Develop an FE model to simulate the flexural behavior, and the internally pressurized GFRP composite overwrapped PVC plastic pipe.
5. Investigate the effect of hybrid composite overwrapped systems on the performance of PVC plastic pipe.
6. Explore the effect of the stacking sequence on the mechanical behavior of GFRP composite overwrapped PVC plastic pipe.
7. Perform impact test analysis on the GFRP composite overwrapped PVC plastic pipe.

REFERENCES

Sathishkumar, T. P., Satheeshkumar, S. & Naveen, J. (2014). Glass fiber-reinforced polymer composites–a review. *Journal of Reinforced Plastics and Composites*, *33*(13), 1258-1275.

Abdul Majid, M. S., Afendi, M., Daud, R., Gibson, A. G., Assaleh, T. A., Hale, J. M. & Hekman, M. (2015). Acoustic emission monitoring of multiaxial ultimate elastic wall stress tests of glass fiber-reinforced epoxy composite pipes. *Advanced Composite Materials*, *24*(1), 1-16.

Alexopoulos, N. D., Bartholome, C., Poulin, P. & Marioli-Riga, Z. (2010). Structural health monitoring of glass fiber-reinforced composites using embedded carbon nanotube (CNT) fibers. *Composites Science and Technology*, *70*(2), 260-271.

Arikan, H. (2010). Failure analysis of (±55) 3 filament wound composite pipes with an inclined surface crack under static internal pressure. *Composite Structures*, *92*(1), 182-187.

ASTM International. (2019). Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe (CIPP). DOI:10.1520/f2019

Bai, J. (Ed.). (2013). *Advanced fiber-reinforced polymer (FRP) composites for structural applications*. Elsevier.

Belarbi, A. & Wang, H. (2011). Bond durability of FRP bars embedded in fiber-reinforced concrete. *Journal of Composites for Construction*, *16*(4), 371-380.

Carmisciano, S., De Rosa, I. M., Sarasini, F., Tamburrano, A. & Valente, M. (2011). Basalt woven fiber-reinforced vinylester composites: Flexural and electrical properties. *Materials & Design*, *32*(1), 337-342.

Davis, P., Melo, L. S., Foxton, R. M., Sherriff, M., Pilecki, P., Mannocci, F. & Watson, T. F. (2010). Flexural strength of glass fiber-reinforced posts bonded to dual- cure composite resin cements. *European journal of oral sciences*, *118*(2), 197-201.

Deogonda, P. & Chalwa, V. N. (2013). Mechanical property of glass fiber reinforcement epoxy composites. *International Journal of Scientific Engineering and Research (IJSER)*, *1*(4), 2347-3878.

Devendra, K. & Rangaswamy, T. (2013). Strength characterization of E-glass fiber-reinforced epoxy composites with filler materials. *Journal of minerals and materials characterization and engineering*, *1*(06), 353.

Dhand, V., Mittal, G., Rhee, K. Y., Park, S. J. & Hui, D. (2015). A short review on basalt fiber-reinforced polymer composites. *Composites Part B: Engineering*, *73*, 166-180.

Diniz Melo, J. D., Levy Neto, F., de Araujo Barros, G. & de Almeida Mesquita, F. N. (2011). Mechanical behavior of GRP pressure pipes with addition of quartz sand filler. *Journal of Composite Materials*, *45*(6), 717-726.

Emiroğlu, M., Beycioğlu, A. & Yildiz, S. (2012). ANFIS and statistical based approach to prediction the peak pressure load of concrete pipes, including glass fiber. *Expert Systems with Applications*, *39*(3), 2877-2883.

Eslami, S., Honarbakhsh-Raouf, A. & Eslami, S. (2015). Effects of moisture absorption on degradation of E-glass fiber-reinforced Vinyl Ester composite pipes and modelling of transient moisture diffusion using finite element analysis. *Corrosion Science, 90*, 168-175.

F. R. Jones. (2010). A review of interphase formation and design in fiber-reinforced composites," J. Adhes. Sci. Technol., vol. 24, no. 1, pp. 171–202.

Fradelou, G. (2013). Research on the development of a" Glass Fiber-reinforced Polyester"(GRP) facade with integrated operable GRP window frames.

Garoushi, S., Säilynoja, E., Vallittu, P. K. & Lassila, L. (2013). Physical properties and depth of cure of a new short fiber-reinforced composite. *Dental Materials*, *29*(8), 835-841.

Ghanbari, A., Fred, F. F. & Rieke, H. H. (2011). Newly developed friction factor correlation for pipe flow and flow assurance. *Journal of Chemical Engineering and Materials Science*, *2*(6), 83-86.

Guedes, R. M., Sá, A. & Faria, H. (2010). On the prediction of long- term creep-failure of GRP pipes in aqueous environment. *Polymer Composites*, *31*(6), 1047-1055.

Hawa, A., Majid, M. A., Afendi, M., Marzuki, H. F. A., Amin, N. A. M., Mat, F. & Gibson, A. G. (2016). Burst strength and impact behavior of hydrothermally aged glass fibre/epoxy composite pipes. *Materials & Design*, *89*, 455-464.

Hoa, S. V. (2017). *Analysis for Design of Fiber-reinforced Plastic Vessels*. Routledge.

Hussain, S. A., Pandurangadu, V. & Kumar, K. P. (2011). Machinability of glass fiber-reinforced plastic (GFRP) composite materials. *International Journal of Engineering, Science and Technology*, *3*(4).

I. Baran, K. Cinar, N. Ersoy, R. Akkerman, and J. H. Hattel. (2016). A review on the mechanical modeling of composite manufacturing processes", Archives of Computational Methods in Engineering, pp. 1-31.

ISO. (2017). Glass reinforcedd thermosetting plastic (GRP) pipes. Determination of initial specific ring stiffness using segment test species cut from a pipe. DOI:10.3403/30210544u

Jain, R. & Lee, L. (Eds.). (2012). *Fiber-reinforced polymer (FRP) composites for infrastructure applications: focusing on innovation, technology implementation, and sustainability*. Springer Science & Business Media.

Keshavamurthy, Y. C., Sharma, D. R. S. & Kulkarni, D. R. (2012). Investigation of Tensile Properties of Fiber-reinforced Angle Ply laminated composites. *International Journal of Emerging Technology and Advanced Engineering*, *2*(4).

Kim, M. J., Jung, W. C., Oh, S., Hattori, M., Yoshinari, M., Kawada, E. & Bae, J. M. (2011). Flexural properties of three kinds of experimental fiber-reinforced composite posts. *Dental materials journal, 30*(1), 38-44.

R.-C. Zhuang, T. Burghardt, and E. Mäder. (2011). Study on interfacial adhesion strength of single glass fibre/polypropylene model composites by altering the nature of the surface of sized glass fibres," Compos. Sci. Technol., vol. 70, no. 10, pp. 1523–1529.

Rafiee, R. (2013). Experimental and theoretical investigations on the failure of filament wound GRP pipes. *Composites Part B: Engineering*, *45*(1), 257-267.

Rafiq, A., Merah, N., Boukhili, R. & Al-Qadhi, M. (2017). Impact resistance of hybrid glass-fiber-reinforced epoxy/nanoclay composite. *Polymer Testing*, *57*, 1-11.

Rodriguez, E. S., Alvarez, V. A. & Montemartini, P. E. (2013). Failure analysis of a GFRP pipe for oil transport. *Engineering Failure Analysis, 28,* 16-24.

S. Feih, E. Boiocchi, G. Mathys, Z. Mathys, A. G. Gibson, and A. P. Mouritz. (2011).Mechanical properties of thermally-treated and recycled glass fibres," Composites Part B, vol. 42, no. 3, pp. 350–8.

S. Rudzinski, L. Häussler, C. Harnisch, E. Mäder, and G. Heinrich.(2011).Glass fibre reinforced polyamide composites: Thermal behavior of sizings," Compos. Part A: Appl Sci Manuf, vol. 42, no. 2, pp. 157–164.

Sayman, O., Deniz, M. E., Dogan, T. & Yaylagan, E. (2011). Failure pressures of composite cylinders with a plastic liner. *Journal of Reinforced Plastics and Composites*, *30*(10), 882-888.

Shi, H. (2018). Model Test on Mechanical Properties of Glass Fiber-reinforced Plastic Mortar Pipes Culvert Under High Embankment. *International Journal of Performability Engineering*. doi:10.23940/ijpe.18.06.p27.13521359

Stamenović, M., Putić, S., Rakin, M., Medjo, B. & Čikara, D. (2011). Effect of alkaline and acidic solutions on the tensile properties of glass–polyester pipes. *Materials & Design*, *32*(4), 2456-2461.

Tabatabai, H. (2005). *Inspection and maintenance of bridge stay cable systems: a synthesis of highway practice.* Washington, D.C.: Transportation Research Board, National Research Council.

Taheri, F. (2013). Advanced fiber-reinforced polymer (FRP) composites for the manufacture and rehabilitation of pipes and tanks in the oil and gas industry.

In *Advanced Fibre-Reinforced Polymer (FRP) Composites for Structural Applications* (pp. 662-704).

Wang, J. (2013). Assessing the durability of the interface between fiber-reinforced polymer (FRP) composites and concrete in the rehabilitation of reinforced concrete structures. *Developments in Fiber-Reinforced Polymer (FRP) Composites for Civil Engineering*, 148-173. doi:10.1533/9780857098955.1.148

Wang, X., Wu, G., Wu, Z., Dong, Z. & Xie, Q. (2014). Evaluation of prestressed basalt fiber and hybrid fiber-reinforced polymer tendons under marine environment. *Materials & Design, 64,* 721-728.

Wu, H. & Eamon, C. D. (2017). Fiber-reinforced polymer composites. *Strengthening of Concrete Structures Using Fiber-reinforced Polymers (FRP),* 11-17. doi:10.1016/b978-0-08-100636-8.00002-8