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College of Technology and Built Environment

School of Mechanical and Industrial Engineering

Stress and Damage Analysis of Glass Fiber Reinforced Composites for Groundwater Riser Pipe Applications Using Numerical Methods

A thesis submitted to School of Mechanical and Industrial Engineering
in Partial Fulfillment of the Degree of Masters of Science (MSc) in
Mechanical Engineering (Mechanical Design)

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ADDIS ABABA UNIVERSITY
COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT
SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

Stress and Damage Analysis of Glass Fiber Reinforced Composites for Groundwater Riser Pipe Applications Using Numerical Methods

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Declaration

I hereby declare that the work which is being presented in this thesis entitled "Stress and Damage Analysis of Glass Fiber Reinforced Composites for Groundwater Riser Pipe Applications Using Numerical Methods" is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

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Abstract

Composite materials are increasingly being used in the application of pipes due to their desirable properties such as high strength-to-weight ratios, corrosion resistance, and increased durability. With the increasing demand in engineering for corrosion-proof and long-lasting material, traditional materials such as cast-iron and PVC are constrained by their durability and reliability. Composite materials such as glass fiber reinforced polymers (GFRP) possess desirable properties that have the potential to overcome such constraints. The primary objective of this research is to investigate the stress, deformation, and damage of composite materials for use in groundwater piping systems. Through this research, it is intended to investigate the damage behavior of a composite pipe subjected to axial loading and internal pressure, which are usual service loads for underground piping systems. To this end, the study utilized finite element analysis (FEA) on Abacus CAE to simulate the behavior of composite materials under various loads and environmental stresses. By modeling different material configurations and their interactions with groundwater, the analysis identified the optimal composite solutions that exhibit both strength and durability. The simulation result indicated a maximum von Mises stress of 33.2 MPa, maximum principal strain of 0.00111 and maximum deformation of 0.3mm under the standard loading condition for dry case and after consideration of moisture absorption, von Mises stress become 39.39 MPa, maximum principal strain raised to 0.00213. In addition, for critical load case von mises stress of 301MPa and principal strain of 0.0094 is recorded for dry condition and von mises stress of 331.2MPa and strain of 0.017 after moisture consideration. Furthermore, Hashin failure index for both fiber and matrix remained well below one for both loading case throughout the structure, confirming no critical damage initiation in any ply for the applied loads for dry case. For the critical loading with moisture, hashin matrix failure index of 2.76 is recorded indicating matrix failure under critical loading condition with moisture.

Keywords: Composite materials, GFRP, groundwater piping, Abaqus CAE, Von Mises stress, Moisture absorption, Hashin failure criteria.

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List of Abbreviation

Abbreviation	Meaning
ABS	Acrylonitrile Butadiene Styrene
AFRP	Aramid fiber reinforced polymer
CF	Carbon fibers
CFD	Computational Fluid Dynamics
CFRP	Carbon Fiber Reinforced Polymers
EHM	Equivalent homogeneous material
FEA	Finite element analysis
FEM	Finite element method
FPF	First ply failure
FRC	Fiber reinforced composites
FRC	Fiber reinforced composites
FRP	Fiber Reinforced Polymers
FW	Filament winding
FWM	Filament winding method
GF	Glass fibers
GFRC	Glass Fiber Reinforced Composites
GRP	Glass-Reinforced Plastic
HDPE	High-Density Polyethylene
MCI	Metal to composite interface
mm	millimeter
PEX	Cross-linked Polyethylene
PPTA	Poly-para-phenylen-terephtalamide
PVC	Polyvinyl Chloride
RBP	Resin bath pultrusion
RC	Reinforced concrete
RCW	Rotary centrifugal winding
RIP	Resin injection pultrusion
RTM	Resin transfer molding
RVE	Representative volume elements
TCP	Thermoplastic composite pipe
WHO	World health organization

Chapter One

Introduction

1.1. Background and Motivation

1.1.1. Ground water

Any of the water that is found in openings, pores, and fissures in the rocks is referred to as groundwater. Groundwater is formed from precipitation in the atmosphere, either directly by infiltration due to rainfall or indirectly through rivers, lakes, or canals. Two-thirds of the world's freshwater reservoir is made up of groundwater, which is a valuable freshwater resource. The most prevalent form of water collection is by bores, or drilled wells. They are bored into an aquifer with a vertical drilling rig. The key components of a bore water supply are shown in Figure 1. The pump is mounted to a riser pipe to transport water to the surface. This riser pipe can be either a series of lengths of plastic or steel pipe, or a flexible tube [1].

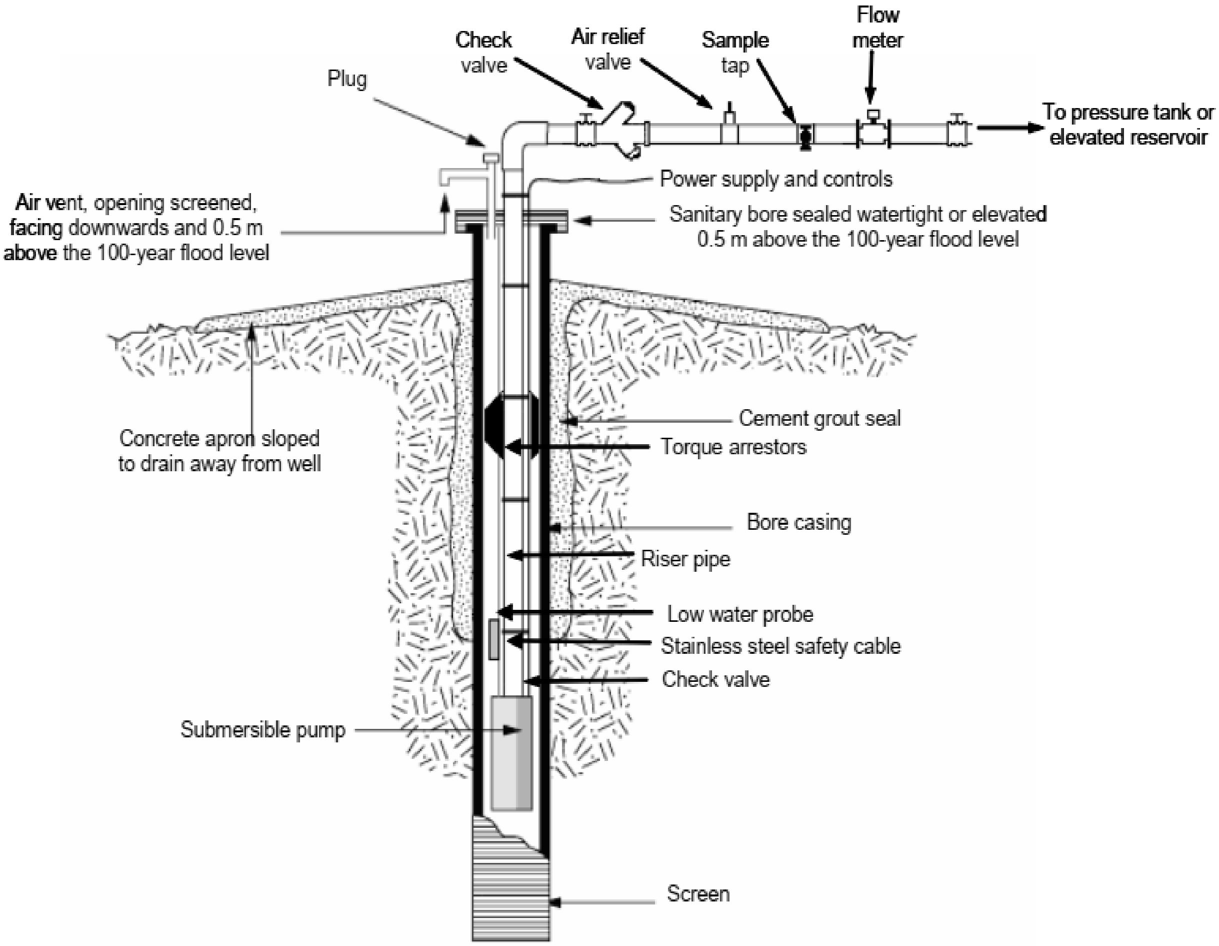


Figure 1: Components of bore water supply [1]

1.1.2. Groundwater Quality

Groundwater suitability for different purposes is determined from its chemical, physical, and microbiological properties. Chemical water analysis involves the identification of the levels of inorganic components. Physical water analysis determines temperature, color, turbidity, odor, and taste (Table 1). According to Arifin and Dariansyah's research [2], flow velocity, salinity, and immersion time affect the corrosion rate. As salinity and flow velocity increase, the corrosion rate of pipe increases and thus the lifespans decrease.

Table 1 : Drinking water quality [2]

Parameters	Undesirable effect produced	Highest desirable level	Minimum desirable level
PH	Taste, excessive scale formation	7.0 to 8.5	6.5 to 9.2
Calcium (mg/L)	Taste, corrosion in hot water system	75	200
Chloride (mg/L)	Mottling of teeth ,disfiguring of skeleton	200	600
Fluoride (mg/L)	Excessive scale formation	1.0	1.5
Total hardness as mg/L of CaCO3	Taste odor	100	500
Mineral oil (mg/L)	Taste		
Phenolic subs (mg/L)	Toxic	0.01	0.3

1.1.3. History of pipe Material

The development of pipe material has been a continuous process driven by technological advancement. Various materials have been used to make pipes over the years, and each has its share of advantages as well as limitations. Wood was previously one of the first materials used to make pipes and was prone to decay, rotting, and leakage. Due to their longer lifespan and resistance to corrosion, clay pipes became a more appropriate option than wood pipes. In addition, ceramic pipes were also widely used, particularly in gravity-fed systems. As compared to wood and clay, metal pipes such as copper and lead pipes have become more popular due to their greater strength and corrosion resistance. Ancient Rome used copper pipes extensively for water supply because they were malleable and long lasting. In contrast, lead contamination from lead pipes caused health issues. Cast iron pipes gained popularity during the Industrial Revolution. Because of its greater strength and long-lasting nature, cast iron was the preferred material for water supply and sewage systems in towns during the nineteenth century. Cast iron, on the other hand, required extensive maintenance and was subject to corrosion. Steel pipes, developed in the 20th century, improved some of the disadvantages of cast iron pipes. Plastic pipes, starting with PVC (Polyvinyl Chloride) pipes, emerged during the mid-twentieth century [3]. Because they are lightweight, corrosion-resistant, and simple to install, plastic pipes revolutionized the industry. For a number of uses, plastic pipes of different kinds, including PEX (cross-linked polyethylene), ABS (acrylonitrile butadiene styrene), and HDPE (high-density polyethylene), have grown in popularity. The latest developments in pipe materials are Fiber Reinforced Polymers (FRP) and Carbon Fiber Reinforced Polymers (CFRP) [5].

Figure 2: Evolution of Pipe Materials [3]

1.2. Composites Materials

Because of its great fatigue strength, high mechanical strength, high strength-to-weight ratio, good corrosion resistance, and lightweight nature, composite materials find extensive use across numerous industries [4], [5], [6]. Composite material water transport pipes are a relatively recent development. Behavior comparisons between pipes constructed from composite materials and those constructed from classical materials (cast iron, concrete, steel) are also extremely useful in design in order to choose the most suitable solution for different situations [7]. Composites are increasingly important due to the growing demand for lightweight materials with high strength for specific applications. Improved materials in manufacturing industries regarding strength, stiffness, density, and lower cost with better sustainability is needed. FRP composites are presented as materials meeting these requirements, finding potential in various fields like construction, mechanical, automobile, aerospace, biomedical, and marine.

1.2.1. Classification of composite material

The composite materials are divided into filler and base materials based on composition. While the filler material can be in sheets, pieces, particles, fibers, or whiskers of natural or synthetic material, the material on which the filler material is retained in is referred to as a matrix or binder material [8].

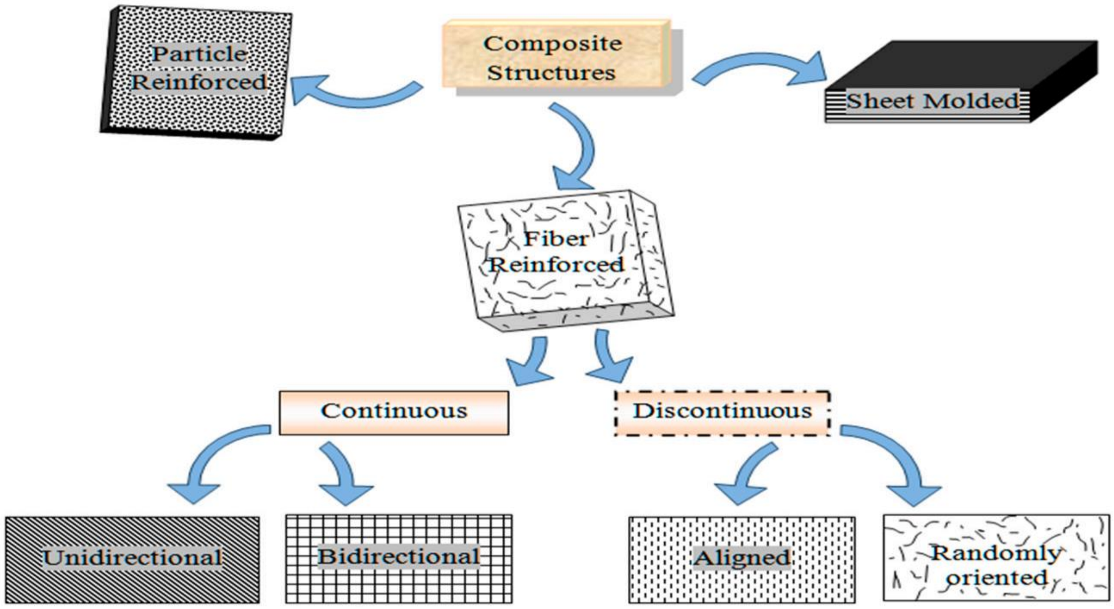


Figure 3: Classification of Composites [8]

FRPs has a polymer matrix reinforced with fibers, such as glass, carbon, or aramid, which give strength and stiffness to the material. These materials possess a higher environmental durability resistance, including to groundwater chemical composition capable of inflicting severe degradation on conventional metals and concrete in the long term [9]. FRP composites are very adaptable for their mechanical properties such that engineers can create materials that precisely meet the needs of groundwater pipeline systems, for example, resistance to internal pressure, resistance to external loads, and resistance to thermal expansion [10]. Moreover, the FRPs' lightweight reduces the overall load on the pipeline system and, therefore, they are desired for new installations as well as for rehabilitating pipelines. Moreover, FRPs in the form of composite pipes are becoming more and more desirable mainly due to their higher moduli, weight savings and lower installation cost [6], [11].

FRP composite pipes have been produced using two different manufacturing processes namely filament winding process (FWM) and rotary centrifugal winding (RCW). Any long fibers in form of roving, chopped strand mats and any thermoset can be used as source materials in FWM. Furthermore, the advantages such as production of larger pipes, hollow pipes, fiber arrangement, high mechanical performance, minimum production time attract the manufacturers towards this process [6].

Polymer composites are attracting increasing global attention due to the widespread use of plastics and their broad range of applications. These composites are typically fabricated by combining various polymer matrices such as thermosets, thermoplastics, rubbers, or their blends, including vinyl ester, epoxy, polyester, polypropylene, and polyethylene with different filler materials. The incorporation of fillers imparts specific advantages that are not present in the neat polymer, thereby reinforcing the matrix and enhancing its overall properties [12]. Moreover, the synergistic integration of functional fillers with highly process able polymers endows polymer based composite systems with multifunctional capabilities, significantly broadening their potential application range [13].

In deep-sea where the weight of conventional metallic equivalents is a limiting factor, lightweight TCP consisting of fiber-reinforced thermoplastic laminate with unreinforced thermoplastic inner and outer liners is suitable. Current global installation of TCP subjects the pipe to high bending moments on spooling onto a storage drum, possibly in alternate thermal conditions [14].

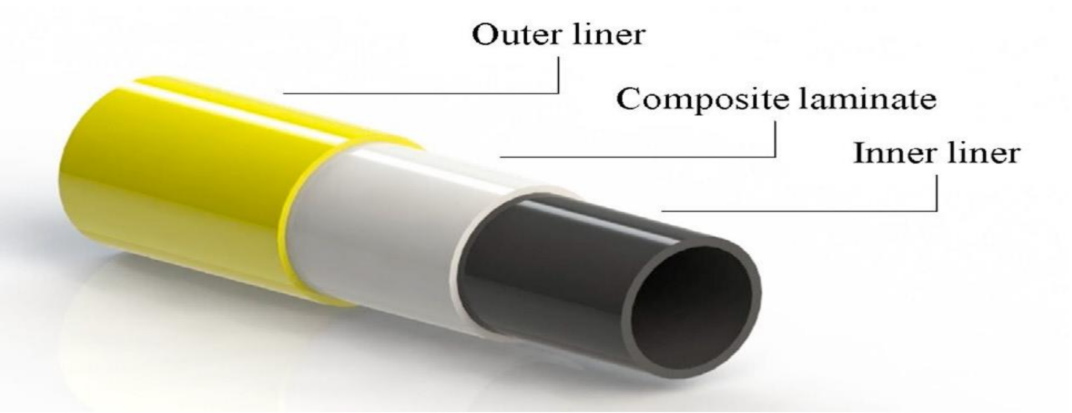


Figure 4: TCP Layers [14]

1.2.2. Glass Fiber Reinforced Composites (GFRC).

The polymers composite has many uses, and hence their use in electronics, transportation, and building is increased. Aerospace applications such as rocket nozzles utilize carbon fiber-reinforced plastic. Fiber strength, matrix characteristics, and interface adhesion between the matrix and the fiber affect the effectiveness of stress transfer, which in turn determines the mechanical response of fiber-reinforced composites (FRCs). Glass fiber (GF) exists in a number of unidirectional forms, including woven mats, chopped fibers, and strand mats, for the improvement of mechanical and tribological properties. Fiber type and orientation at the stage of manufacturing ultimately determine the composite performance [13].

Figure 5: Digital images of a) unwound glass fibers, b) woven glass fibers [13]

Glass fibers represent about 90% of all FRPs and are therefore among the most prevalent polymer reinforcements. The most popular and traditional glass fiber is e-glass. Besides, carbon the term "new breed of high strength materials" applies to fibers, which are comprised of graphitic and non-crystalline segments. Carbon fibers exhibit the highest strength and specific modulus among all the reinforcing fibers. They are water-insensitive and capable of maintaining tensile strength at high temperatures. Poly-para-phenylen-terephtalamide (PPTA) is the rigid molecular form of aramid fiber Kevlar [14], [15].

1.2.3. FRP Production method and end fitting

Pultrusion and filament winding are the two main methods used to produce FRP composite tubes with constant, tubular cross-sections. Pultrusion is capable of producing long FRP pipes with small diameters. However, it is less suited for fabricating risers, as they often require larger diameters. In contrast, filament winding is more suitable for producing large-diameter composite tubes, although it is typically limited to a few meters in length due to the constraints of the mandrel [3], [8], [16], [29].

Fiber-reinforced polymer (FRP) composite pipe have higher initial material and production costs compared to common metals. However, their maintenance costs are lower, and studies predict a 37% reduction in overall installation costs .The design and manufacture of composite risers can be broadly categorized into three main components: the composite riser body, the metal end fittings where multiple risers are joined, and the metal-to-composite interface (MCI). The manufacturing process for risers can thus be discussed in two main aspects: the riser body and the MCI with its associated end fittings. The metal-to-composite interface (MCI) plays a important role in providing a strong connection between the composite riser and the metallic end fittings at the pipe’s end. This interface is essential for effectively transferring loads between the pipes. Efficient MCI designs are critical, as their length and mass can significantly affect the weight-effectiveness of composite risers [16].

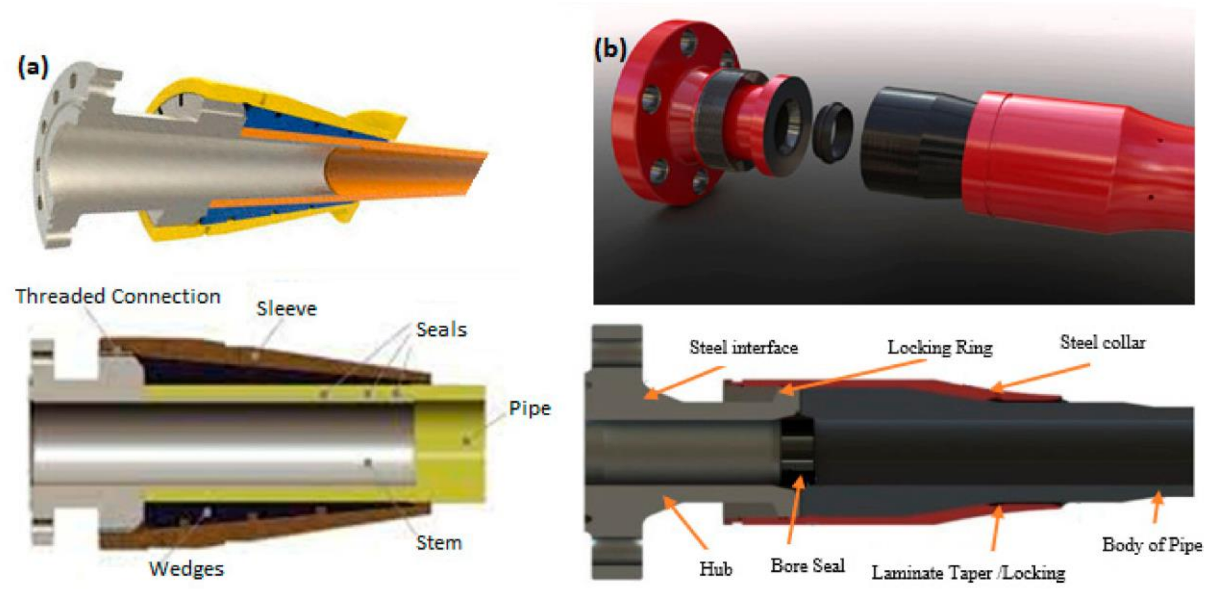


Figure 6: End-fitting designs for (a) Airborne end fitting and (b) Magma end-fitting [11]

Study by D.-C. Pham, N. Sridhar, X. Qian, A. J. Sobey, M. Achintha, and A. Shenoi, [16] Presented several designs for composite riser end fittings, as shown in Fig. 7. The trap-lock end fitting (Fig. 6a) is the most widely used design, allowing load transfer between the composite and metal components. Another design, the swaged end fitting (Fig. 4b), uses metallic inner and outer sleeves to sandwich the composite pipe. The inner sleeve fits into the composite bore, while the outer sleeve is swaged to create an interference fit with the composite. Load transfer occurs through friction and mechanical interference. However, this design may lead to high stress concentrations and potential damage at the interfaces, particularly where the inner mandrel is inserted. As a result, it may be best suited for composite pipes with smaller diameters. The metal liner end fitting (Fig. 6c), often used in hybrid composite, involves a metal liner welded directly to the end fitting, with composite materials wound over the liner. A rubber layer is applied before winding. This design allows axial loads to be carried by the metal liner, while the composite material handles hoop loads. A new end fitting design was made (Fig. 4d) for a monolithic structure extending from bore to surface riser, made from high-strength carbon fiber and PEEK thermoplastic polymer. This design allows the thickness at the pipe end to be built up, making it possible to replace the end fitting and increase the strength to match that of the pipe.

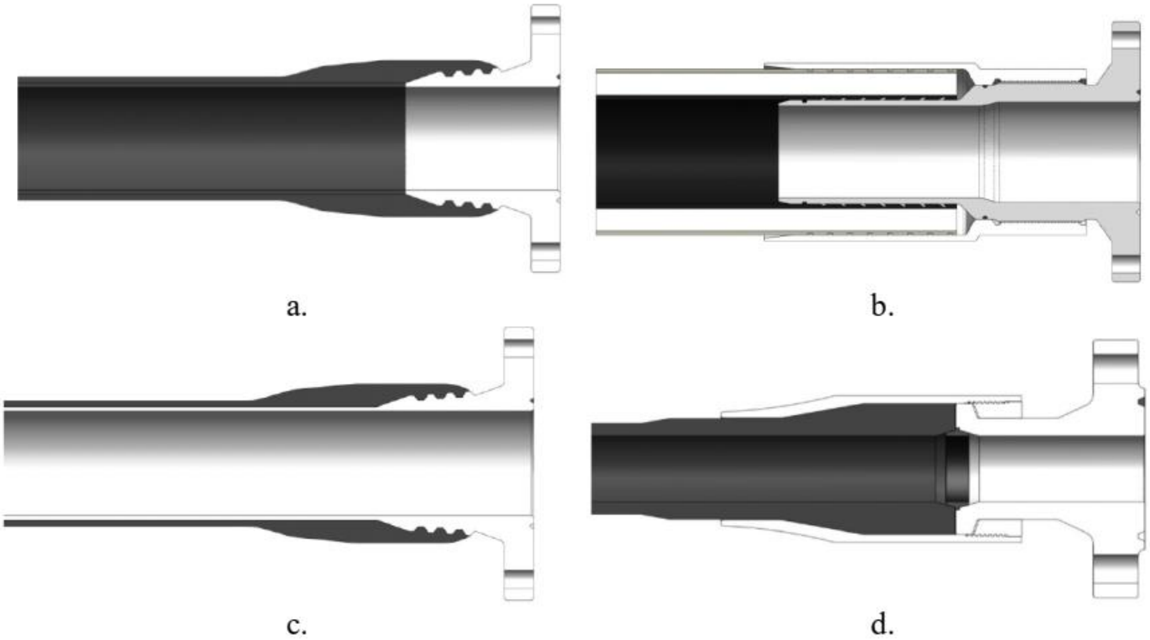


Figure 7: Different end fitting designs presented including trap lock end fitting fitting (a), swaged end fitting (b), metallic liner end fitting (c) and Magma end fitting (d) [16]

The primary goal of this research is to explore how numerical analysis can be used to predict the performance and longevity of composite pipes in groundwater systems. Specifically, this research will aim at the impact of various parameters, such as the type of reinforcement material, fiber orientation, and matrix material, on the mechanical behavior and durability of composite pipes. Research will also seek to determine if it is possible to use composite materials to achieve sustainability in groundwater infrastructure by reducing maintenance costs and increasing the service life of pipes [17].

The findings of this research are expected to be a worthy contribution to the wealth of information on the use of composite materials for engineering applications in general and, more particularly, in groundwater pipeline systems. With its deeper insight into the material's behavior and performance under real conditions, the study will have significant implications for the design, optimization, and installation of composite pipes in groundwater systems. The outcome of this research has the potential to guide future standards and regulations for the use of composite materials in water transport systems, leading to more sustainable, cost-effective, and durable infrastructure solutions [18]. Furthermore, the numerical models developed in this research will serve as a foundation for subsequent research efforts in the field of composite materials, paving the way for further innovations in the design of next-generation piping systems.

Application of composite materials to groundwater pipeline systems is not without challenges. Design and performance of the composite pipes must take into account several issues, including various mechanical properties of the matrix and the fibers, the manufacturing process, and environmental conditions where the pipes are expected to operate. Particularly, the complex interaction behavior between the reinforcement and matrix materials, and the influence of moisture and temperature cycling on composite properties, constitute fundamental challenges to making reliable long-term predictions [19]. Furthermore, the retention of the material's structural integrity over time, especially under cyclic loading and environmental exposures is a key factor in determining the applicability of composite materials to groundwater pipes.

This research attempts to address these challenges a thorough numerical study of composite material application for groundwater piping systems. By using advanced computational tools such as Finite Element Analysis (FEA), the research aims to simulate the mechanical behavior of composite pipes under real loading conditions such as internal pressure, external loads, and moisture absorptivity. FEA allows for the complete modeling of complex material behavior such as fiber orientation, material heterogeneity, and component interaction of the composite. Numerical models developed in this research will clarify the stress distribution, deformation patterns, and modes of failure in composite pipes under different environmental conditions, thus allowing for the optimization of their design for groundwater applications [20].

In addition to its focus on mechanical performance, this study also examined the environmental and economic effects of composite material application in groundwater pipe systems. Among the key advantages of FRP composites is corrosion resistance, which represents a significant problem for traditional materials applied in groundwater systems. Corrosion can severely reduce the longevity of metal pipes, which can lead to leaks, reduced service life, and increased maintenance expenses. Composite materials, on the other hand, offer a high level of protection against corrosion, reducing the need for frequent inspections and replacements [21]. Furthermore, the lightweight nature of composites reduces the transportation and installation cost, making composites an economically viable option for use in groundwater in both developing and developed nations [22].

The need for durable and long-lasting groundwater transportation systems is of paramount importance, particularly for regions with issues of aging infrastructure, corrosion, and environmental sustainability. Pipe materials such as steel, concrete, and clay have been used historically in groundwater systems. These materials, however, possess certain disadvantages when used in the long term, including susceptibility to corrosion, loss of structural integrity over time, and expensive maintenance [21]. Consequently, there is an increasing demand for innovative materials that offer improved performance and longevity. Composite materials, which combine two or more distinct materials to form a new material with enhanced properties, have emerged as a promising alternative for various civil engineering applications, including groundwater pipelines. Their inherent advantages in terms of high strength-to-weight ratios, resistance to corrosion, and flexibility make them a viable option for addressing the shortcomings of traditional materials [22].

The most notable barriers that affect the usage of composite pipe to its full capability are (i) manufacturing ways and infrastructure to cost effectively produce long tubular composite structures (ii) a lack of full-scale and in-situ results for verification and certification, thus resulting in a requirement for material properties to assess long term damage and (iii) modelling that takes into account the interaction of the wide range of loads that risers see in-situ and stochastic analysis techniques to help reduce the large safety factors in the currently available design standards. Effective numerical approaches considering for fluid- structure relation are essential for better forecasting the response of composite pipe under harsh deep ocean medium. Reliability and fatigue studies of composite risers are limited; it is recommended that further research in these fields are crucial to ensure expanded utilization of composite risers in deep-water applications [23].

1.3. Motivation

Despite growing interest in composite pipes for groundwater applications, numerical simulation of composite materials under environmental and mechanical loading conditions typical of groundwater pipe installations has been the focus of relatively limited research efforts. This lack of research is a barrier to more widespread adoption of composite piping systems, as engineers will not accept replacing traditional materials without complete validation of performance for specific applications [24]. Numerical analysis has emerged as an integral part of composite material design and analysis since it enables the simulation of complex loading conditions and the prediction of long-term behavior without the cost and time investment of physical testing. In particular, finite element analysis (FEA) provides a powerful tool for simulating the performance of composite materials under external and internal loading conditions such as pressure, temperature changes, and soil interaction [25].

Composite materials offer a number of advantages, including resistance to chemical degradation, ease of transportation and installation, and enhanced durability, making them an attractive alternative for infrastructure applications [26]. Despite these benefits, composites' application in groundwater piping remains limited. Composite materials, particularly fiber-reinforced polymers (FRPs), have been one of the innovative materials in engineering practices that demand high strength, low weight, and resistance to corrosion. These materials are increasingly being applied in piping systems due to their high mechanical properties and sustainability in aggressive environmental conditions. Groundwater pipes are particularly vulnerable to environmental degradation such as water and soil corrosion, along with mechanical stresses from external and internal pressures. Traditional pipe materials like steel or concrete typically do not meet the performance and durability requirements for such severe conditions [27].

It is the intention of this research to fill this gap by developing and using numerical models to predict the behavior of composite pipes under conditions typical in groundwater systems. With FEA techniques, the study will focus on the optimization of fiber orientation, matrix material properties, and pipe geometries for the improvement of composite pipe performance and longevity. The outcome of this research will provide valuable insight into how these types of materials can be best utilized for piping systems under constant mechanical stress and environmental degradation. Additionally, the study will offer an economical way of screening composite materials for application in groundwater pipe systems without having to use exhaustive experimental testing. This study can significantly advance the use of composite materials in infrastructure for more durable, efficient, and sustainable piping systems for groundwater control [28].

1.4. Statement of the problem

Groundwater piping system integrity is critical to delivering access to water resources with dependability, but the traditional materials, such as polyvinyl chloride (PVC) and cast iron, are extremely limited in terms of durability and environmental resistance. These materials are likely to suffer from corrosion, mechanical breakdown, and degradation with time, leading to costly repairs and potential disruption in the supply of water. With urban infrastructure aging and pressures increasing, it is important to look for alternative materials that will yield superior performance and lifespan in the groundwater environment.

Composite materials, particularly carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP), are identified as potential substitutes for conventional piping materials. The composites retain a superior strength to weight ratio, better chemical resistance, and reduced corrosion vulnerability. However, with their assumed advantages, scarce literature is present on stress strain analysis and damage behavior under the specific conditions in groundwater systems.

Moreover, identification and awareness of the stress distribution and damage nature in such materials are indispensable for the development of effective design principles and standards. Delamination, cracking, and environmental deterioration can significantly influence the life and performance of composite pipes. A detailed numerical analysis is needed to simulate various loads and environmental exposure conditions to establish an understanding of how such materials evolve.

Lastly, the final aim of the study is to address such pressing problems by conducting a numerical analysis of composite materials for application in groundwater pipe systems. By analyzing stress and strain and damage behavior, the research aims to further illuminate the use of GFRP as an effective material, particularly in groundwater systems. The findings not only advance the technology of composite materials but also promote more sustainable and efficient groundwater management policies.

1.5. Objectives

1.5.1. General objectives

The primary objective of this research is to conduct numerical analysis of glass fiber reinforced polymers (GFRP) pipe for the application in groundwater pipe systems.

1.5.2. Specific objectives

The specific objective of this study will be;

- To analyze stress distribution, deformation, and strain to identify how GFRC respond to typical loading conditions and environmental factors (moisture).
- To investigate the damage behavior/Analysis associated with the use of GFRC.

1.6. Scope

This study investigated the numerical response of composite materials specially designed for use in groundwater piping system applications. Focus will be on the performance under various composite materials under various types of loading, e.g., pressure, and environmental conditions typical of groundwater conditions. The research employed finite element analysis (FEA) using ABACUS CAE to simulate the mechanical behavior of such materials and allow for critical analysis of stress distribution, deformation, and damage analysis. From the comparison of different composite compositions, the research will identify the most appropriate materials that can be used to enhance durability and efficiency in use in groundwater pipes. Besides this, the long-term performance of such composite materials under real conditions is studied in this research by including parameters such as moisture absorption.

The ultimate goal of this research is to contribute effectively to the choice and construction of composite materials that have the potential to fuel innovative solutions to improve the current problems affecting groundwater infrastructure. This research, apart from contributing to the knowledge base, will also aim to help engineers and manufacturers design more long-lasting and sustainable piping systems.

1.7. Significance of the Study

The significance of this study lies in the fact that it can advance groundwater management systems' knowledge and use of composite materials. As traditional piping materials like PVC and cast iron get increasingly obstructed by corrosion and deterioration, alternative solutions like (GFRP) and (CFRP) become necessary. This research gained significant findings on the mechanical behavior of such composites, to demonstrate how the employment of these composites would enhance groundwater pipes' durability and effectiveness towards the realization of enhanced water resources management.

Also, the investigation addressed the significant issue of damage actions of composite materials in groundwater. Comprehension of failure-mode mechanisms such as delamination and environmental degradation is crucial. This research will contribute to enhancing the standards and guidelines for design to develop more reliable and safe groundwater piping systems. By closing the gap between theoretical understanding and practical implementation, this research will have a significant effect on the field of groundwater management and engineering.

1.8. Expected Outcomes

The primary expected outcome of this research is understanding the structural behavior of composite materials, specifically glass fiber reinforced polymers (GFRP), for application in groundwater pipes. Through the use of finite element analysis (FEA), the study predicts establishing performance factors such as distribution of stress, deformation, and overall structural integrity under various loading conditions. These observations will provide one basis for determining the feasibility of employing these composites as alternatives to traditional materials like PVC and cast iron for groundwater control.

A second significant outcome will be to identify and characterize the potential damage behavior of the use of composite materials for groundwater application. With the analysis of delamination and cracking mechanisms through simulation and experiment, the research is expected to produce guidelines and recommendations that enhance the design and application of composite pipes. The results will play a significant role in ensuring the durability and reliability of piping systems in groundwater, resulting in more effective and sustainable water resource management.

Chapter Two

2. Literature Review

2.1. Introduction

Composite materials have played a critical role throughout human history. Composites provide a range of benefits over fully dense materials (such as steel, aluminum, etc.) that include low mass, high strength and stiffness, improved damping of vibrations, design flexibility, and resistance to corrosion and wear. Thanks to these unique properties, composite materials are used in everything from simple household products to advanced industries like biomedicine, sport, marine industry, and building. For manufacturing high-performance FRP composites, numerous fiber forms like glass, carbon, aramid, basalt, paper, wood, or asbestos have been discovered or developed since years ago. However, glass fibers (GFs) and carbon fibers (CFs) are most commonly used fibers in manufacturing FRP [18], [19], [20].

The increasing need for sustainable and durable materials in infrastructure has highlighted the potential of composite materials, particularly glass fiber reinforced polymers (GFRP) and carbon fiber reinforced polymers (CFRP), for applications in groundwater piping systems. These materials are characterized by their high strength-to-weight ratios and exceptional resistance to corrosion, making them advantageous compared to traditional materials like PVC and cast iron [28]. However, despite their mechanical benefits, challenges related to compatibility with existing infrastructure and the effects of environmental exposure on their performance are not yet fully understood [30]. A comprehensive understanding of the behavior of composite materials under various loading conditions and environmental factors is essential for their successful implementation in groundwater systems. Previous studies have identified potential failure modes such as delamination and cracking, which can arise from thermal expansion mismatches and chemical interactions with groundwater [31].

Composite materials, typically consisting of a matrix (such as polymer or resin) and reinforcement (such as glass, carbon, or aramid fibers), are increasingly utilized in various industrial applications, including the construction of pipelines. These materials offer exceptional resistance to corrosion, particularly in environments where metals are prone to degradation due to contact with water or chemicals. One of the primary advantages of composite materials in pipeline applications is their ability to withstand aggressive environmental conditions without succumbing to corrosion or scale formation. Materials such as Glass Fiber Reinforced Polymer (GFRP) have been extensively studied for use in water and wastewater pipelines. Study by Yang, H., et al. [32] found that composite pipes, particularly those made of GFRP, exhibit excellent mechanical properties such as high tensile strength, which enhances their suitability for groundwater applications.

The long-term durability of composite pipes in groundwater systems depends on the interplay of environmental conditions, material properties, and the mechanical demands placed on the pipeline. Research indicates that composite materials can maintain their mechanical properties under various environmental conditions. A study by Gupta, P., & Shah [33] demonstrated that GFRP retains strength and stiffness even when subjected to prolonged exposure to moisture, further supporting its use in groundwater applications.

2.2. Glass Fiber Reinforced Composites

The mix of qualities that composites provide is not possible for their constituent materials to duplicate Matrix materials often utilized in GFRP composites include organic polyester, thermostable, vinyl ester, phenolic, and epoxy resins. Mechanically, they are controlled by matrix strength, chemical stability, fiber/matrix interface bonding, and fiber strength and modulus [34].The two most popular reinforcement materials utilized in the creation of composite pipes are carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP). One of the most widely used composites is glass fiber reinforced resin (GFRP). To create composites, fibers which can be classified as continuous or discontinuous are dispersed throughout a resin matrix. Both chopped strands and continuous fibers are used in the continuous filament winding method used to create GFRP pipes. Randomly inserted chopped strands are interspersed with continuous fibers in the circumferential direction. A covering of short-fibered sand is also used to strengthen the pipes. Strips of continuous fibers are frequently arranged in different directions. Composites with continuous fibers are renowned for their great rigidity and strength. However, their applications are typically restricted to shell-like geometries because of their poor formability. Recently, discontinuous-fiber composites have drawn interest because to their easier production process and cheaper cost. These composites are made up of continuous fibers arranged in helical and hoop layers along either the circumferential or the arbitrary directions. Composites made of discontinuous fibers are especially well suited for quick, large-scale production [35].

The strength of discontinuous-fiber composites is directly related to the length of the fiber, as shown in Figure 8. Discontinuous fibers longer than 20 mm are considered long-fiber reinforcements, while those shorter than 20 mm are categorized as short-fiber reinforcements. In discontinuous fibers, the length and orientation angles vary, and the fibers are divided into four groups: aligned strands, randomly oriented strands, preferentially aligned fibers, and randomly oriented fibers. The flexural behavior of filament-wound GFRP pipes has been shown to be significantly influenced by the diameter-to-thickness ratio, whose increase can increase the pipe's flexural capacity. As well, the composite pipes have been shown to possess considerable buckling strength as a result on decreasing of the diameter-to-thickness ratio and increasing of the fiber angle. Prior studies have also demonstrated that the thickness and number of layers of the pipe wall can have a major impact on how it bends.

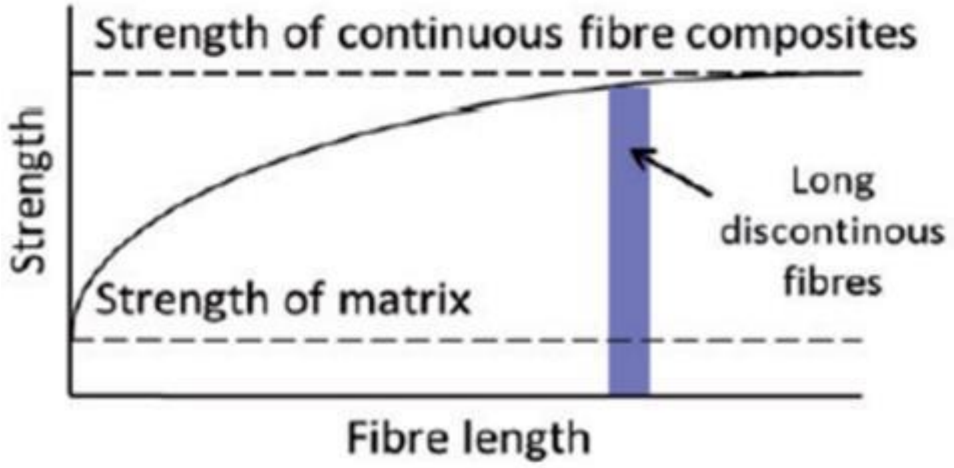


Figure 8: Effect of fiber length on composite strength [35]

2.2.1. Material properties of GFRC

Raw material is pressed through small holes to create fibers, which are pulled to enable molecular alignment along the axis of the fiber and solidified under different conditions. The industry offers an enormous range of man-made (organic and inorganic) and natural (cellulosic/plant, animal, mineral) fibers. Yet the most popular fibers for manufacturing high-performance FRP composites are glass (GF) and carbon (CF) fibers, which are categorized under the group of inorganic synthetic fibers (SFs). These two fibers GFs and CFs will be described in detail in succeeding sections. Glass fibers are at present the most versatile manufacturing materials compared to others. They are produced from raw materials, which is found in unlimited quantities. A number of GF used primarily in GFRP composites, depending on the raw materials and their ratios applied to produce glass fibers [29].

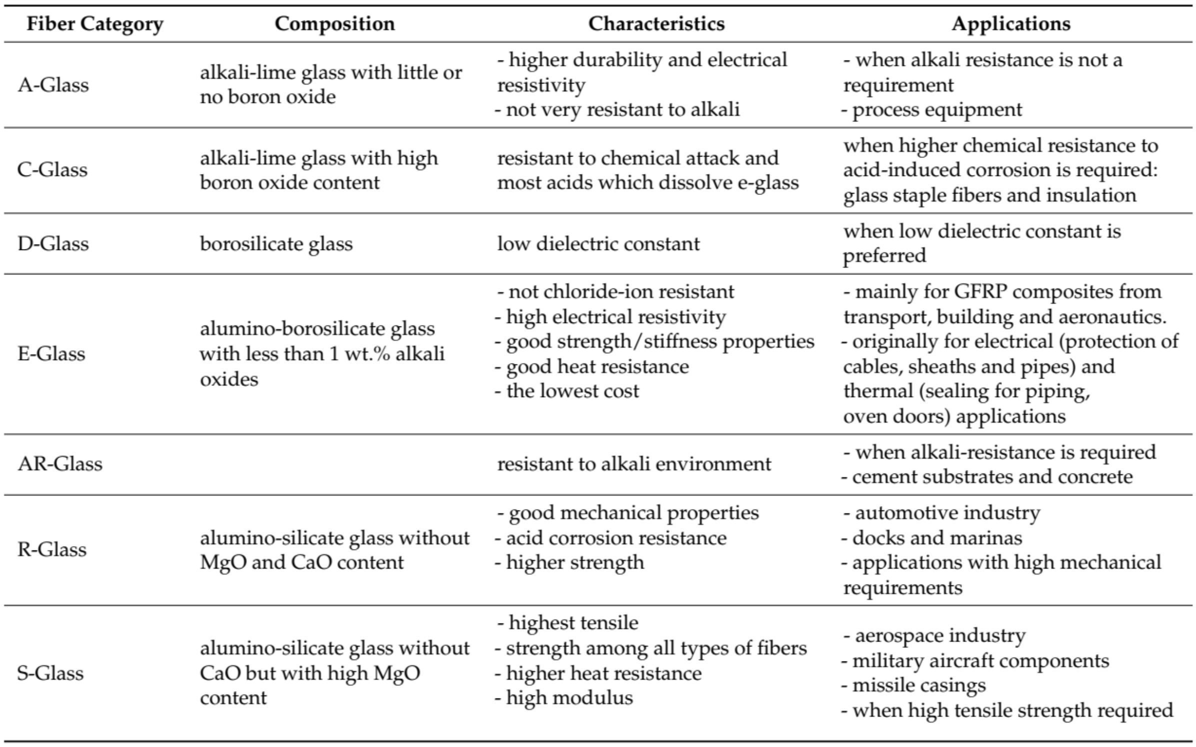
Glass Fibers are widely used polymer reinforcements, making up nearly 90% of all FRPs, with E-glass (electrical grade glass) being the oldest and most popular type. Fiber-reinforced composites' mechanical behavior is mostly determined by the fibers' capacity to transfer stress, which is influenced by the fiber's strength, the matrix, and the interfacial adhesion between them. Glass fibers are used in various forms (longitudinal, woven mat, chopped fiber, and chopped mats) to enhance mechanical and tribological properties [13].

Figure 9: Classification of fibers [29]

The classification of composite materials based on their content (matrix and filler) and structure is discussed, with a focus on fiber-reinforced composites (FRCs**)**. FRCs are further categorized by fiber length into continuous and discontinuous fiber reinforcements, as well as hybrid fiber-reinforced composites which utilize two or more types of fibers in a single matrix [8]. The paper notes that young's Modulus, tensile strength, and chemical stability are characteristics directly mapped upon the fibers, while other properties like dissipation factor and dielectric constant are graded on the designed glass specimens. Tables 2 and 3 are mentioned to show the chemical composition, special features, main applications, and main properties of various GFs. Figure 9 illustrates different types of glass fibers, including continuously long threaded, woven and random, chopped strand mat, and chopped fibers.

The chemical compositions of GFs in wt% are shown in Table 3. The physical and mechanical properties of GF are shown in Table 4 and 5.

Table 2 : Chemical composition, characteristics and main applications of glass fibers [34]



Fiber Category	Composition	Characteristics	Applications
A-Glass	alkali-lime glass with little or no boron oxide	- higher durability and electrical resistivity - not very resistant to alkali	- when alkali resistance is not a requirement - process equipment
C-Glass	alkali-lime glass with high boron oxide content	resistant to chemical attack and most acids which dissolve e-glass	when higher chemical resistance to acid-induced corrosion is required: glass staple fibers and insulation
D-Glass	borosilicate glass	low dielectric constant	when low dielectric constant is preferred
E-Glass	alumino-borosilicate glass with less than 1 wt.% alkali oxides	- not chloride-ion resistant - high electrical resistivity - good strength/stiffness properties - good heat resistance - the lowest cost	- mainly for GFRP composites from transport, building and aeronautics. - originally for electrical (protection of cables, sheaths and pipes) and thermal (sealing for piping, oven doors) applications
AR-Glass		resistant to alkali environment	- when alkali-resistance is required - cement substrates and concrete
R-Glass	alumino-silicate glass without MgO and CaO content	- good mechanical properties - acid corrosion resistance - higher strength	- automotive industry - docks and marinas - applications with high mechanical requirements
S-Glass	alumino-silicate glass without CaO but with high MgO content	- highest tensile - strength among all types of fibers - higher heat resistance - high modulus	- aerospace industry - military aircraft components - missile casings - when high tensile strength required

Table 3: Chemical compositions of glass fibers in wt%.[13]

Type	(SiO_2)	(Al_2O_3)	(TiO_2)	(B_2O_3)	(CaO)	(MgO)	(Na_2O)	(K_2O)	(Fe_2O_3)
E-glass	55.0	14.0	0.2	7.0	22.0	1.0	0.5	0.3	-
C-glass	64.6	4.1	-	5.0	13.4	3.3	9.6	0.5	-
S-glass	65.0	25.0	-	—	—	10.0	-	-	-
A-glass	67.5	3.5	-	1.5	6.5	4.5	13.5	3.0	-
D-glass	74.0	-	-	22.5	—	-	1.5	2.0	-
R-glass	60.0	24.0	-	—	9.0	6.0	0.5	0.1	-
EGR-glass	61.0	13.0	-	—	22.0	3.0	-	0.5	-
Basalt	52.0	17.2	1.0	—	8.5	5.2	5.0	1.0	5.0

Table 4: Physical and mechanical properties of glass fiber [13]

Type	Density (g/cm^3)	Tensile strength GPa	Young's modulus (GPa)	Elongation (%)	Coefficient of thermal expansion (10-7/oC)	Poison's ratio	Refractive index
E-glass	2.58	3.445	72.3	4.8	54	0.2	1.558
C-glass	2.52	3.310	68.9	4.8	63	-	1.533
S-glass	2.46	4.890	86.9	5.7	16	0.22	1.521
A-glass	2.44	3.310	68.9	4.8	73	-	1.538
R-glass	2.54	4.135	85.5	4.8	33	-	1.546
EC-Glass	2.72	3.445	85.5	4.8	59	-	1.579
AR-glass	2.70	3.241	73.1	4.4	65	-	1.562

Table 5: Mechanical properties of various glass fiber products [13]

Types	Unit	Woven cloth	Chopped strand mat	Continuous roving
Glass content	%	55	30	70
Tensile strength	N/mm$_2$	300	100	800
Compressive strength	N/mm$_2$	250	150	350
Flexural strength	N/mm$_2$	400	150	1000
Flexural modulus	N/mm$_2$	15000	7000	40000
Impact strength	kJ/m$_2$	150	75	250
Coefficient of linear thermal expansion	×10^{-6}/°C	12	30	10
Thermal conductivity	W/mK	0.28	0.2	0.29

2.2.2. Manufacturing processes of GFRC

There are conventional and advanced manufacturing processes for FRP composites. Conventional methods include pre-preg layup, hand lay-up, spray-up, vacuum bag molding, resin transfer molding (RTM), vacuum infusion (VARTM), compression molding, pultrusion, and injection molding, each with its own process and applications. Advanced techniques includes electrospinning for nanoscale fiber fabrication, additive manufacturing (3D printing) for complex geometries, and filament winding for producing hollow, often cylindrical structures [8].

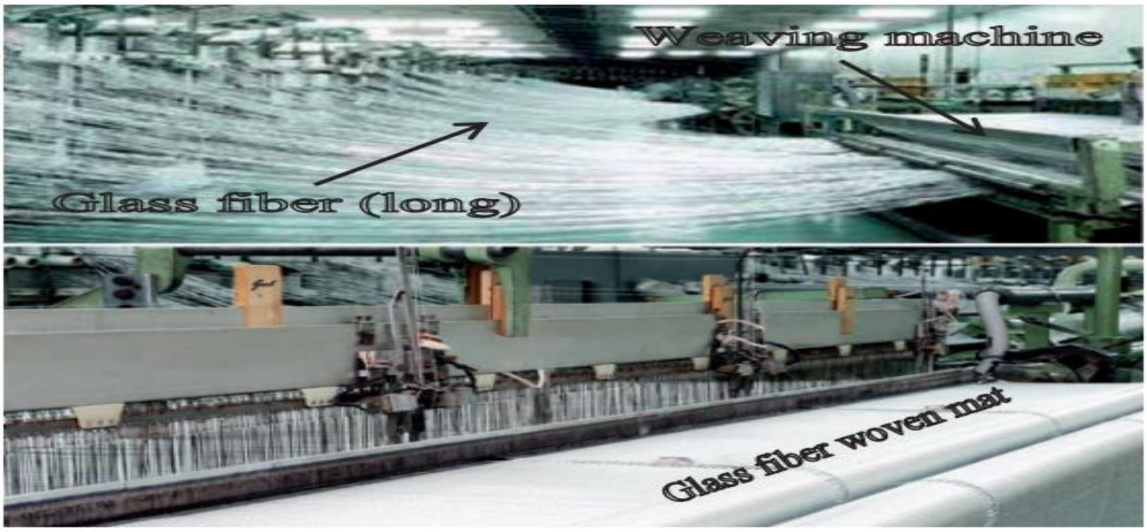


Figure 10: Preparation of glass fiber woven mat [30]

Advances in manufacturing techniques have greatly enhanced the properties and reliability of composite materials for pipeline applications. Automated processes such as filament winding and resin transfer molding (RTM) have allowed for more consistent and controlled fabrication of composite pipes [30]. Understanding these manufacturing implications is vital for ensuring consistent material quality. The GFRP composites were prepared by adopting various manufacturing techniques as discussed below. The preparations of random and woven mat GFs are shown in Figures 9 and 10.

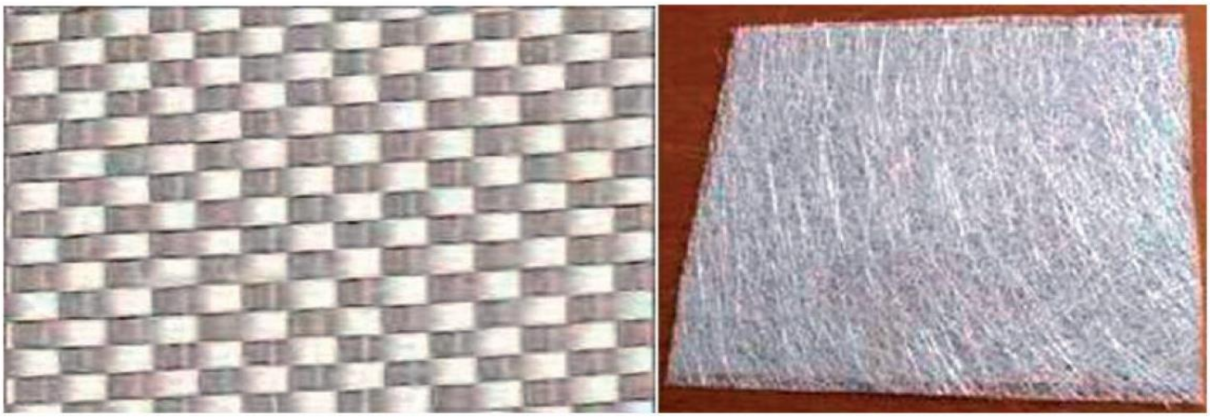


Figure 11: Woven and random glass fiber mat [30]

The composite structures industry must improve FRP material manufacturing processes through the creation of new types of reinforcements, resin systems, and compounding the materials together to meet the demands of a high-pressure and dynamic marketplace. The main objectives of automating and enhancing FRP manufacturing processes are to decrease handling time and expense as well as the weights and sizes of FRP parts. Besides the extensive range of material combinations that have been developed for FRP composites, a variety of advanced techniques are now possible and available for producing CFRP and GFRP products [30].

2.2.2.1 Filament Winding Process

One of the techniques that can be used to automate the manufacturing process is filament winding (FW). FW produces tubular FRP composite structures with extremely high tensile strength that is open end (e.g., cylinders, pipes, bicycle fork and rim) or closed end (e.g., chemical and fuel storage tanks, stacks, rocket motor cases, pressure vessels, and drive shafts). FW can cross-weave prepreg sheets, monofilaments, and roving's of GF, CF, or Kevlar fiber with a rotating mandrel to fabricate axisymmetric and non-axisymmetric parts. Since FW is one of the few automated techniques available for the manufacture of FRP composites, it can make parts of high quality and with high repeatability at lower cost of labor. Fiber content, fiber type, winding angle, thickness, and tow or bandwidth of the fiber bundle are the primary controlled variables for winding. The angle of wound fiber is significant since it plays a significant role in determining the nature of the finished FRP part. A lower-angle design (helical or polar) will offer longitudinal strength, while a high-angle "hoop" will create greater circumferential strength.

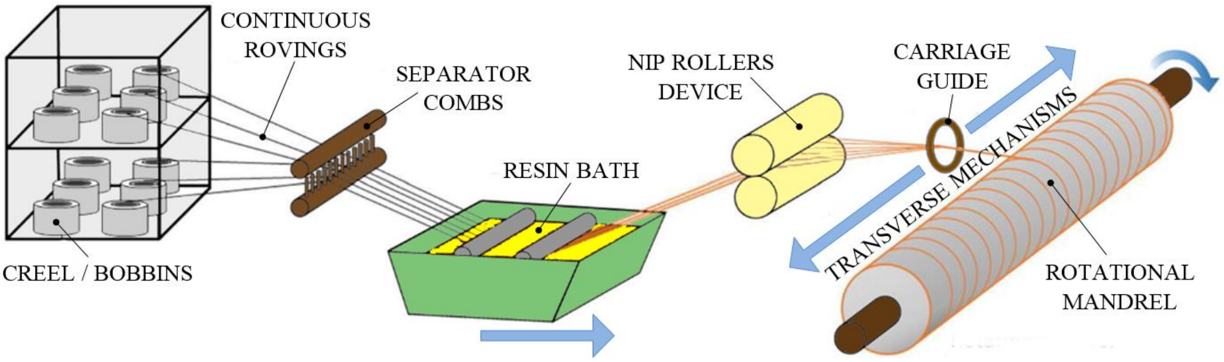


Figure 12: Schematic diagram of a typical filament winding process. [3], [8], [29]

Gathering the fibers from a set of creels, sorting them by running them through a textile comb, and then running them through a resin bath make up the first process of the "wet" FW process. By drawing the roving fibers with a continuous tension at the resin bath outflow, a wiping device, such as squeeze rollers, aims to regulate the amount of resin that will be applied to the fibers. The impregnated roving’s also become a flat band of fibers after exiting through a ring, comb, or straight bar. At this point, the already created band (or prepreg sheet in the case of "dry" FW) is positioned on the mandrel, and while the mandrel rotates, the carriage system moves back and forth in order to impregnate the fibers with it. By controlling the carriage and the mandrel speeds, the winding pattern of the intended part is obtained. When the laminate reaches the desired thickness, the mandrel is cured. Once the composite resin has dried completely, the hollow composite piece is removed from the molded area by removing the mandrel. Collapsible (inflatable or segmented) mandrels for bigger pieces to make removal from the cured part easy are feasible. Low-melting alloys, dissolvable plasters, and eutectic salts are used for the preparation of the mandrel in the production of small lots of tiny parts [3], [8], [29].

2.2.2.2 Pultrusion Process

The term "pull" and "extrusion" are two distinct words, which together comprise the word "pultrusion." Two most widely used PT processes are resin-injection pultrusion (RIP) and resin-bath pultrusion (RBP). The PT composite synthesis process is precisely the same as the extrusion process. In the PT process, the material is pulled through pre-determined dies, whereas in the extrusion process, the material is pushed through the dies. There is no other difference. FRP composites with a glass-reinforced, carbon-reinforced, aramid fiber-reinforced, or blend-reinforced thermoplastic or thermoset polymer are made with the application of PT technology. The majority of pultruded FRP laminates are manufactured by employing roving-oriented downward on the major axis of the product. The PT process is shown in Figure 13 and the steps are described below:

i. The raw material lay-up is precisely molded into the desired shape by mixing various reinforcements.
ii. The lay-up goes through a pre-set guide (pre-die) to align the reinforcements in the profile. After passing through the guides,
iii. A resin is infused into the fibers. In order to get fully wetted fibers, the lay-up is submerged in the resin tank. Then after the leaving of the resin tank,

iv. The PT metal die is penetrated by the resin-impregnated reinforcements. The die is actively cooled and heated to manage polymerization (curing of thermosets) or crystallization (freezing of thermoplastics).
v. The profile is drawn through the PT die with a pulling system. To provide a smooth and uniform pull, the puller system provides a return stroke that is quicker than pulling stroke.
vi. It is trimmed to the needed or desired length when it reaches the cut-off saw. The formed parts can be square, round, rectangular, H-, U-, or I-shaped, and they are determined by size and shape through the cross of the forming dies.

The temperature of the die, preheating, and fiber transit rate are the three most important factors that influence the quality of the goods produced.

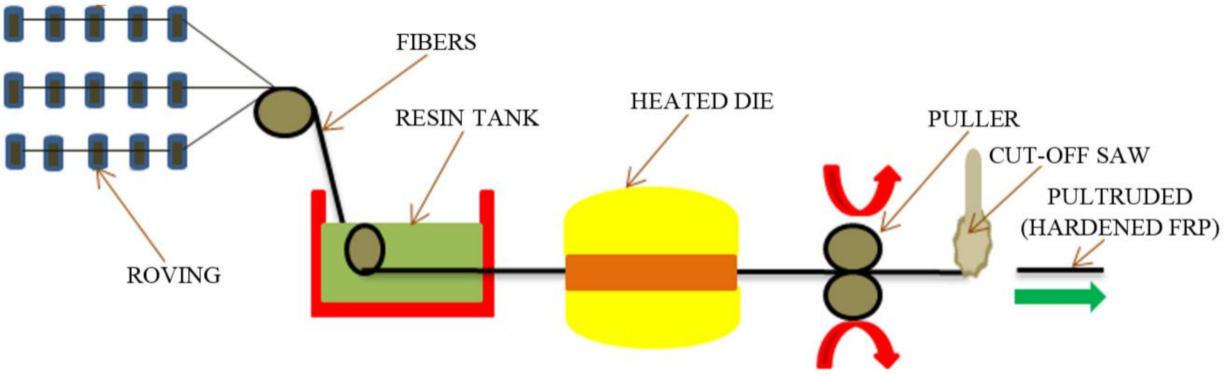


Figure 12: Schematic of the pultrusion process for the fabrication of FRP composites [3], [8], [29]

2.2.3. Applications of GFRC in Engineering

In industry, composite pipes are widely used. Among the many advantages of multi-layer filament-wound composite structures are their high strength and stiffness, resistance to corrosion, and thermal stability. Subsequently, with advances in manufacturing technology, the interest in using fiber-reinforced composite pipes benefit from their ability to replace metal pipes. The energy industry has accepted composite pipes to more situations where metals suffer corrosion or a lightweight is required. Steel has been used in major piping systems, providing a good performance under harsh mechanical loading (e.g., high pressure, large pipe displacement, etc.). Steel pipes deteriorate under corrosive conditions because of internal and external corrosion and initial leakage, which may develop partial or total failure. Some recent studies have taken into account the use of new resistant and noncorrosive materials such as glass and carbon fiber reinforced plastic composite. Fiberglass-reinforced polymer (FRP) is widely applied in many fields due to its superior performance, including use in oil and gas pipes, bridge construction, industrial and public buildings, marine building, and underground infrastructures. Three commercially available materials—carbon-fiber-reinforced polymer (CFRP), glass-fiber reinforced polymer (GFRP), and aramid-fiber reinforced polymer (AFRP)—can easily be introduced into an energy-related pipe. As FRP technologies are non-metallic and noncorrosive by nature, they are less susceptible to chloride corrosion than steel, and introducing FRP can considerably improve the corrosion resistance of the structure [36], [37].

2.3. Mechanical Behavior of Composites

2.3.1. Stress-strain characteristics

Mechanical properties and failure mechanism of short and randomly oriented glass-fiber composite pipes under three-point bending tests were experimentally investigated [35]. The load-carrying capacity, failure mechanism, and deformation performance of the pipes were the primary interests of this study.The main objective of this research was to explore the load-bearing capacity, failure mechanism, and deformation performance of such pipes. The study involved testing 14 well-instrumented composite pipe samples with different diameters, thicknesses, lengths, and nominal pressures. The key findings of the study are: The length-to-diameter (L/D) ratio is an influential parameter that influences the load-carrying capacity of pipes. A larger L/D ratio reduces the load-bearing capacity with increasing flexural behavior. The diameter-to-thickness (D/t) ratio is another effective parameter, where a larger D/t ratio enhances the load-bearing and cross-section deformation capacities. Increasing the nominal pressure from 6 bar to 16 bar enhances the stiffness and strength performance of composite pipes but reduces the cross-section deformation capacity to some extent. The hoop strains were generally larger than the longitudinal strains, and higher pipe pressure and pipe diameter resulted in larger strains. The finite element analysis could accurately predict the structural responses of the composite pipe specimens, demonstrating the validity and reliability of the experimental results.

The paper J. L. C. Diniz, R. D. Vieira [38] was focused on the stress and strain analysis of pipelines with localized metal loss, examining the behavior of damaged pipes under internal pressure. The experiments revealed that long defect regions behave like strips, deforming elastically and plastically in the circumferential and thickness directions. The non-corroded thick walls parallel to the strip restrain longitudinal strains. The study also found that the burst pressure of pipes with defects largely depends on the defect geometry and the restraints caused by adjacent thicker walls, rather than the overall pipe boundary conditions. This model uses thin pipe strength of material equations, a bulging correction factor, and the von Mises criterion. The model's predictions were compared against experimental and numerical results, showing good agreement with a maximum deviation of 10% and an average deviation of +4% .

2.3.1. Mechanical Behavior of Fiber Reinforced Composites

The reinforcement of a polymeric matrix with fibers leads to significant improvements in the mechanical behaviors of the polymer, along with advantages like light weight, high strength-to-weight ratio, good weathering and dimensional stability, low maintenance costs, and the ability to tailor material properties. The paper notes that longer, more isotropic and unidirectional aligned fibers tend to yield the best mechanical performance. The flexibility in fiber length, direction, and type broadens the application range of FRP composites, allowing for customization for specific mechanical requirements [13]. The mechanical properties of fiber-reinforced polymers (FRPs) depend on several factors, including the relative proportions of fiber and matrix, the mechanical properties of the constituent materials (such as the fiber, matrix, and any additives), the orientation of the fiber within the matrix, and the manufacturing method. While the Young's modulus and tensile strength of FRP composites are generally lower than that of the fibers themselves, the volume fraction of fibers typically ranges between 50% and 65%. As a result, each FRP composite exhibits unique mechanical characteristics, making it suitable for specific structural applications. For example, glass fibers are significantly more cost-effective than carbon fibers, but some forms of glass fiber can be highly sensitive to the alkaline environments found in concrete. Additionally, glass fibers have a lower elastic modulus compared to carbon fibers. Regardless of the type of fibers used, FRP materials exhibit similar stress-strain behavior: they are linear and elastic up to the point of brittle rupture under tension. This means that, unlike steel, FRPs lack ductility. Their brittleness limits the ductile behavior of reinforced concrete (RC) members that are strengthened with FRP composites. The matrix in fiber-reinforced polymers (FRPs) serves as the binder, playing several critical roles in the composite material. It holds the fibers together, protecting them from abrasion and environmental degradation. Furthermore, the matrix transfers force between individual fibers and aids in the separation and dispersion of the fibers inside the composite. It is also essential for ensuring chemical and thermal compatibility with the fibers [37].

A comparison of mechanical properties of FRP with steel is provided in Table 3
Table 6: Typical comparative properties of FRP and steel [36]

Material	Tensile Strength (MPa)	Modulus of Elasticity (MPa)
Glass Epoxy	1050	55000
Carbon Epoxy	1500	180000
Aramid Epoxy	1400	76000
Steel	400-1000	200000

The below table gives the mechanical and physical properties of FRP and steel materials. FRPs are more powerful and less heavy than steel. FRPs also have linear elastic mechanical properties with no distinct yielding stage, which results in a decreased failure strain and rate of elongation. In addition, except for some CFRPs with high elastic modulus, the FRP materials have a lower Young's modulus than steel [36].

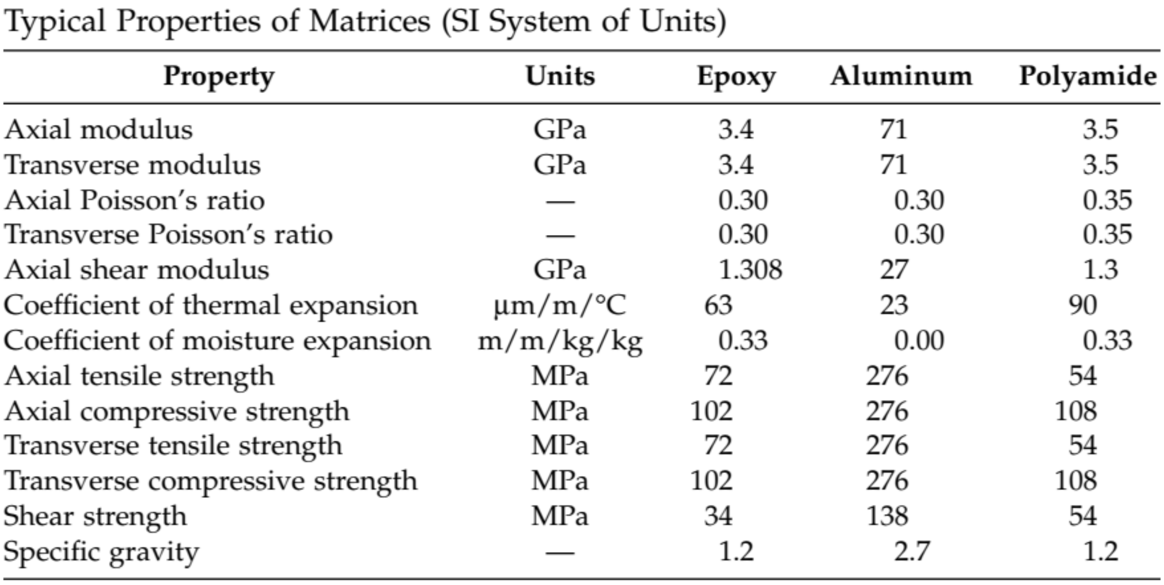
Table 7: Comparison of basic physical and mechanical properties between FRP materials and steel [36].

Material Type	Density (g/cm3)	Longitudinal Coefficient of Linear Expansion (10–6/◦C)	Tensile Strength (MPa)	Young's Modulus (GPa)	Ultimate Elongation %
GFRP	1.25–2.10	6.0–10.0	483–1600	35–51	1.2–3.1
CFRP	1.50– 1.60	−9.0– 0.0	600–3690	120– 580	0.5– 1.7
AFRP	1.25– 1.40	−6.0– 2.0	1720–2540	41– 125	1.9– 4.4
* BFRP	1.90– 2.10	9.0– 12.0	600–1500	50– 65	1.2– 2.6
Steel	7.85	11.7	483–690	200	6.0– 12.0

Table 8: Main physical and mechanical properties of glass fibers

Properties		Type of Glass Fiber							
		A	C	D	E	QR	R	S	S-2
Physical	Density (g/cm3)	2.44	2.52–2.56	2.11–2.14	2.54–2.60	2.70	2.54	2.48–2.49	2.46
Mechanical	Tensile Strength (MPa)	3310	3310	2415	3450	3241	4135	4585	4890
	Elongation at Break (%)	4.8	4.8	4.6	4.8	4.4	4.8	5.4	5.7
	Young’s Modulus (GPa)	68.9	68.9	51.7	72.4	73.1	85.5	85.5–46.9	46.9
	Poisson’s Ratio	0.183	0.276		0.2			0.22	0.23
	Shear Modulus (GPa	29.1	27.0		30.0			35.0	35.0

Table 9: Properties of matrices



Typical Properties of Matrices (SI System of Units)

Property	Units	Epoxy	Aluminum	Polyamide
Axial modulus	GPa	3.4	71	3.5
Transverse modulus	GPa	3.4	71	3.5
Axial Poisson’s ratio	—	0.30	0.30	0.35
Transverse Poisson’s ratio	—	0.30	0.30	0.35
Axial shear modulus	GPa	1.308	27	1.3
Coefficient of thermal expansion	µm/m/°C	63	23	90
Coefficient of moisture expansion	m/m/kg/kg	0.33	0.00	0.33
Axial tensile strength	MPa	72	276	54
Axial compressive strength	MPa	102	276	108
Transverse tensile strength	MPa	72	276	54
Transverse compressive strength	MPa	102	276	108
Shear strength	MPa	34	138	54
Specific gravity	—	1.2	2.7	1.2

The study J. H. H. Williams, [39] investigated the response of Glass Fibre Reinforced Polymer (GFRP) pipe to longitudinal bending caused by vertical ground deformation, simulating a normal fault. The study aims to address the lack of understanding of GFRP pipe failure mechanisms, despite its potential as a lightweight and corrosion-resistant alternative to steel in oil and gas distribution pipelines.

GFRP pipes with the tested dimensions (D/t ratio of 35) demonstrate remarkable flexibility under vertical ground deformation. Serviceability limit states (leakage) were reached in pressurized pipes before ultimate failure. The biaxial strength characteristics of GFRP material under combined bending and overburden pressure warrant further investigation. The study provides valuable experimental data on the response of buried GFRP pipes to vertical ground deformation, a topic with limited previous research. The research contributes to a better understanding of the structural behavior of GFRP pipes under challenging geotechnical conditions, providing data that can inform future design and risk assessment for pipeline infrastructure in areas prone to ground movement.

Mechanical Properties of GFRP Matrix Composites mechanical properties of various GFRP composites based on different fiber types, matrix resins, manufacturing techniques, and testing conditions is discussed. It covers: Tensile strength, Young's modulus, elastic strain, flexural properties, and impact strength in woven-mat GF-reinforced unsaturated polyester composites with varying fiber volume fractions [34].

2.4. Groundwater Riser Pipe Applications

Groundwater originates from atmospheric precipitation, either directly through rainfall infiltration or indirectly from surface water bodies like rivers, lakes, or canals. Common sources of groundwater supply include sands, gravel, sandstones, and limestone formations, although it can also be drawn from impervious rocks like granite if they have an overburden of sand or grave. Groundwater is highlighted as a valuable freshwater resource, constituting about two-thirds of the world's fresh water reserves. Its global reservoir is estimated to be approximately 5.0 × 10^24 L, significantly larger than the volume of water in all the world's rivers and freshwater lakes. Groundwater is utilized for agricultural, industrial, and domestic purposes. It accounts for roughly 50% of livestock and irrigation water usage and just under 40% of water supplies. In rural areas, a significant 98% of domestic water use comes from groundwater. The utilization of groundwater is increasing due to the high capital and maintenance costs associated with surface water development, particularly in developing countries. Improved technology, such as deep boring in the form of boreholes that meet WHO drinking water quality standards, also contributes to this increased reliance on groundwater.

The paper describes different methods of groundwater abstraction, including hand-dug wells, hand-pump operated shallow wells, and submersible pump operated deep wells or boreholes. Water holes are identified as the oldest means of obtaining subsurface water and are classified into four types requiring full conventional treatment. Wells are defined as holes intersecting the water table within water-bearing rocks (aquifers) and are categorized as shallow (less than 15 m deep) or deep (greater than 50 m deep) based on the location of impervious strata. Deep wells (boreholes) can reach depths above 100 to 150 meters, particularly in sedimentary formations, and serve large communities due to their high yield, although they involve high construction and maintenance costs. Regular maintenance and rehabilitation are crucial for deep wells to prevent clogging and corrosion of well screens. Hand-dug wells, constructed manually, are susceptible to pollution but their sanitary status can be improved with features like lining, covers, aprons, and drains. The approximate yield of a properly constructed hand-dug well is estimated between 2,500 to 7,500 m^3/day, although most domestic ones yield less than 500 m^3/day [40].

Groundwater's physical properties, such as its large storage volume and ubiquitous distribution, make it a reliable source less sensitive to rainfall fluctuations and often less capital-intensive to access than surface water. Its natural filtration also often results in high-quality drinking water [41]. This paper investigated the influence of soil characteristics, specifically pH levels (neutral, basic, and acidic), on the structure and long-term behavior of Glass-Reinforced Plastic (GRP) composite materials used for groundwater transport pipes. The authors aimed to study how different soil pH values affect the GRP composite material and calculated a pipe damage index and Pearson correlation coefficients for axial tension based on experimental data. Acidic soil significantly reduces the lifespan of buried GRP pipes, which needs to be considered during the design phase [42].

2.5. Numerical Methods for Damage and Mechanical Behavior Analysis

2.5.1. Overview of numerical methods used in composite material analysis

Water absorption impact on physical properties are a very critical aspect to be taken into account when applying composites to water. When the specimens were dried back to their original condition, the hydrothermal effect of water absorbed was completely reversible, according to a study on the influence of water absorption by structural carbon fiber epoxy-matrix composites [4]. For spooling and operating load cases, Hashin and Max Stress failure criteria have been used to calculate the yielding of plastic liners and failure of FRP layers. Spooling capacity will be lost if the stacking sequence of the laminate is optimized for operation, and vice versa. Therefore, TCP designed for harsh operating environments will always need big diameter storage spools that will have an impact on lifting hardware, installation vessel capacity, and other elements in the short term [7].

Studies by Thompson, P. H., Perry, R., & Green, [21] used advanced simulation techniques to predict the long-term performance of composite pipes, revealing that a combination of internal pressure and external load is often the critical factor in failure. Finite element analysis is today a standard tool for the performance evaluation of composite materials under various loading conditions. Computational methods, i.e., Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD), are significant in evaluating the performance of composite materials in pipeline systems. By using these methods, stress, strain, and failure can be simulated under various operational conditions. FEA models developed by various researchers have shown how the use of numerical analysis contributes to predicting the structural integrity of composite pipes under external loads and internal pressure.

One of the most significant areas of research is the application of numerical simulations for predicting the behavior of composite pipes under actual conditions. By simulating actual loading conditions, including groundwater pressure fluctuation, temperature, and ambient soil movement, researchers are able to predict composite pipe performance over their lifespan. FEA allows for advanced simulations that can be used by researchers to predict stress distribution, deformation, and failure modes [44]. It is a critical method for understanding the behavior of GFRP and CFRP in real-world applications.

Computational modeling is at the core of predicting the performance of composite materials. Advanced modeling techniques can provide an estimate of how these materials will behave in varying conditions to assist in designing and installing improved groundwater piping systems [45]. Numerical models are already being widely used to model the distribution of stress within composite pipes to identify failure points before they occur. The finite element method (FEM) has proven effective at simulating the manner in which composite materials will respond to outside and inside forces. Researchers such as Santos, T. F., et al [46] employed FEM in simulating composite pipe behavior under various loading conditions such as axial load, internal pressure, and bending stresses.

The paper presents a comprehensive review of the application of the finite element method (FEM) to the analysis of composite materials. Strategies for composites modeling, including micromechanics-based, equivalent homogeneous material (EHM), and a combination of the two. The paper discusses the advantages and drawbacks of each. Multiscale modeling approaches, whereby it is feasible to model composite behavior from the nanoscale to the macroscale. This includes the application of representative volume elements (RVEs) and homogenization techniques. Constitutive laws for different types of composite materials, such as anisotropic, orthotropic, and transversely isotropic. The paper presents the mathematical formulations for these material models. The strengths and limitations of these criteria are discussed. Types of finite elements used for modeling composites, such as solid, beam, plate, shell, and cohesive elements. The review highlights how FEM is used to optimize designs, predict failure, and analyze complex phenomena in these domains [47].

2.5.2. Previous Numerical Studies on Composites

The study by T. A. Sebeay and A. Ahmed [36], numerically investigated the behavior of glass-fiber-reinforced plastic (GFRP) composite pipes subjected to constant hydrostatic internal pressure. The study aims to examine the stresses and failure behavior of these pipes by varying winding angles, pipe lengths, and wall thicknesses. The authors used finite element analysis (FEA) with ABAQUS/CAE 2020 to simulate 18 different GFRP composite pipe models. S4R shell elements were employed for the modeling. The study considered pipes with winding angles ranging from [±40]3 to [±70]3, pipe wall thicknesses between 3.78 and 5.1 mm, and lengths from 110 to 660 mm. Hashin damage criteria were adopted to evaluate different failure modes, focusing on tensile and compressive fiber and matrix failures. The GFRP composite pipe was modeled with symmetric/encastre boundary conditions at both ends and subjected to a uniform internal pressure of 10 MPa.

The paper investigated the effects of Winding Angles. The results showed that the highest pressure capacity was observed at a winding angle of [±55°]3. Hoop and axial stress increased up to this angle and then decreased. This finding aligns with the literature suggesting an optimum winding angle around 54.5° for filament-wound pipes under internal pressure. As the L/D ratio increased (due to increased pipe length with constant diameter), pressure capacity decreased. Hoop stress, axial stress, S. Mises stress, and longitudinal and transverse stresses also generally decreased with increasing L/D ratio. The study found that a decreased D/T ratio (due to increased wall thickness with constant diameter) led to an increased pressure capacity. Pressure capacity increased with pipe thickness from 3.78 to 5.1 mm.

The numerical model was validated by comparing its results for a [±55]3 pipe with a 3.78 mm thickness and 450 mm length to experimental data from a previous study, showing excellent agreement in terms of internal pressure capacity. The study identified matrix tensile failure as the primary concern for pipe failure. Failure was considered to occur when the Hashin damage criterion for matrix cracking reached one, leading to potential leakage and structural damage. The average total deformation across all 18 models was reported as 0.37 mm. The authors concluded that winding angles and pipe thickness play a vital role in improving the pressure capacity of GFRP composite pipes. They also highlighted the importance of considering the L/D and D/T ratios in pipe design. The paper recommends future research to focus on the long-term durability of composite pipes under various environmental conditions, their buckling and crushing behavior under external hydrostatic pressure, and the degradation of interfacial bonding at the micro-scale [36].

S. B. Baştürk's [48] study investigated the influence of orientation of fibers in the glass fiber reinforced polymer (GFRP) face sheets on the mechanical response of GFRP/polyvinyl chloride (PVC) foam sandwich composites. The study compares +45/-45 oriented fiber clothes and 0/90 (cross-ply) oriented composites' behavior with compressive and flexural loading. Laminated sandwich composites were produced by a hand lay-up procedure. The face-sheets were made of E-glass fabrics of 600 g/m² areal density bonded to an epoxy resin. A 10 mm thick PVC foam with a density of 80 kg/m³ was used as the core material. Three layers of glass fabric were used for each face-sheet, resulting in a total face-sheet thickness of approximately 4 mm. The samples were cured at room temperature for 48 hours and then post-cured at 80°C for 8 hours before being cut into specific dimensions according to ASTM standards for mechanical testing. The study concluded that for the tested GFRP/PVC sandwich composites, both 0/90 and +45/-45 fiber oriented GFRP skins exhibited similar performance when considering all quasi-static tests, with no significant superiority for either in all aspects. While the EW compressive strength was similar, the +45/-45 orientation showed higher energy absorption. In flexure, the 0/90 orientation showed slightly better strength and a higher failure load to weight ratio, although the face-sheet bending strength values were close .

2.6. Damage Models in Composite Materials

Some of water pipe failure modes include circumferential break, longitudinal split, joint failure, and holes These failure modes are associated with differing forces acting on the pipe. For example, circumferential breaks are often caused by tensile and loading forces, longitudinal splits by transverse and radial forces (like internal pressure), joint failures by tensile or compressive forces, and holes by radial forces combined with corrosion. Joints are integral and can be similar across materials or material-specific. Common types include spigot and socket, bolted mechanical, flanged, butt welded, and push fit. Failures include leaking, fracture, disconnection, and gasket failure, often due to poor installation or ground movement [49].

Circumferential break on an asbestos cement pipe.

Longitudinal split on a polyvinyl chloride pipe.

Corrosion pin hole on an iron pipe.

Joint failure (disconnection or gasket failure) on an asbestos cement pipe.

Figure 13: Modes of failure [49]

Corrosion and Chemical Degradation deteriorate pipes through wall thinning and affect joints. Corrosion rates in metal pipes depend on soil properties (pH, moisture, resistivity, aeration, temperature, salts). Iron corrodes faster than DI and steel, with different failure modes (catastrophic failure vs. leaks). Aggressive soils and disturbed bedding can accelerate corrosion. AC pipes experience lime leaching (in acidic, low-ion water or with very soft conveyed water) and sulphate attack. PVC and PE are corrosion-resistant but vulnerable to organic chemicals, chlorinated water (causing oxidation and embrittlement), UV exposure (for PVC), and biotic factors [49].

2.6.1. Types of Damage in Composites

Key elements influencing pipe failure mechanisms include environmental conditions, material property, internal and external loads. It is extremely difficult to comprehend how the factors are interconnected and how this affects pipe failures. Pipe breakage is caused by operational and environmental conditions affecting pipes whose integrity has been compromised by corrosion, degradation, installation, or manufacturing defects [49]. Joint/connection failure, brittle failure, split pipe, transverse break, graphitization, pitting holes, longitudinal, circumferential failures, spiral cracking, blowout hole, etc., are some of the above types of failure, which are witnessed. Physical properties (size and material), adjacent soil parameters (fracture potential and corrosivity), and temperature have been found to be the most vital among those that lead to mains failures [50].

Failure distributions were established for various pressure and temperature gradient pairings according to the von Mises criterion for isotropic liners and interactive Tsai-Hill for laminates reinforced by fibers. The failure coefficient of the inner liner rises in a sharp fashion when the internal temperature rises at low pressure [7]. It was clear that the most prominent methods of analyzing the failure of composite pipes are hydrostatic, internal, and external pressures. Energy absorption by the combined or independent actions of compressive, tensional, and torsional loading also causes composite pipes to buckle. The buckling response of composite pipes subjected to the FRP composite pipe torsional stress depends on the length, thickness, and diameter of the pipe, as well as the reinforcing elements, matrix, and restraint type [5].

Thermal expansion and contraction due to temperature changes also influence the performance of composite piping materials used in groundwater piping. Effects of thermal cycling on composite pipes showed that composite piping materials that have low coefficients of thermal expansion are more compatible with variable-temperature environments [21]. Temperature and humidity changes are some of the environmental conditions that can significantly affect the performance and lifespan of composite materials [31]. Failure modes of composite materials in pipeline applications include varying delamination, fiber breakage, matrix cracking, and de-bonding between the fibers and the matrix. Failure under internal pressure, external loads, and environmental factors needs to be examined where groundwater pipes are involved. Research conducted by Bhatti, M. M., et al. [51] showed that delamination is the most common mode of failure in composite pipelines under cyclic loading or high-pressure environments. Internal pressure, such as that found in pipelines carrying groundwater, can cause massive stress in composite material. Dvorak, D., et al. [52] concluded that internal pressure would cause matrix cracking, misalignment of the fibers, and then pipe rupture. Numerical computations involving FEA models have also been used to predict initiation and growth of these failure mechanisms with outcomes showing that composite pipes with inappropriately aligned fibers are more prone to failure under internal pressure.

External loads, e.g., traffic loading or soil movement, in groundwater pipeline systems can lead to failure of composite pipes. Studies by Behera, L., & Mishra [53] have shown that the external load resistance of the pipe relies on both the fiber orientation and the matrix properties. Under bending stress or compressive load, composite pipes tend to deform excessively and crack or buckle, particularly in areas where the pipe is laid underground. Fatigue failure constitutes a major problem in pipeline utilization, as the material is subjected to repeated loading and unloading. Fatigue failure within composite materials can be demonstrated through micro cracks, fiber-matrix debonding, or delamination growth. Vichare, D., et al. [54] conducted an experiment demonstrating the importance of fatigue analysis when designing composite pipelines. Computer models to mimic cyclic loading conditions are required so that composite material fatigue behavior under cycles of groundwater pressure can be understood. Flaws in manufacture, such as voids, misalignment of fibers, and resin-rich areas, can seriously help degrade the integrity of composite pipes.

The environmental characteristics, such as temperature fluctuations, moisture content, and microbial proliferation, may greatly influence the performance of composite materials. Wet and humid exposure, according to studies by Liao, M., et al. [55], may lead to water absorption by the polymer matrices, which may have the possibility of affecting the mechanical properties of the composites. Therefore, environmental durability testing in simulated groundwater conditions is crucial in establishing the long-term performance of composite pipes. The space between reinforcement fibers and the matrix material is a critical research area when working with composite materials. Debonding and delamination can lead to failure if these elements do not bond well together. Research by Calado, A., et al. [56] demonstrated that surface treatment or chemical modification of the matrix-reinforcement interface was capable of enhancing the overall strength and failure resistance of composite pipes.

2.6.2. Factors Affecting Damage Evolution in GFRC

Failure analysis of a thermoplastic composite pipe (TCP) under loads experienced during deep-water riser operation and spooling, utilizing finite element (FE) modeling was presented. The study considers the impact of temperature-dependent material properties on the structural integrity of the pipe. The operating load model incorporates internal and external pressures, axial tension, and through-wall thermal gradients arising from the temperature difference between the pipe contents and the surrounding ocean. The TCP layout studied consists of a fiber-reinforced thermoplastic laminate sandwiched between unreinforced thermoplastic inner and outer liners. The laminate is composed of eight 1 mm-thick unidirectional AS4/APC-2 carbon/PEEK layers, arranged in four different stacking sequences labeled A, B, C, and D. Temperature-dependent material properties for the laminate and liners were considered. Perfect bonding between layers was assumed [14].

The paper evaluates failure of the isotropic liners using the von Mises criterion, where a strength ratio (Sr) less than or equal to 1.0 indicates yielding. First ply failure (FPF) in the FRP laminate is assessed using both the Maximum Stress (Max Stress) theory and the Hashin criterion. The Max Stress theory predicts failure when any stress component exceeds the material's strength in that direction. The strength ratio for the laminate is the reciprocal of the failure index for Max Stress and the reciprocal of the square root of the failure index for Hashin. The Hashin criterion is noted to be consistently more conservative than Max Stress due to its consideration of stress interaction effects.As a result, TCP designed for extreme operating conditions will likely necessitate the use of large radius spools for transportation and installation, which has implications for the size of installation vessels and associated equipment. The authors suggest that future work should focus on further validation of lamina failure criteria under combined loading conditions to potentially refine safety factors in design guidelines [14].

The research presents a detailed 3D finite element (FE) model to analyze the stress state and failure response of a thermoplastic composite pipe (TCP) under combined loading. A 3D FE model was developed to study the effects of through-wall thermal gradient on stress-based failure of TCP under combined pressure and axial tension illustrative of a deep-water riser application. The effects of varying pressure and thermal gradient combinations on local TCP failure response were analyzed. The response under different axial tensions at low/high pressures and temperatures was investigated and alternative laminate ply stacking sequences for the TCP were assessed. Temperature-dependent properties were used to define the TCP materials for thermomechanical analysis [57].

In addition, the paper examined the impact of fiber orientation on the mechanical properties of sandwich composites consisting of GFRP face-sheets and PVC foam core. The study encompasses flatwise compression, edgewise compression, and flexural behavior of +45/-45 and 0/90 fiber orientation in the GFRP face-sheets of the sandwich composites. The test indicated that the +45/-45 and 0/90 fiber orientations are both excellent in edgewise compression strength and flexural response with no performance advantage of one over the other. The findings of the test of flatwise compression illustrate the core-dominated nature of the 0/90 GFRP/PVC sandwich composites [48].

2.7. Compatibility of Composites with Groundwater

Composite material suitability for groundwater is crucial to the long-term integrity of a pipeline. Groundwater will generally carry dissolved salts, gases, and other chemicals that will affect the pipe material. Laboratory tests have shown that the dissimilar thermal expansion coefficients of GFRP, CFRP, and traditional materials can lead to stress concentrations and failure points. To determine the performance of composite pipes in groundwater systems, laboratory testing and field trials need to be conducted. The laboratory tests simulate the actual operating scenario and provide valuable information for the validation of numerical models. Their failure-resistance and integrity in structure due to corrosion or material degradation were subjected to various groundwater pressures [58]. It is suggested in researches that while GFRP and CFRP provide durability in the long term, manufacturing and disposal at the end of life can have an extreme environmental effect [59]. These are crucial parameters to be ascertained in order to make material selection sustainable.

2.8. Design and cost Considerations for Composite Groundwater Pipes

The laminate has the most influence on the performance of thermoplastic composite risers. With the right design and manufacture, it is possible to obtain notable benefits over the steel and thermoset counterparts in terms of lightweight, low top-tension, and a wide safety margin in static strength. For composite risers to be successful, laminate design is essential. In order to minimize the global response of the composite risers, such as their deflections, excited modes, and RMS stresses, high axial stiffness is preferred. To endure stress and pressure in a deep-water environment, respectively, high axial strength and hoop strength are required. For the top half of the riser span, where high tension is dominated by larger current magnitudes close to the seawater surface, it is therefore advised to use joints with more axial plies, while the lower half, where pressure is crucial, should use joints with more hoop plies [60].

Selecting the appropriate composite material for groundwater pipe applications involves considering various factors, such as mechanical strength, chemical resistance, and thermal stability. The optimization of material properties is essential for ensuring the reliability and cost-efficiency of groundwater pipelines. Some of the work that has been conducted is on the use of GFRP in piping systems. For example, a work by William Toh, Long Bin Tan, Rajeev K. Jaiman, Tong Earn Tay, Vincent Beng ChyeTan [61] proved the effectiveness of using GFRP pipes in corrosive conditions, with their potential to be used for groundwater purposes. CFRP has been extensively employed in structural applications because of its high strength and low weight. Both GFRP and CFRP possess satisfactory mechanical properties, including high tensile strength and stiffness. An understanding of these properties is necessary to evaluate their applicability in groundwater systems. One of the most significant advantages of composite material is that it resists corrosion. GFRP and CFRP do not corrode when they are exposed to moisture and aggressive chemicals present in groundwater [30]. This property enhances the strength and reliability of piping systems under harsh conditions.

The composite pipeline design has to take into consideration pressure ratings, external loading, and environmental conditions. Numerical analyses are typically employed to maximize the composite pipe design in order to achieve performance requirements with minimal material expense. A study conducted by Li,X.,et al. [62] emphasized the need to include failure mode analysis and stress analysis in the design phase to enhance the reliability of composite groundwater pipes.

2.9. Key Findings from the Literature

The field of composite materials, and more specifically in the field of using groundwater pipes, has been of particular interest due to their potential to enhance durability, mechanical properties, and economic feasibility of buried infrastructure. Extensive research on developing and characterizing composite materials has been conducted, focusing on the role of fiber reinforcement and matrix for enhanced strength, corrosion resistance, and environmental concerns. Scientists have also explored the use of high order numerical methods, such as finite element analysis (FEA) and computational fluid dynamics (CFD), to model the behavior of composite pipes under various loading and environmental conditions. Experiments have shown that composites, i.e., carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP), offer improved performance compared to traditional materials, e.g., concrete or steel, in terms of weight saving and chemical degradation under groundwater.

In recent years, much attention has been given to the integration of numerical analysis with experimental verification as a primary approach for evaluating the prospects of composite materials for groundwater pipes. Researchers have developed multi scale models to forecast the mechanical behavior of composite pipes under a variety of pressure, temperature, and chemical exposure conditions. These studies are valuable in describing failure mechanisms, stress distribution, and long-term durability of composite materials in hostile environments. In addition, published literature on design optimization of composite material properties for a specific pipe application is directed towards the importance of optimizing the orientation of fibers, composition of the matrix, and the process of manufacture in order to produce desirable levels of performance. The existing body of research indicates the capability of composites as a potential substitute for traditional materials in groundwater pipe systems, necessitating the need for further numerical analysis to optimize their design and use.

2.10. Gap in literatures

Although a vast amount of work has been accomplished in the field of mechanical performance and behavior of composite materials in pipeline technology, still a significant gap is present to ascertain the failure modes of composite pipes deployed specifically under groundwater conditions. Literature most often focuses on general failure mechanisms such as cracking, delamination, or deboning of matrices and fibers but does not address the special failure modes evolved as a result of combined groundwater conditions and long-term stress of operation comprehensively. Environmental exposure-induced composite pipe failure in terms of water pressure fluctuation, chemical reaction with groundwater, and soil displacement is inadequately researched. Many studies do not consider interaction among these factors with one another and with passage of time to lead to failure, thus obtaining limited information about composite pipe's true lifespan and reliability under actual field conditions. More sophisticated numerical analysis of failure mechanisms taking into account such complexes, actual field conditions will be needed to predict composite pipes' longevity and safety in groundwater systems.

In addition, there is a significant gap in research regarding the compatibility of composite materials with the surrounding environment, especially in groundwater pipe applications. The areas of compatibility involve interactions between the composite material and water chemistry, temperature, and mechanical stresses caused by the surrounding soil or other structures. Lack of proper understanding of such compatibility issues can lead to unexpected degradation or failure in composite pipes with time. Numerical models used in recent research cannot accurately describe actual behavior of composite materials in terms of long-term performance and failure. This gap will be addressed by developing more advanced numerical models that can capture the interaction between material degradation, mechanical loading, and environmental compatibility, to make more precise failure prediction and optimize composite pipe design.

Chapter Three

3. Theoretical Framework and Methodology

3.1. Introduction

This chapter outlines the numerical modeling techniques, material characterization, simulation setup, and damage criteria used to analyze the mechanical behavior and damage behavior of Glass Fiber Reinforced Composites (GFRCs) in groundwater riser pipe applications. This study investigates the damage behavior, axial stress, radial stress, hoop stress, and total strain of a GFRP composite pipe of specified winding angles, pipe lengths, and pipe thicknesses. Theoretical modeling was carried out to estimate the load-bearing capacity of the GFRP composite pipe and damage behavior using Hashin damage criteria after being subjected to hydrostatic internal pressure. To analyze the GFRP composite, numerical method with Abacus software are used.

3.2. Material Properties and Characterization

The material properties and characterization of Glass Fiber Reinforced Composites (GFRCs) are significant in determining their performance in structural applications such as groundwater riser pipes. GFRCs combine the mechanical strength of glass fibers with the toughness of an epoxy resin matrix to develop a composite material with stronger mechanical properties and resistance to environmental challenges such as corrosion and chemical exposure. The resin and glass fibers are mixed to create a highly strong and resilient material that can be utilized across engineering applications, including in groundwater riser pipes. GFRC's material was simulated as a unidirectional laminate of an epoxy polymer matrix with E-glass fibers dispersed. The assumptions used are:

- Up to damage initiation, the composite behaves as a linear elastic orthotropic material.
- Perfect bonding exists between fiber and matrix.
- Rule of mixture is used to obtain properties of plies.

The mechanical properties of Glass Fiber Reinforced Composites (GFRCs) such as compressive strength, tensile strength, shear strength, and flexural properties are determined from properties of the glass fibers and the resin matrix. The epoxy matrix plays a role in the compressive strength, but the fibers are the ones that prevent buckling or crushing under compression. Glass fibers provide the impact toughness of the composite material, which is important for dynamic load conditions such as unintended impacts or ground vibrations. GFRCs generally possess good fatigue strength, i.e., they can withstand cyclic loads without significant degradation. This is a requirement for application where the riser pipe experiences repeated pressure cycles over life.

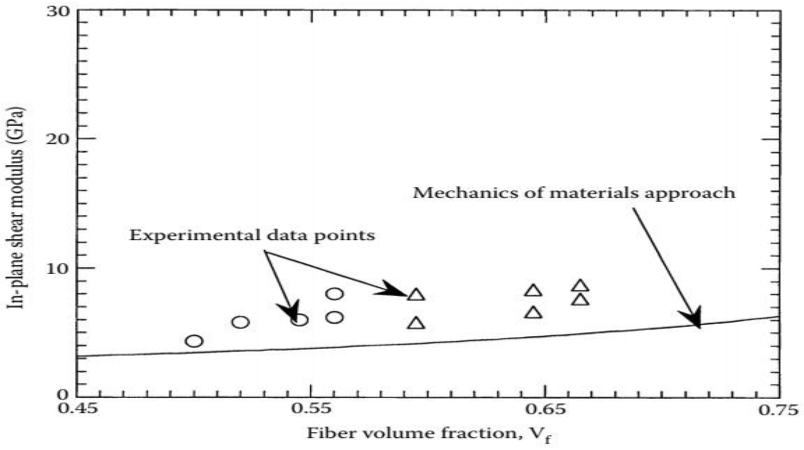


Figure 14: in-plane shear modulus as a function of fiber volume fraction and comparison with experimental values for a unidirectional glass/epoxy lamina

3.3. Numerical Analysis Techniques

Complex engineering problem that cannot be solved analytically can be solved by numerical methods. Numerical methods are used in this research to simulate the mechanical response and development of damage in GFRC groundwater riser pipes under various conditions of loading. Numerical methods are used to solve problems with complex geometry, nonlinear materials, and dynamic loadings by approximating solutions. Finite Element Analysis (FEA) is a tool to analyze the mechanical behavior of composite materials, including GFRCs. FEA is conducted by dividing the domain into an element mesh and solving equations of motion of the individual elements to obtain a global solution. Global and local behavior of composite structures can also be simulated by FEA. Material modeling of GFRCs entails the inclusion of both the mechanical attributes of the glass fibers as well as the matrix of epoxy resin.

3.4. Modeling of Groundwater Riser Pipes

The primary objective of this section is to develop a numerical model of groundwater riser pipes constructed from Glass Fiber Reinforced Composites (GFRCs) and investigate their mechanical performance under varying loading conditions using ABAQUS software. The model will predict the behavior of GFRC pipes under internal and external loading, providing an insight into how the material will behave in real groundwater systems. The material of the riser pipe is E-glass fiber reinforced with epoxy matrix, which is one of the most commonly used composites in such applications due to its high mechanical performance and corrosion resistance. The geometry, boundary conditions, meshing, and simulation setup of the riser pipe model are shown in the subsequent subsections.

3.4.1. Geometry and Dimensions of the Riser Pipe Model

The geometry and dimensions of the ground water riser pipe model are vital to ensuring that the numerical analysis accurately reflects the behavior of the actual system under working conditions. The riser pipe is modeled as a long cylinder with a constant radius, mimicking the structural configuration of typical underground pipes. The total depth of the borehole considered for this study is 120m and the length of each pipe is 6m that resemble real-world products. For modelling purpose internal and external radius considered for this study are 50 mm and 56 mm respectively. The pipe wall thickness is assumed 3 mm, which is less than a typical thickness for pipes used in moderate-pressure environments. The laminate comprises ten 0.3 mm-thick layers. The length of the pipe section modeled in this study is 1.5m meters, representing a typical section of a riser pipe. A longer pipe could be modeled by considering periodic boundary conditions, but for this analysis, a single section is sufficient to capture the relevant mechanical behavior. The geometry of the composite pipe modeled is summarized with table:

Table 10: Pipe dimension of the model

Description	Unit	Size
Pipe outer diameter (mm)	mm	56
Pipe inner diameter (mm)	mm	50
Wall thickness	mm	3
Number of laminate	Pcs	10
Laminate thickness	mm	0.3
Length of Pipe	mm	1500

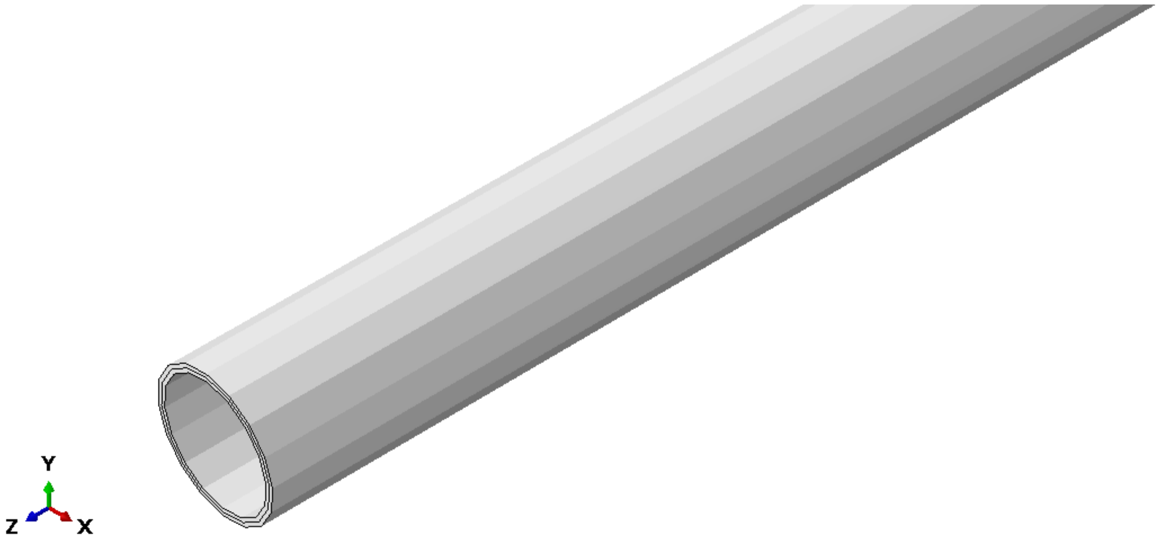


Figure 15: Pipe Model

3.4.2. Material Properties

Glass fiber reinforced with epoxy is proposed for borehole pipes due to its excellent combination of strength, corrosion resistance, and lightness. The glass fibers have high tensile strength and durability, while the epoxy matrix has good chemical resistance, so the pipe is ideal for corrosive underground conditions. In addition, GFRC pipes also possess a longer service life and lower maintenance requirements than the traditional metal pipes and are a cost-effective and reliable choice for borehole application. The riser pipe is modelled by glass fiber reinforced composite (GFRC) material, which consists of E-glass fibers and epoxy resin matrix. E-glass fibers are widely used in composite materials because they possess a high strength-to-weight ratio, corrosion resistance, and low cost. Epoxy has high adhesive strength, good water resistance, and low shrinkage. Young's modulus, shear modulus, poisons ratio and other properties of E-Glass fiber and epoxy matrix from literature review part is stated below.

Table 11: Properties of E-glass fiber and Epoxy Matrix [39]

Property	Unit	E-Glass Fiber	Epoxy Matrix
Young's Modulus	GPa	72.4	3.4
Shear Modulus	GPa	30	1.308
Poisons Ratio	-	0.2	0.3
Density	g/cm3	2.58	1.2

3.4.3. Laminate properties for Pipes

Filament winding is one of the automated processes for FRP composites' manufacturing and can produce high-quality and highly repeatable components at reduced labor cost. For structural filament wound pipes, 60% fiber volume fraction is common because it offers an optimal balance between mechanical performance and manufacturability. As a result, for this research sixty percent fiber volume fraction is considered. Engineering laminate properties of E-glass/epoxy composite pipe specifically;

- E1: Longitudinal modulus (fiber direction)
- E2: Transverse modulus (perpendicular to fibers)
- E3: through-thickness modulus
- G12, G13, G23: Shear moduli
- ν12, ν13, ν23: Poisson's ratios

are essential when modeling the laminate for pipe analysis. We will calculate lamina properties using rule of mixture as follows.

Longitudinal modulus (E1):

$$E_1 = V_f E_f + (1 - V_f) E_m$$

$$E_1 = 0.6x72.4 + (1 - 0.6)x3.4 = \ 44.8 \text{ GPa}$$

Transverse modulus (E2 = E3):

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{(1 - V_f)}{E_m}$$

$$\frac{1}{E_2} = \frac{0.6}{72.4} + \frac{(1 - 0.6)}{3.4}$$

$$E_2 = E_3 = 7.94\ GPa$$

In-plane shear modulus (G12, G13):

$$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{(1 - V_f)}{G_m}$$

$$\frac{1}{G_{12}} = \frac{0.6}{30} + \frac{(1 - 0.6)}{1.308}$$

$$G_{12} = G_{13} = G_{23} = 3.07\ GPa$$

Poisson's ratio (ν12):

$$v_{12} = V_f v_f + (1 - V_f) v_m$$

$$v_{12} = 0.6 * 0.2 + (1 - 0.6) * 0.3 = 0.24$$

To calculate the Young's modulus of a composite after considering moisture content, we must account for the degradation in the mechanical properties, primarily the matrix, due to moisture absorption. Moisture affects resin (matrix) more than fiber. We use a degradation factor D(M) to modify the matrix modulus:

$$E_m(\mathrm{M}) = E_m dry.(1 - D(M))$$

- M is moisture content (%)
- D(M)is degradation coefficient (typical values for epoxies: 0.05 to 0.2 per % moisture)

If moisture content M=1%, and degradation rate is 10% per %, then:

$$E_m(\mathrm{M}) = E_m dry.(1 - 0.1) = 0.9 E_m$$

By updating the rule of mixtures using the moisture-adjusted matrix modulus we can recalculate the Composite Modulus and other properties for analyzing the effect of water absorption.

The composite consists of E-glass fibers embedded in an epoxy matrix. The mechanical properties used in the simulation are summarized in Table below.

Table 12: Ply properties of GFRP Composite

Property	**Value (M= 0%)**	**Value (M=2%)**	**Note**
Longitudinal Young's modul, E_1	44.8GPa	44.5GPa	Fiber direction (0°)
Transverse Young's moduli, $E_2 = E_3$	7.94GPa	6.4GPa	Transverse directions (90°, Z)
Shear modulus G_{12}	3.07GPa	2.487GPa	In-plane shear
Shear modulus , G_{13}	3.07GPa	2.487GPa	Fiber to thickness
Shear modulus, G_{23}	3.07GPa	2.487GPa	Transverse shear
Poisson's ratio , v_{12}	0.24	0.24	Major Poisson's ratio
Poisson's ratio, v_{13}	0.24	0.24	Assumed as v12
Poisson's ratio, v_{23}	0.3	0.3	Matrix-dominated
Property	Value	Value	K (Degradation coefficient)
Longitudinal tensile strength, Xt	700MPa	420MPa	0.1
Longitudinal compressive strength, Xc	79MPa	63.2MPa	0.2
Transverse tensile strength, Yt	79MPa	51.35MPa	0.35
Transverse compressive strength, Yc	65MPa	48.75MPa	0.25
Longitudinal shear strength, S12	50MPa	37.5MPa	0.25
Transverse shear strength, S23	50MPa	30MPa	0.4

To incorporate degradation due to moisture in Abaqus

$$P(M) = P_0\left(1 - k.\frac{M}{M_{Sat}}\right)$$, Where:

- P(M): Property at moisture content M
- P0: Dry property
- k: Degradation coefficient (specific to property)
- Msat: Saturation moisture content (2%)

3.4.4. Laminate Layup / Winding Pattern

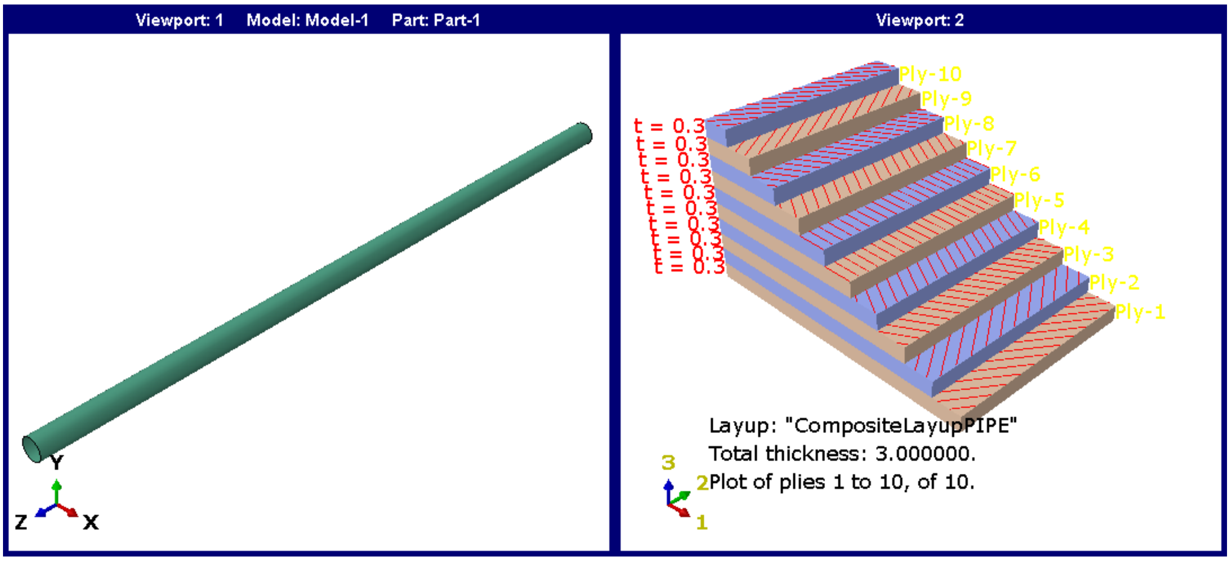
Using a (55/−55/30/−30/0)s stacking sequence in a GFRP (Glass Fiber Reinforced Polymer) composite pipe provides balanced and mechanically efficient structure for pipes subjected to complex loading conditions such as internal pressure, torsion, and axial loading. The layup is selected particularly to achieve optimum strength and stiffness in multiple directions.

- ±55° plies are ideal for hoop stress resistance; the layers improve resistance to torsion and render the pipe more resistant to twisting loads.
- ±30° plies provide moderate shear strength and help with stress redistribution between the ±55° and 0° plies.
- The 0° plies are aligned on the pipe's longitudinal axis and play a significant role in providing high axial stiffness and strength such that the pipe is resistant to axial loading and capable of withstanding elongation or buckling.

Compared to more conventional layups like [0/90]s or [±45]s which preferentially localize strength in just two predominant directions, the $(55/-55/30/-30/0)_s$ sequence offers a broader distribution of mechanical properties across the circumference and length of the pipe. This reduces the level of internal stress, reduces the possibility of delamination and improves fatigue resistance to cyclic loads. Additionally, this layup improves the pipe's damage tolerance and overall durability, such that the pipe is improved for long-term application. In general the $(55/-55/30/-30/0)_s$ layup sequence is an optimized layup that performs better under multi-axial loading than traditional fiber orientations, ensuring that the composite pipe is stronger, more durable, and more resistant.

Table 13: Ply winding pattern

Layer	Orientation	Layer thickness	Purpose
1–2	±55°	2 × 0.3 mm = 0.60 mm	Main hoop strength
3–4	±30°	2 × 0.3 mm = 0.60 mm	Axial support
5	0°	0.3 mm	Axial stiffness
6	0°	0.3 mm	Final longitudinal layer
7–8	±30°	2 × 0.3 mm = 0.60 mm	Further axial/bending reinforcement
9–10	±55°	2 × 0.3 mm = 0.60 mm	Outer hoop and impact resistance



Layup: "CompositeLayupPIPE"
Total thickness: 3.000000.
Plot of plies 1 to 10, of 10.

Figure 16: Composite layup

3.5. Boundary Conditions and Load Cases

In order to simulate the mechanical response of the GFRC riser pipe accurately, appropriate boundary conditions and load cases must be applied. These conditions represent how the pipe interacts with its surrounding environment (soil and groundwater) during operational conditions.

3.5.1. Fixed Boundary at Pipe Ends

The ends of the riser pipe are assumed to be fixed, representing the point of attachment to other sections of the pipeline or supporting structures at wellhead. This boundary condition restricts translations and rotations, preventing rigid body motion. This is a typical condition for pipes that are connected to a fixed infrastructure.

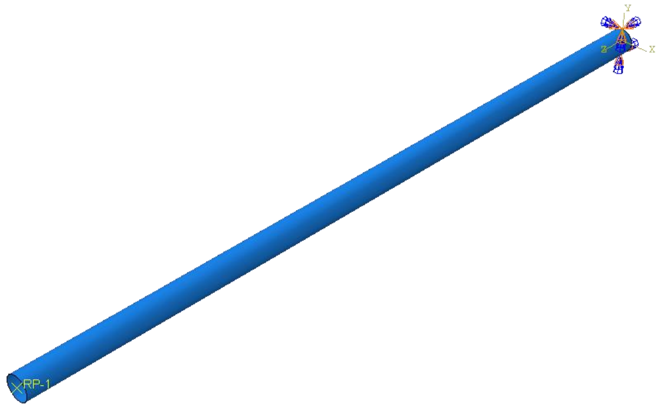


Figure 17: Fixed End boundary condition

3.5.2. Axial Load (Due to Pipe Self-Weight, Fluid Column and pump weight)

3.5.2.1 Pipe weight:

To calculate the weight of a composite pipe (E-glass/epoxy), we need to find the volume of the composite material and then multiply it by its density. From the standard pipe length and geometry defined above:

- $D_O = 56mm, \;\; D_i = 50mm, \;\; L = 6000mm$

Calculate the volume of the pipe wall

$$V = \frac{\pi}{4}\left({D_O}^2 - {D_i}^2\right).L \;= \frac{\pi}{4}(56^2 - 50^2).6000 = 2{,}997{,}079.4mm3 = 2{,}997.08cm3$$

Composite density depends on the fiber volume fraction V_f and the densities of fiber and matrix.

$\mathrm{\rho_c = V_f.\rho_f + (1 - V_f).\rho_m} = 0.6 * 2.58 + (1 - 0.6) * 1.2 =$**2.028 g/cm3**

Weight of each pipe

$W = \rho_C.V.g$=2.028g/cm3*2,997.08cm3*9.8m/s2=59,565.17gm/s2=59.56kgm/s2= **59.56N**

Based on the total depth of the well which is 120m the total number of pipe is 20 and total weight of pipe become **1,191.2N**

3.5.2.2 Pump weight

Pump weight comprises the weight of pump and motor. For this study, standard average weight of 7.5KW pump is considered and average data is taken from pump manufacturer's catalogue.

Table 14: Pump performance data

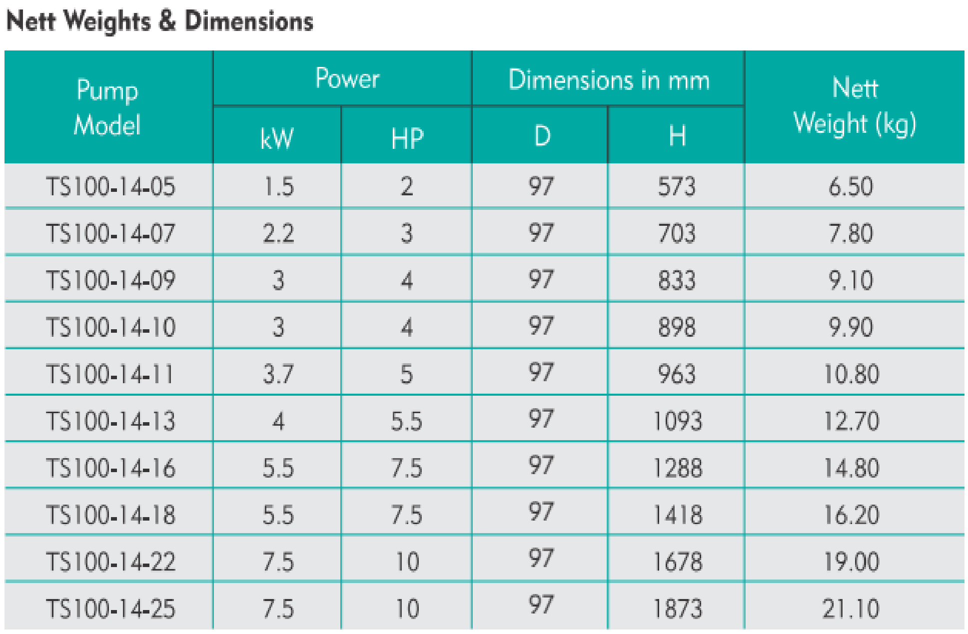
PERFORMANCE DATA

TS SERIES 〉 **4"** 〉 **14 m^3/h**

Model : **TS 100 - 14**　Outlet Size : **2"**　**2900 rpm**

Pump Model	Power		lpm	0	66.6	100	133.3	166.6	200	233.4	266.4	300
	kW	HP	m^3/h	0	4	6	8	10	12	14	16	18
TS 100-14-05	1.5	2	TOTAL DYNAMIC HEAD IN METRES	31	30	29	28	26	23	20	16	12
TS 100-14-07	2.2	3		42	41	40	39	37	33	29	24	15
TS 100-14-09	3	4		56	55	53	51	47	43	38	32	25
TS 100-14-10	3	4		65	63	60	57	54	49	43	37	29
TS 100-14-11	3.7	5		75	72	70	66	62	56	50	42	32
TS 100-14-13	4	5.5		85	83	80	75	70	64	56	47	36
TS 100-14-16	5.5	7.5		104	102	99	95	89	81	71	59	44
TS 100-14-18	5.5	7.5		119	115	112	107	100	91	81	56	50
TS 100-14-22	7.5	10		141	136	132	127	120	111	96	78	58
TS 100-14-25	7.5	10		161	156	152	145	137	125	110	91	68

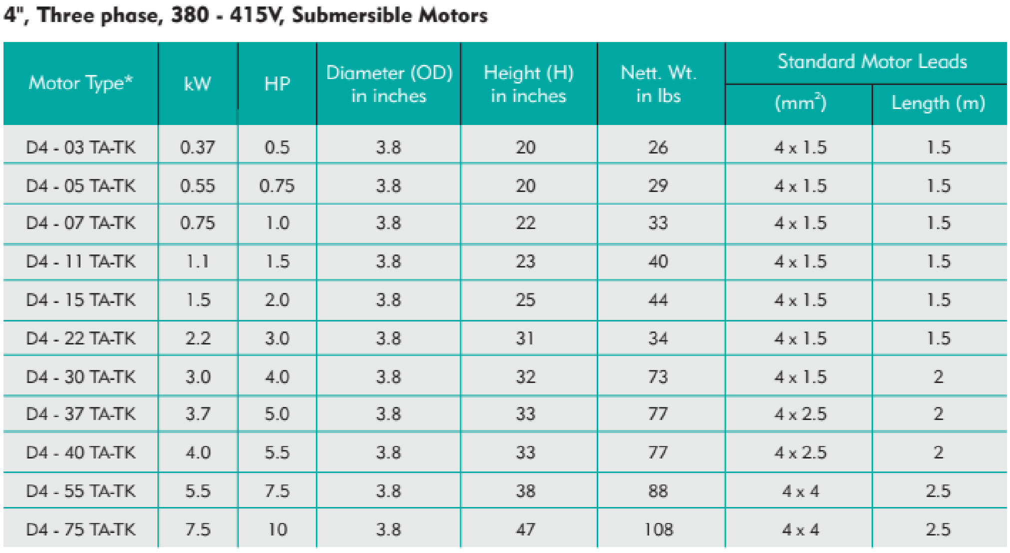
Table 15: Pump Specification



Nett Weights & Dimensions

Pump Model	Power		Dimensions in mm		Nett Weight (kg)
	kW	HP	D	H	
TS100-14-05	1.5	2	97	573	6.50
TS100-14-07	2.2	3	97	703	7.80
TS100-14-09	3	4	97	833	9.10
TS100-14-10	3	4	97	898	9.90
TS100-14-11	3.7	5	97	963	10.80
TS100-14-13	4	5.5	97	1093	12.70
TS100-14-16	5.5	7.5	97	1288	14.80
TS100-14-18	5.5	7.5	97	1418	16.20
TS100-14-22	7.5	10	97	1678	19.00
TS100-14-25	7.5	10	97	1873	21.10

Table 16**:** Motor specification



4", Three phase, 380 - 415V, Submersible Motors

Motor Type*	kW	HP	Diameter (OD) in inches	Height (H) in inches	Nett. Wt. in lbs	Standard Motor Leads	
						(mm^2)	Length (m)
D4 - 03 TA-TK	0.37	0.5	3.8	20	26	4 x 1.5	1.5
D4 - 05 TA-TK	0.55	0.75	3.8	20	29	4 x 1.5	1.5
D4 - 07 TA-TK	0.75	1.0	3.8	22	33	4 x 1.5	1.5
D4 - 11 TA-TK	1.1	1.5	3.8	23	40	4 x 1.5	1.5
D4 - 15 TA-TK	1.5	2.0	3.8	25	44	4 x 1.5	1.5
D4 - 22 TA-TK	2.2	3.0	3.8	31	34	4 x 1.5	1.5
D4 - 30 TA-TK	3.0	4.0	3.8	32	73	4 x 1.5	2
D4 - 37 TA-TK	3.7	5.0	3.8	33	77	4 x 2.5	2
D4 - 40 TA-TK	4.0	5.5	3.8	33	77	4 x 2.5	2
D4 - 55 TA-TK	5.5	7.5	3.8	38	88	4 x 4	2.5
D4 - 75 TA-TK	7.5	10	3.8	47	108	4 x 4	2.5

$$\mathrm{W}_{\text{pump + motor}} = \mathrm{W}_{\text{pump}} + \mathrm{W}_{\text{motor}} = \left(\frac{108}{2.205} + 21.10\right) * 9.8 = (48.99kg + 21.10kg) * 9.8$$

$$= 70.09kg * \frac{9.8m}{s2} = 686.88N$$

3.5.2.3 Fluid weight

$$W_{fluid} = m_{fluid}.\mathrm{g} = \rho_{fluid}.V.g$$

$$W_{fluid} = m_{fluid}.\mathrm{g} = \rho_{fluid}.V.g \qquad \text{Where}$$

$$\rho_{fluid} = \rho_{water} = 1000kg/m3$$

g=9.81m/s2

$$\mathrm{V} = \frac{\pi D^2}{4}\mathrm{h} = \frac{\pi(50mm)^2}{4} * 120 * 1000\mathrm{mm} = 235{,}619{,}449.02\mathrm{mm3} = 0.235\mathrm{m3}$$

$$W_{fluid} = \rho_{fluid}.V.g = \frac{1000kg}{m3} * 0.235m3 * \frac{9.81m}{s2} = 2{,}305.35N$$

Total axial load

$$W_{total} = W_{pipe} + W_{pump+motor} + W_{fluid}$$

$$= 1{,}191.2\mathrm{N} + 686.88N + 2{,}305.35N = 4{,}183.43N$$

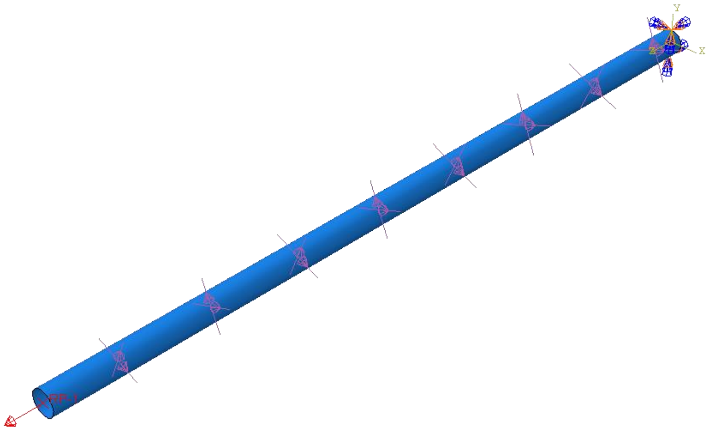


Figure 18: Axial Load on Pipe

3.5.3. Internal Fluid Pressure:

In the analysis of the submerged water pipe, only the hydrostatic pressure is considered, as it is the most dominant force acting on the pipe. Any other potential stresses, such as dynamic pressure due to movement of water or atmospheric pressure, are too small. And if the pipe is stationary and the water supply is slow or steady, transient and dynamic pressures do not count. Therefore, focusing solely on hydrostatic pressure simplifies the analysis without compromising safety or accuracy for most applications in the real world. A uniform internal fluid pressure is considered to be applied on the inner surface of the riser pipe to simulate the pressure exerted by the groundwater or fluid inside the pipe. This pressure comprises hydrostatic pressure from the water column and pump discharge pressure.

$$P_{total} = P_{hydrostatic} + P_{pump}$$

The pressure exerted by a column of water at a depth h is given by the hydrostatic pressure formula

$P_{hydrostatic} = \rho g h$, Where:

- P is the pressure at depth h (in Pascal’s, Pa).
- ρ is the density of water (kg/m³).
- g is the acceleration due to gravity (m/s²).
- h is the height of the water column (m).

The **discharge pressure** can be derived from the head using the following relationship:

$P_{pump} = \rho g H$, Where,

- P pump is the pressure at the pump discharge (in Pascals, Pa).
- H is the head (in meters).

- ρ is the density of water (typically 1000 kg/m3 for fresh water).
- g is the acceleration due to gravity (9.81 m/s2).

$P_{\text{hydrostatic}}$= 1000kg/m3* 9.81m/s2*125m = **1.226MPa**

$$P_{total} = 1.177\text{MPa} + 1.226\text{MPa} = \mathbf{2.403MPa}$$

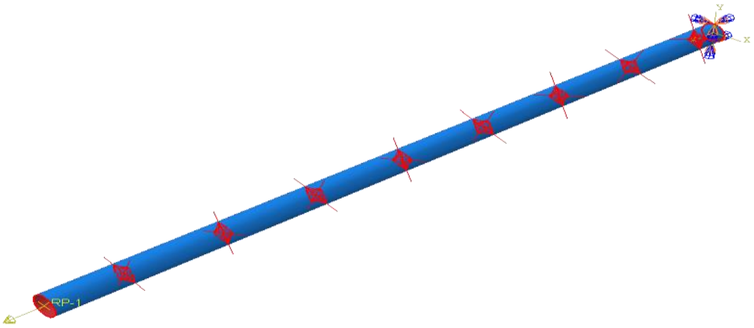


Figure 19: Internal Pressure

Depending on the operational conditions, internal fluid pressure typically ranges from **0.5 MPa to 2.5 MPa** for groundwater applications. The internal pressure is applied as a normal load along the pipe's inner surface, contributing to hoop stresses on the pipe walls.

Table 17: Summarized load

ITEM	Load type	Unit	Value
1	Axial load (Force)	N	4,183.43
2	Internal fluid Pressure	MPa	2.403

3.5.4. External Soil Pressure, water Absorption, Buoyancy and Thermal effect

In the analysis of GFR composite groundwater pipe, the external soil pressure, thermal, and buoyancy effects have been excluded. These are site condition-based decisions where the soil loads are minimal, temperature gradients are negligible, and the pipe installation depth and surrounding soil density minimize the buoyancy forces. These all are hence seen to be considered as contributing minimally to the structure performance of the pipe. Water absorption can alter the long-term mechanical properties of the composite by causing matrix plasticization, degradation of the fiber-matrix interface, and swelling, all of which reduce the pipe's stiffness and strength. By placing the focus on water absorption, the design better reflects the actual environmental conditions affecting long-term structural strength in groundwater applications. The pipe is assumed to be buried underground inside casing. As a result external soil pressure is negligible for the column pipe. Furthermore, for this study, uniform ground water temperature is assumed and thermal effect is negligible for this case. The water absorption effect is considered and analyzed for the fully saturated moisture content of 2%.

3.6. Meshing and Simulation Setup

The numerical model is discretized into smaller elements through meshing, which allows for the finite element analysis (FEA) to be conducted efficiently. A fine mesh is applied to areas of the riser pipe that are expected to experience high stress gradients, such as the pipe ends, and regions under high internal pressure. A finer mesh around these areas ensures that localized phenomena like damage initiation and stress concentrations are captured more accurately.

The mesh consists of tetrahedral elements for a 3D simulation, as this element type is commonly used in complex geometries. These elements allow for precise representation of the pipe's curvature. The element size near critical regions is chosen to balance computational efficiency and accuracy. For this model, an element size of 2 mm is applied.

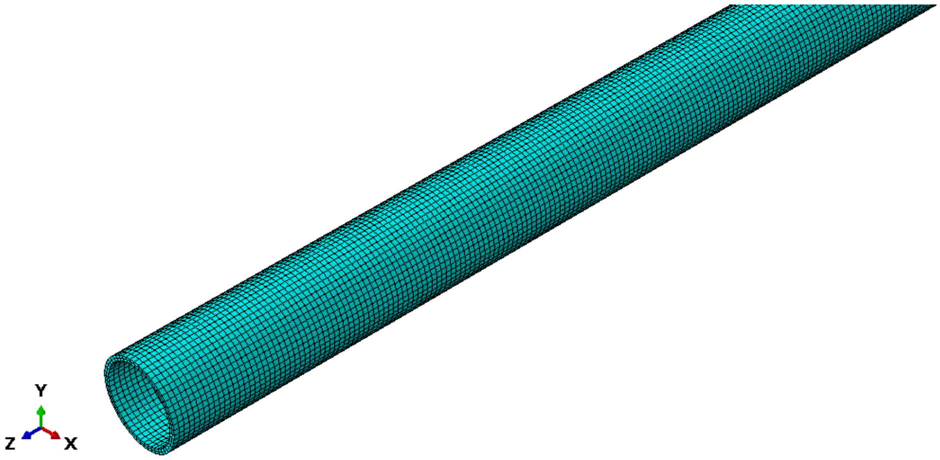


Figure 20: GFRC Pipe Mesh

The material properties of E-glass fibers and epoxy resin (discussed earlier) are assigned to their respective regions of the model. Boundary conditions (fixed supports, internal fluid pressure and weight) are applied to simulate real-world constraints and loadings. A 3D shell/solid model was developed in ABAQUS CAE, with the following BC and loading.

- Boundary Conditions: One end fixed other end subjected to loading.
- Axial load applied at the other end
- Internal pressure of 2.403MPa is applied to evaluate internal pressurization behavior.
- Progressive damage modeling using Hashin failure criterion,

3.7. Damage Models and Constitutive Equations

The damage analysis aims to predict the progression of material degradation in the GFRC riser pipe under the applied loading conditions. Several damage models and failure criteria are utilized to simulate damage mechanisms, such as matrix cracking and fiber breakage. Understanding and modeling damage in GFRCs is essential for predicting the material's behavior under real-world loading conditions. The damage models and constitutive equations allow simulation of degradation of the composite material under load so that failure can be predicted. Damage mechanics of GFRCs involves modeling of damage accumulation in the matrix and the fiber. The damage may initiate in the form of micro cracks in the matrix, fiber breakage, or delamination at the fiber-matrix interface. The propagation of these damages is governed by constitutive equations representing the relation between the stress, strain, and damage variables.

3.7.1. Continuum Damage Mechanics (CDM)

CDM approach is used for simulating the progressive damage of the composite material. In CDM, the material stiffness reduces with the increase in damage, and the damage variables are updated in each load increment. The model can capture the micro crack growth in the matrix and fiber failure. The material properties, i.e., the stiffness matrix, are refreshed in each analysis step based on the damage state. The CDM model accounts for the development of cracks in the matrix and the loss of load-carrying capability.

3.7.2. Cohesive Zone Model (CZM)

The CZM is used to model the delamination or failure at the interface between the glass fibers and the epoxy matrix. This model is particularly useful for simulating the crack initiation and propagation at the fiber-matrix interface, which can lead to catastrophic failure in composite materials. It is crucial for capturing the delamination or debonding behavior that may occur when the interfacial stress exceeds the bonding strength.

3.7.3. Maximal Strain Theory

This theory is another approach employed to predict failure in composite materials. It predicts that failure will be achieved when the composite is under maximum strain. This theory can be applied along with other failure criteria to provide a complete explanation of composite failure under load.

3.7.4. Hashin’s Failure Criterion

Hashin's failure criterion is extensively used for estimating the failure modes in composite materials under multiaxial loading. Hashin's failure criterion takes into consideration different failure modes, including fiber failure in compression and tension and tensile matrix cracking and matrix shear failure. The criterion is used to determine failure initiation based on stresses and strains of the composite. The criterion considers the fiber and matrix stresses and selects the possible failure based on the applied load conditions.

3.8. Criteria for Failure in GFRCs

When evaluating various failure modes using several stress components, the Hashin criteria are applied. In 2D classical lamination theory, the Hashin criterion is typically applied, and point conversion is employed as the material degradation model when calculating point stress. The criterion is applied to three-dimensional situations, where the transverse normal stress component is subject to the maximum stress criterion. The damage initiation was predicted using Hashin's failure criteria, which included four damage initiation processes to identify matrix and fiber failures under tension and compression. The following failure modes are part of Hashin's criterion:

Tensile fiber failure for $\sigma_{11} \geq 0.0$

$$\left(\frac{\sigma_{11}}{X_T}\right)^2 + \left(\frac{\sigma_{12} + \sigma_{13}}{{S_{12}}^2}\right)^2 \geq 1.0$$

Compressive fiber failure $\sigma_{11} < 0.0$

$$\left(\frac{\sigma_{11}}{X_C}\right)^2 \geq 1.0$$

Tensile matrix failure for $\sigma_{22} + \sigma_{33} > 0.0$

$$\left(\frac{\sigma_{22} + \sigma_{33}}{{Y_T}^2}\right)^2 + \frac{{\sigma_{23}}^2 - \sigma_{22}\sigma_{33}}{{S_{23}}^2} + \frac{{\sigma_{12}}^2 + {\sigma_{13}}^2}{{S_{12}}^2} \geq 1.0$$

Compressive matrix failure $\sigma_{22} + \sigma_{33} < 0.0$

$$\left[\left(\frac{Y_C}{2S_{23}}\right)^2 - 1\right]\frac{\sigma_{22} + \sigma_{33}}{Y_C} + \frac{(\sigma_{22} + \sigma_{33})^2}{4{S_{23}}^2} + \frac{{\sigma_{23}}^2 - \sigma_{22}\sigma_{33}}{{S_{23}}^2} + \frac{{\sigma_{12}}^2 + {\sigma_{13}}^2}{{S_{12}}^2} \geq 1.0$$

Where the subscripts T and C represent tensile and compressive strengths of the laminate, respectively, and σ ij for the stress component. For tensile load, the strength coefficients are X_T, Y_T, and Z_T; for compression load, X_C, Y_C, and Z_C. Also, shear strengths in the respective primary orientation of the material are S12, S13, and S23. Because it takes into account how various in-plane stress components interact with one another, it can make a precise calculation of the initiation of failure based on the Hashin failure criteria. Because GFRP composite pipes have a thickness to diameter ratio of 0.06, less than 0.1, they were assumed thin-walled. Any time one of the modes of failure, like matrix cracking, attained one in the Hashin damage criteria, the pipe was deemed failed. Later, the composite pipe would not be functional as it would burst or leak.

3.8.1. Damage Analysis and Criteria

Stresses computed using the FE models are used to evaluate failure of isotropic liners and FRP laminate. Liner yielding is evaluated according to the von Mises criterion. The von Mises stress is:

$$\sigma_{VM} = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}}$$

and the strength ratio is:

$$s_r = \frac{\sigma_y}{\sigma_{VM}}$$

Where σy is the yield strength. A ratio of Sr ≤ 1.0 indicates failure. In this study, first ply failure (FPF) of the laminate is evaluated according to Maximum Stress (herein “Max Stress”) and Hashin criteria. The Max Stress theory assumes failure occurs when any lamina stress component exceeds the corresponding allowable stress. The failure index is

$$I_F = \max \left\{ \begin{matrix} \sigma_1/X_T \ \ if\ \sigma_1 > 0\ \ or\ \ |\sigma_1|/X_C\ \ if\ \sigma_1 < 0 \\ \sigma_2/Y_T\ \ if\ \sigma_2 > 0\ \ or\ \ |\sigma_2|/Y_C\ \ if\ \sigma_2 < 0 \\ \sigma_3/Z_T\ \ if\ \sigma_3 > 0\ \ or\ \ |\sigma_3|/Z_C\ \ if\ \sigma_3 < 0 \\ |\tau_{23}|/Q \\ |\tau_{13}|/R \\ |\tau_{12}|/S \end{matrix} \right\}$$

Where X, Y and Z are tensile and compressive strengths (subscripts ‘T’ and ‘C’) along material directions 1, 2 and 3 respectively; Q, R, S are shear strengths in planes 23, 13, 12 respectively.

Chapter Four

4. Results and Discussion

4.1. Introduction

This chapter presents the results obtained from the numerical simulations conducted on glass fiber-reinforced polymer (GFRP) composite riser pipes and interprets the stress result under different loading conditions. The study employed finite element analysis (FEA) using ABAQUS CAE, with progressive damage modeling based on failure criteria suitable for composite materials (Hashin). The focus is on a pipe with an internal diameter of 50 mm, length of 1.5 meters, wall thickness of 3 mm, and a symmetric 10-ply laminate layup [55°, -55°, 30°, -30°, 0°]s made from unidirectional E-glass/epoxy lamina. The results focus on the stress-strain behavior, damage initiation and progression, and overall mechanical performance under internal pressure and axial loads simulating in-service conditions. The damage behavior and hashin failure index are evaluated using Hashin failure criteria.

4.2. Von Mises Stress Result

An appropriate measure of the behavior of a composite pipe under multiaxial loading conditions, such as internal pressure, axial tension, and external environment loads, is the von Mises stress at the pipe plies. Composite pipes, in contrast to isotropic materials, are composed of multiple layers (plies) with different fiber directions. The layup configuration and material ply properties are therefore fundamental in assessing the stress distribution. According to classical lamination theory, the global stress components in cylindrical coordinates are converted into the local ply coordinate system to find von Mises stress for each ply.

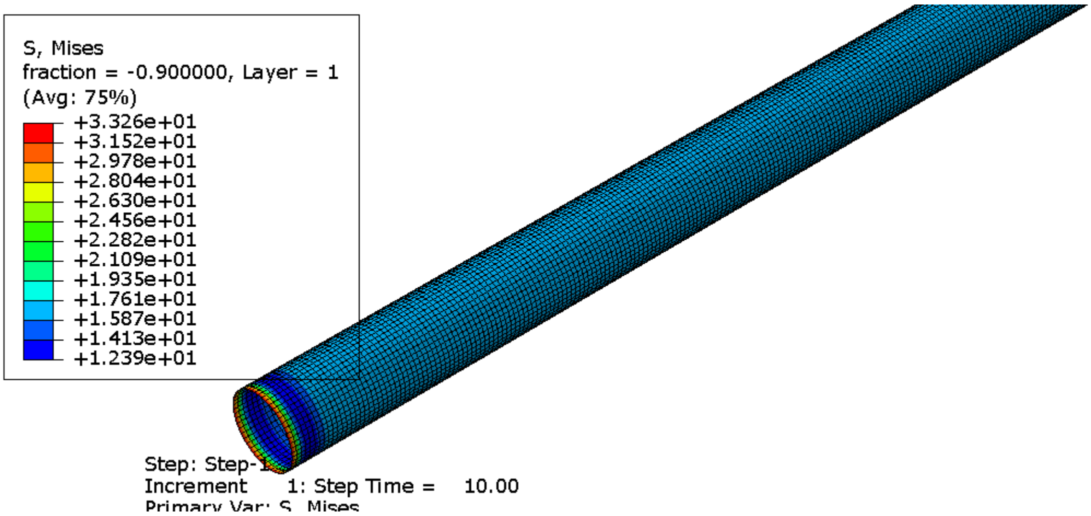


Figure 21: Von Mises Stress in MPa

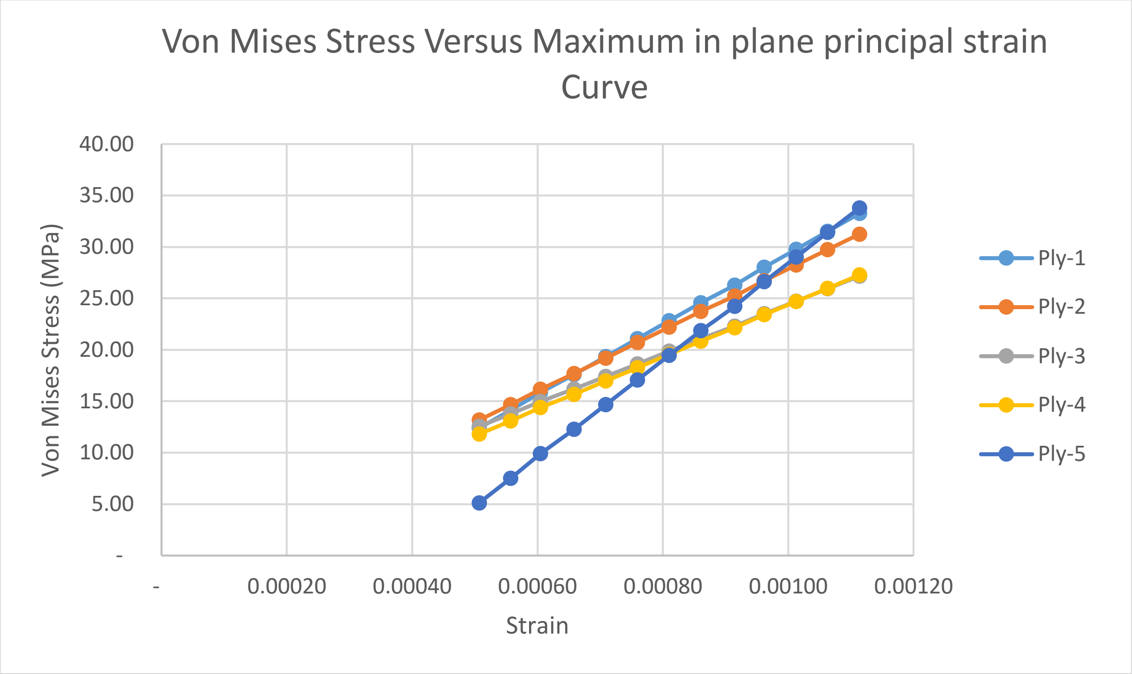


Figure 22: Von Mises Stress versus maximum in plane principal strain

Under normal operating condition, the maximum value of von mises stress is observed on ply one and its value is 33MPa. The stress strain curve of plies shown above indicates linear relation of von mises stress with strain.

4.3. Global Stress result

The global stress results of the composite pipe indicates the stress value , calculated in cylindrical coordinates with the Z-direction in the direction of the pipe length and the θ-direction in the direction of the global Y-direction (0, 1, 0), and it gives a general view of the mechanical behavior of the pipe.

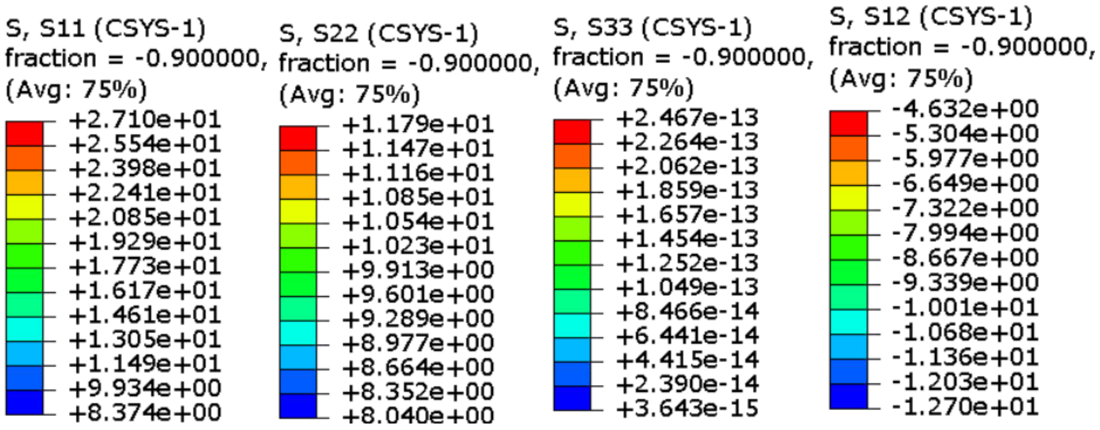


Figure 23: Global Stress Result in MPa

The Von Mises stress captures the equivalent sum of all stresses, which can be used to verify for potential yield or failure. Here, S11 represents the axial stress along pipe length (direction Z), S22 is the radial outward stress from the center of the pipe and S33 is the hoop or circumferential stress (direction θ, Y-axis direction), and. The S12 component is utilized to bring about shear stress in the axial-hoop direction. These are values needed to account for pipe strength and integrity under internal pressure and mechanical loadings.

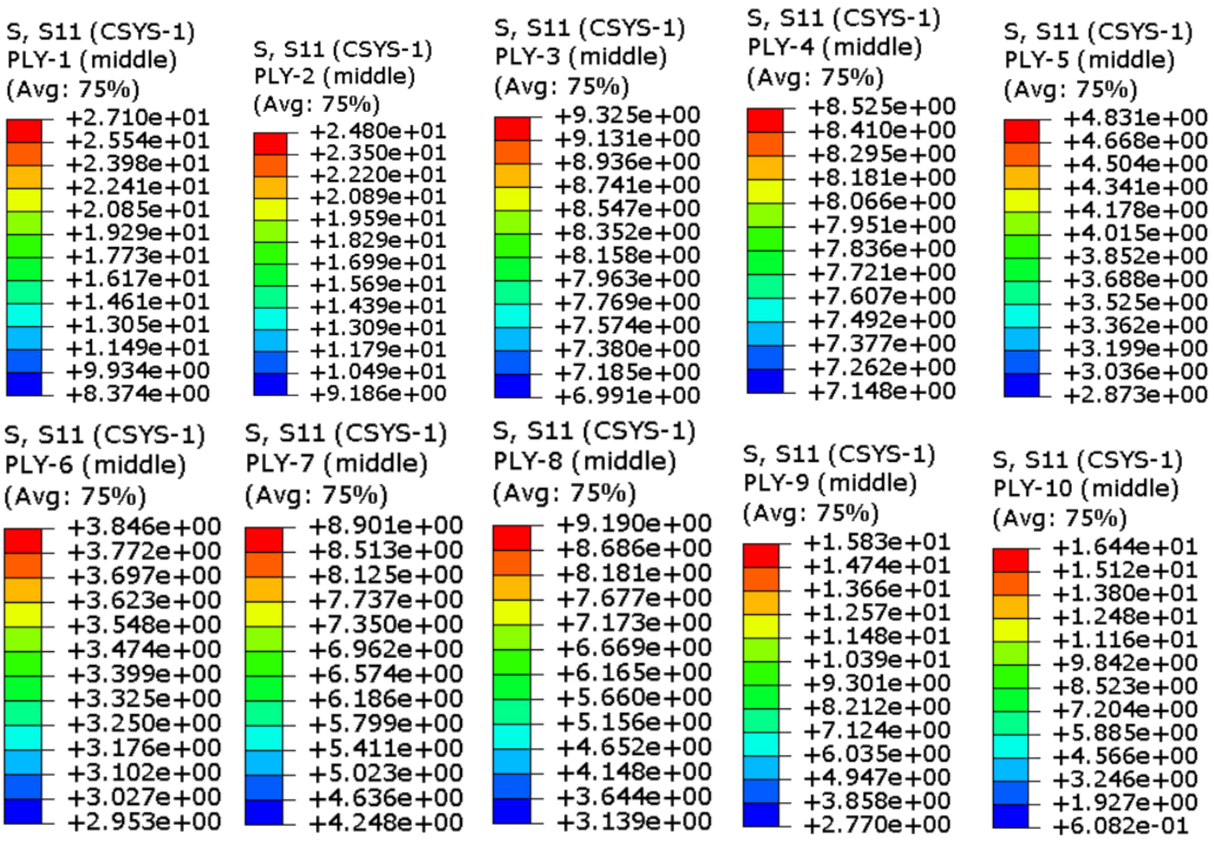


Figure 24: Axial stress result of plies in MPa

The Ply stress output of the 10-ply GFRP composite pipe in Abaqus provides stress information for each ply. Detailed analysis of S11, S22, S33, and S12 for each of the 10 plies is required to form an understanding of internal load distribution, identify potential points of failure, and indicate the performance of the composite pipe plies under working loads. The stress components vary from ply to ply depending on the fiber directions and laminate stack sequence.

4.4. Global Strain result

The global strain values of the GFRP composite pipe in Abaqus provide an indication of how the pipe deforms. E11 is the axial Z-direction strain, E22 is the strain from the center of the pipe and E33 is circumferential or hoop strain in the θ-direction (Y-direction), and E12 is in-plane shear strain between the axial and the hoop direction. Maximum in-plane principal strain (E max in plane) is the largest tensile strain of the pipe wall, which is crucial in computing potential failure or delamination in composite layers. Such strain components are employed in structural response and deformation pattern evaluations at service loads.

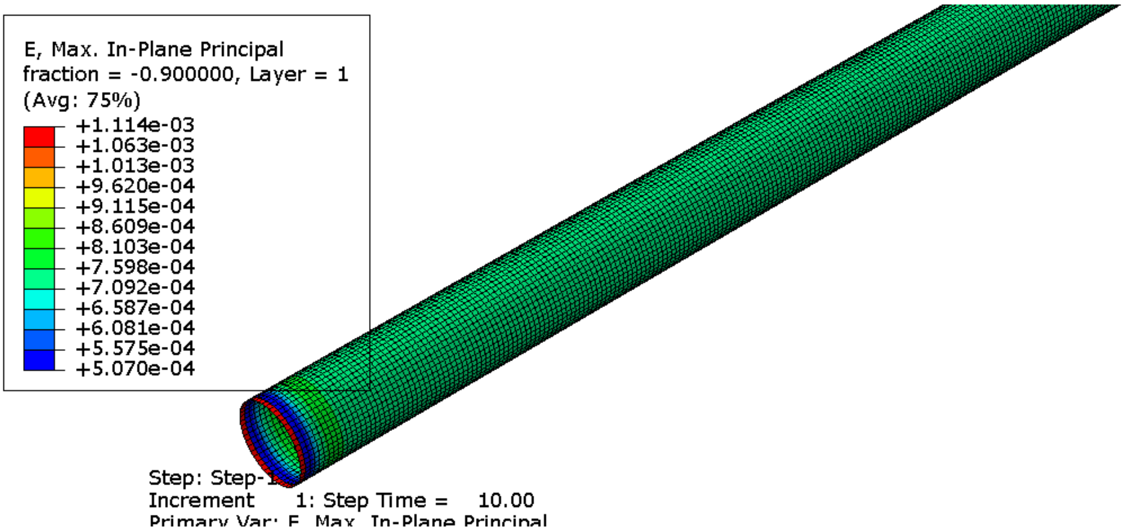


Figure 25: E max In plane principal strain

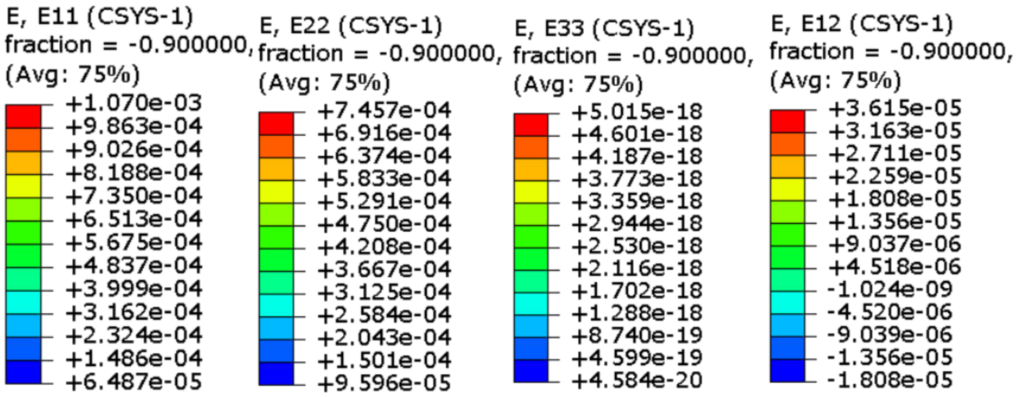


Figure 26: Global Results of strain

The Ply strain outputs of the 10-ply GFRP composite pipe in Abaqus provide important information about deformation behavior of each ply. E11, E22, E33, and E12 analysis of the whole 10 plies is of highest importance in terms of understanding deformation at the ply level, detection of potential damage initiation, and obtaining composite structure reliability under loading conditions. These components of strain differ across the laminate due to differences in fiber orientation and location of the ply.

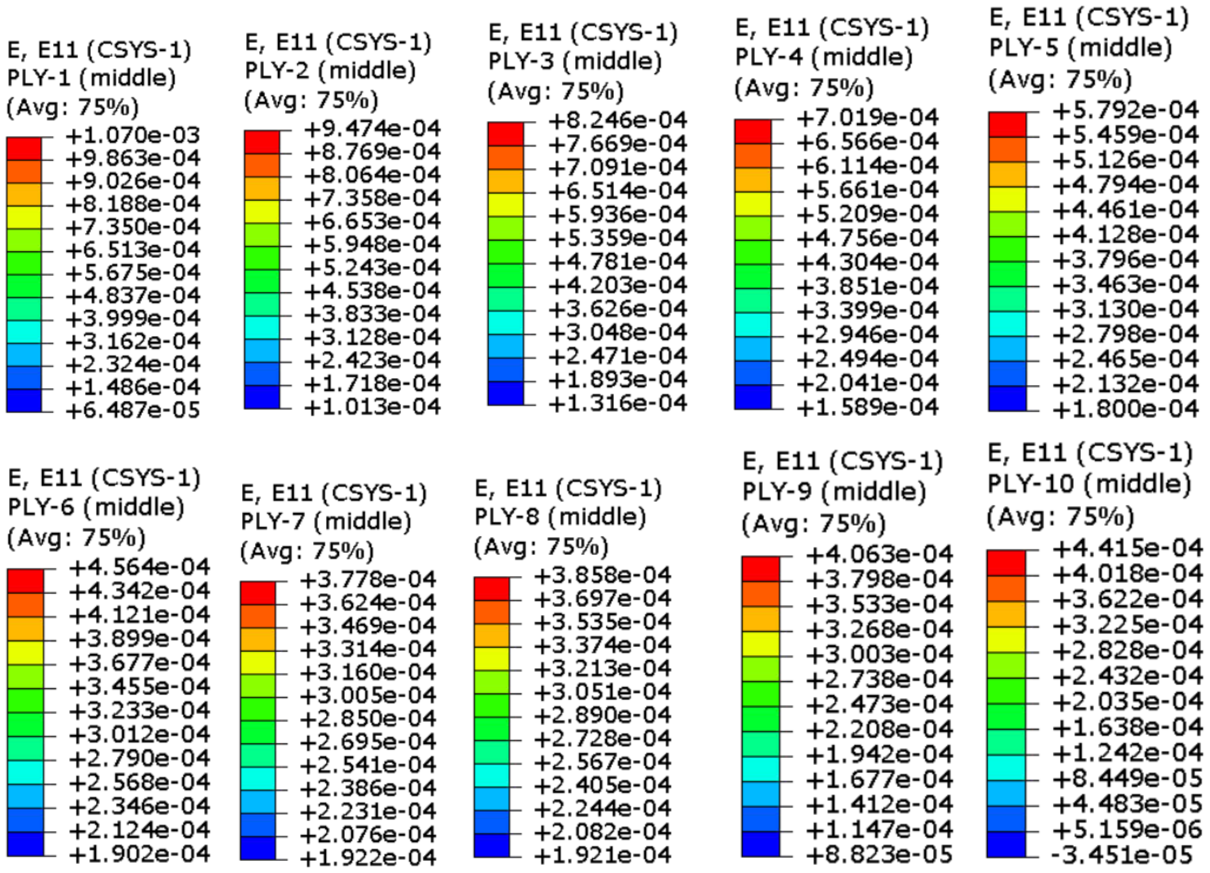


Figure 27: Axial Strain result of plies

4.5. Deformation Result

In the displacement results of the composite pipe analyzed in cylindrical coordinates, U represents the total spatial displacement magnitude, combining movements in the radial, circumferential, and axial directions. Total displacement for result of the composite pipe for normal loading condition is stated below.

The components U1, U2, and U3 correspond to displacements in the radial (Ur), circumferential or hoop (Uθ), and axial (Uz) directions, respectively. These directional results are essential for understanding the behavior of cylindrical composite structures, as they reveal how the pipe expands, twists, or elongates under applied loads. Evaluating displacement in the cylindrical system is especially critical for composite materials due to their direction-dependent stiffness and deformation characteristics.

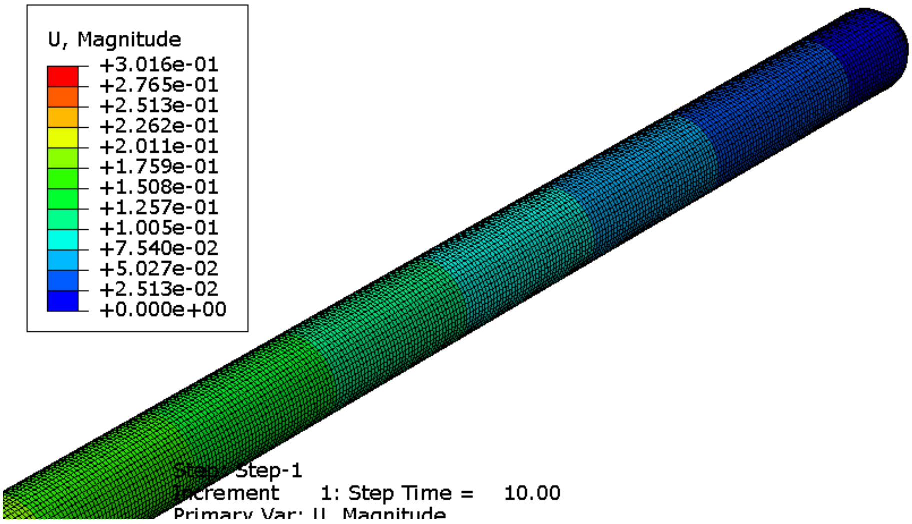


Figure 28: Spatial Displacement Magnitude in mm

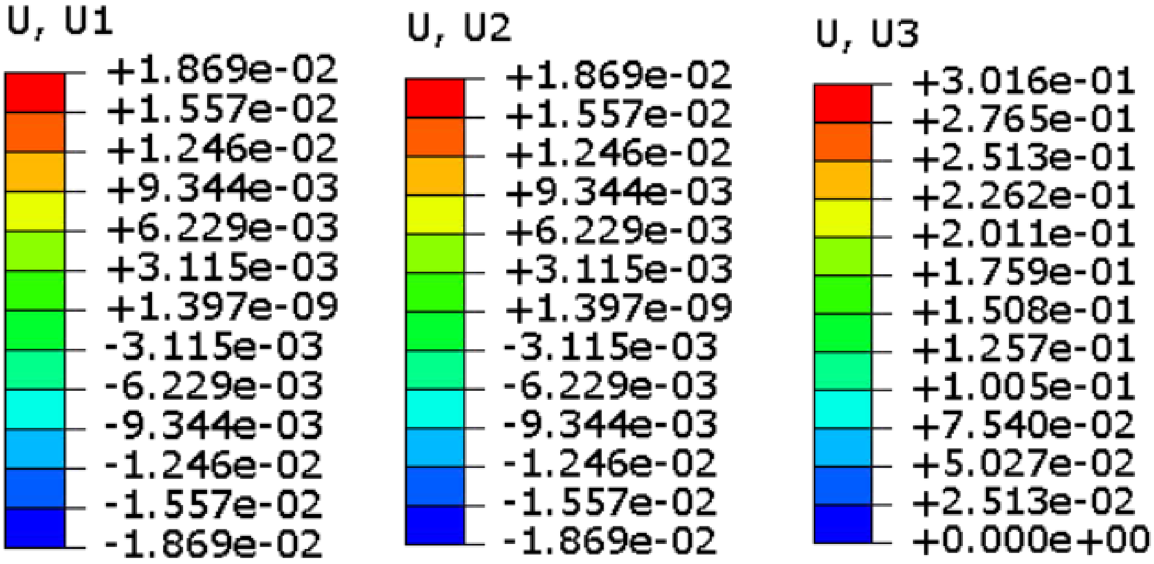


Figure 29: Displacement/deformation components

4.6. Stress and Strain Analysis of GFRC Pipe

The stress-strain graph of the GFRP composite pipe obtained from Abaqus shows a linear elastic region. The Von Mises stress indicates the overall equivalent stress experienced by the pipe, useful for assessing yielding under complex loading. The maximum in-plane stress corresponds to the highest tensile stress within the pipe wall, typically along the hoop or axial direction, while the minimum in-plane stress reflects the lowest (often compressive) stress in the plane. These values are critical for evaluating the pipe’s structural integrity and predicting failure under internal pressure or external loading.

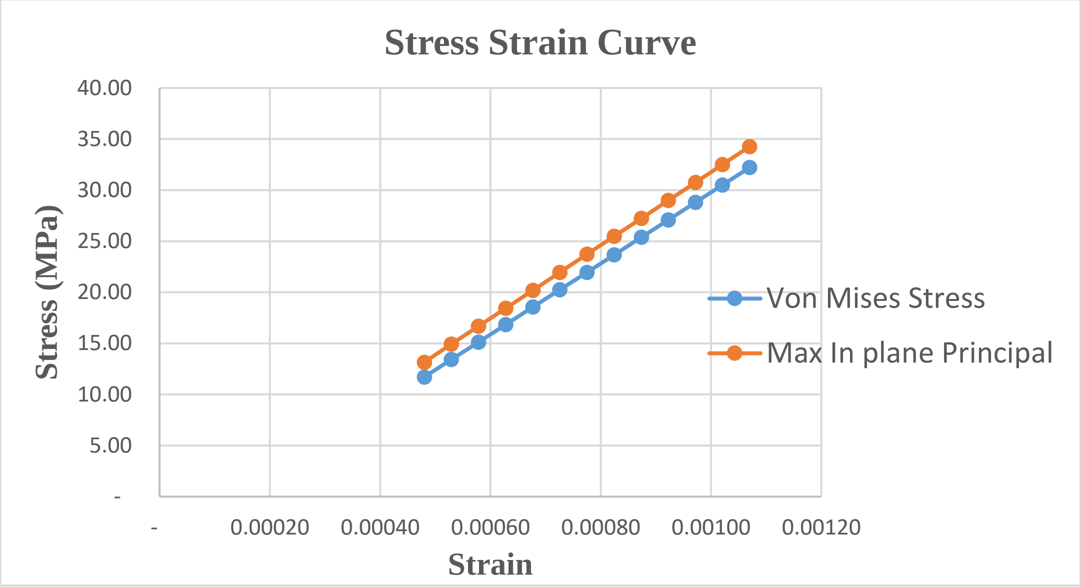


Figure 30: Stress versus Strain curve

4.6.1. Axial stress versus axial strain

The axial response of plies under load is given in the axial stress and axial strain result above. Ply 1 is the most loaded layer in the laminate, as can be observed from its highest axial stresses. Its ability to carry a greater percentage of the applied load is because of its fiber closely aligned to the axial direction. To get the critical condition of stress in the laminate and the structural behavior of the composite pipe, it is essential to obtain the maximum value of S11 and E11 in ply 1. Axial stress strain curve for ply 1 and 2 are provided in figure 31.

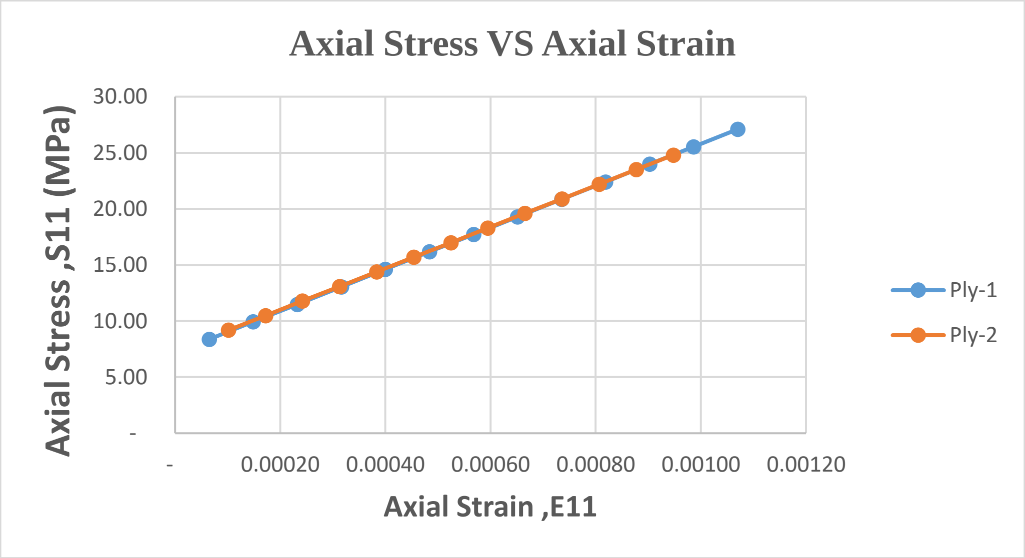


Figure 31: Axial stress versus axial strain

4.6.2. Radial stress and strain result of plies

The radial stress and strain on composite pipe layer represents the radial response of each layer due to pressure loading. Maximum radial stresses are observed at ply-4 with maximum value of 22.3MPa and comparable values for all plies in radial direction. Maximum response is regulated by the orientation of fibers of the ply and laminate's position.

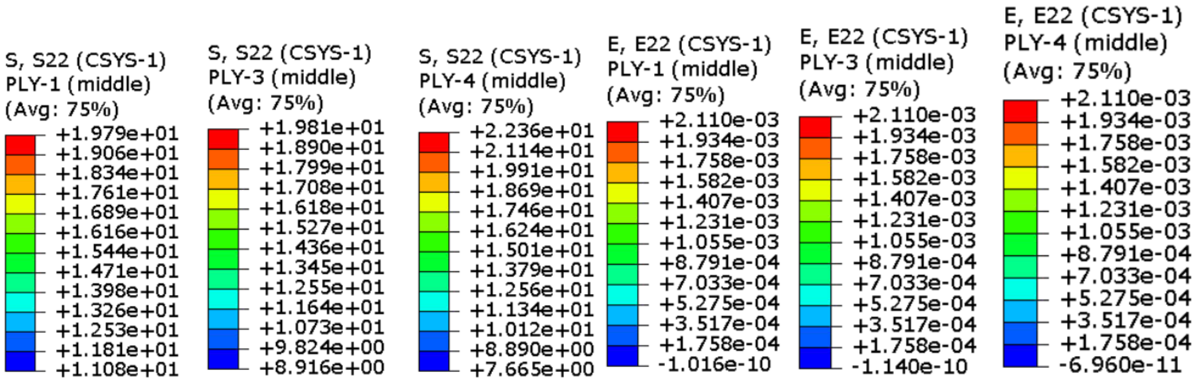


Figure 32: Radial Stress and Strain result

4.7. Effect of water absorption on stress and strain result

The water absorption of a 10-ply GFRP composite pipe has a significant influence on its mechanical behavior. Moisture uptake in GFRP composites typically follows Fickian diffusion, with the moisture content gradually increasing over time until saturation. As moisture diffuses through the polymer matrix, it leads to plasticization, swelling, and micro cracking, especially at the fiber-matrix interface. These effects degrade key material properties such as elastic modulus, tensile strength, and interlaminar shear strength.

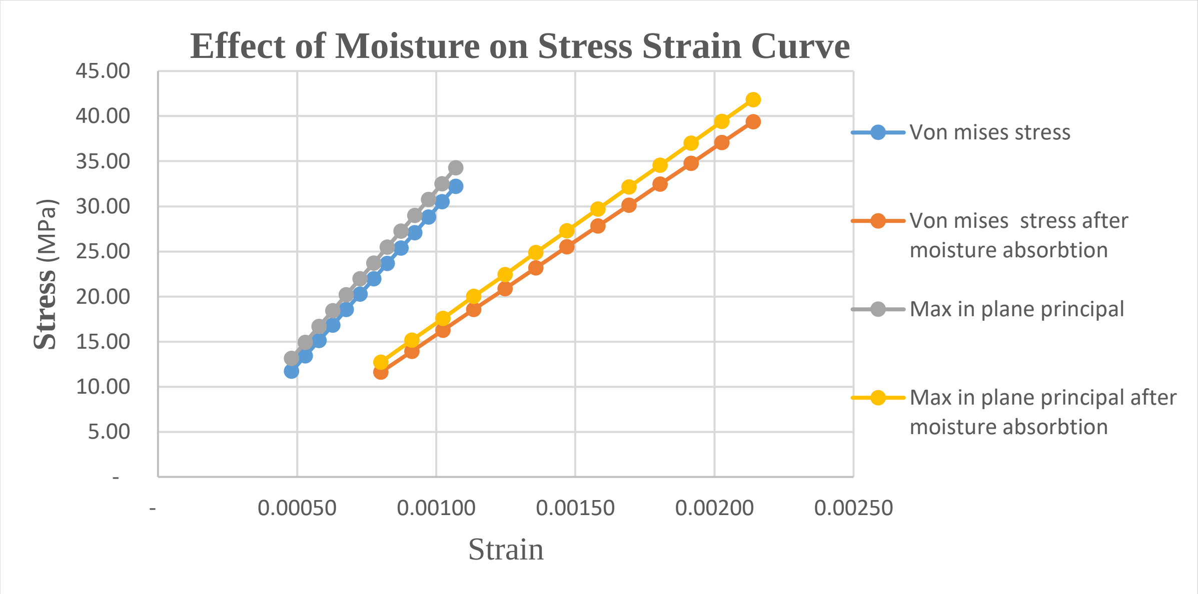
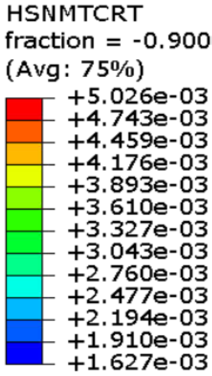
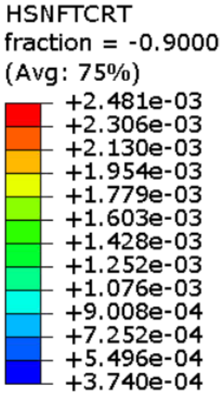
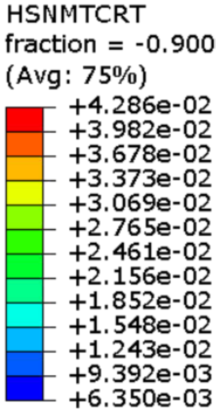
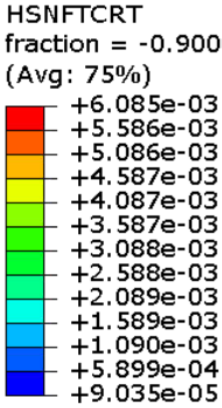


Figure 33: Effect of moisture on stress and strain result

Moisture content of around 1.5–2.0% by weight is common saturation level for many GFRP systems and the stiffness may reduce by 10–20% and the strength by 15–30%, depending on the resin system and fiber orientation. In shell element modeling within Abaqus CAE, these degradations are typically incorporated by reducing the material properties in the input data. Accurately simulating these effects is essential for assessing the long-term performance and durability of composite pipes in humid, or submerged service conditions.

Table 18: Hashin's Failure index for dry and moisture absorption

Pipe Condition	Matrix failure index	Fiber failure index
Dry	 HSNMTCRT fraction = -0.900000, (Avg: 75%) +5.026e-03 +4.743e-03 +4.459e-03 +4.176e-03 +3.893e-03 +3.610e-03 +3.327e-03 +3.043e-03 +2.760e-03 +2.477e-03 +2.194e-03 +1.910e-03 +1.627e-03	 HSNFTCRT fraction = -0.900000, (Avg: 75%) +2.481e-03 +2.306e-03 +2.130e-03 +1.954e-03 +1.779e-03 +1.603e-03 +1.428e-03 +1.252e-03 +1.076e-03 +9.008e-04 +7.252e-04 +5.496e-04 +3.740e-04
With moisture consideration	 HSNMTCRT fraction = -0.900000, (Avg: 75%) +4.286e-02 +3.982e-02 +3.678e-02 +3.373e-02 +3.069e-02 +2.765e-02 +2.461e-02 +2.156e-02 +1.852e-02 +1.548e-02 +1.243e-02 +9.392e-03 +6.350e-03	 HSNFTCRT fraction = -0.900000, (Avg: 75%) +6.085e-03 +5.586e-03 +5.086e-03 +4.587e-03 +4.087e-03 +3.587e-03 +3.088e-03 +2.588e-03 +2.089e-03 +1.589e-03 +1.090e-03 +5.899e-04 +9.035e-05

Hashin failure index shown on table 18 illustrates pipes with moisture as higher value of HSNMTCRT and HSNFTCRT indicating earlier failure of pipe with moisture compared to the dry pipe.

4.8. Critical Load Considerations for Borehole Pipe

When preparing a finite element model in ABAQUS CAE for analyzing water borehole pipes critical loads that exist during rehabilitation or maintenance have to be considered. It is essential to define and apply all relevant load types to accurately simulate operational conditions. The internal hydraulic pressure typically ranges from 10 to 20 MPa and this should be applied as a surface load on the internal wall of the pipe to represent forces from high-pressure jetting and fluid surging. Axial loads must be included to account for the tensile and compressive forces generated during the insertion and withdrawal of pumps and tools; these may range from 10 to 20 kN, for our case and can be applied as concentrated or distributed axial forces at pipe ends.

External pressure loads resulting from flashing events caused by rapid vapor collapse or sudden inflows should be applied as external pressure loads in the range of 1 to 5 MPa. Overburden or hydrostatic pressures can be included as uniform or graded pressure distributions along the outer pipe surface. Chemical degradation effects, while not modeled as direct loads, should be considered in the material definition by reducing material properties such as modulus of elasticity or yield strength in affected regions. In order to consider chemical degradation effect and other unseen loading the composite pipe is analyzed by assuming a safety factor of 20% with the following loadings. For the critical load analysis internal hydraulic pressure of 30MPa, Axial load of 40KN and External pressure (on pipe wall) of 10MPa are considered.

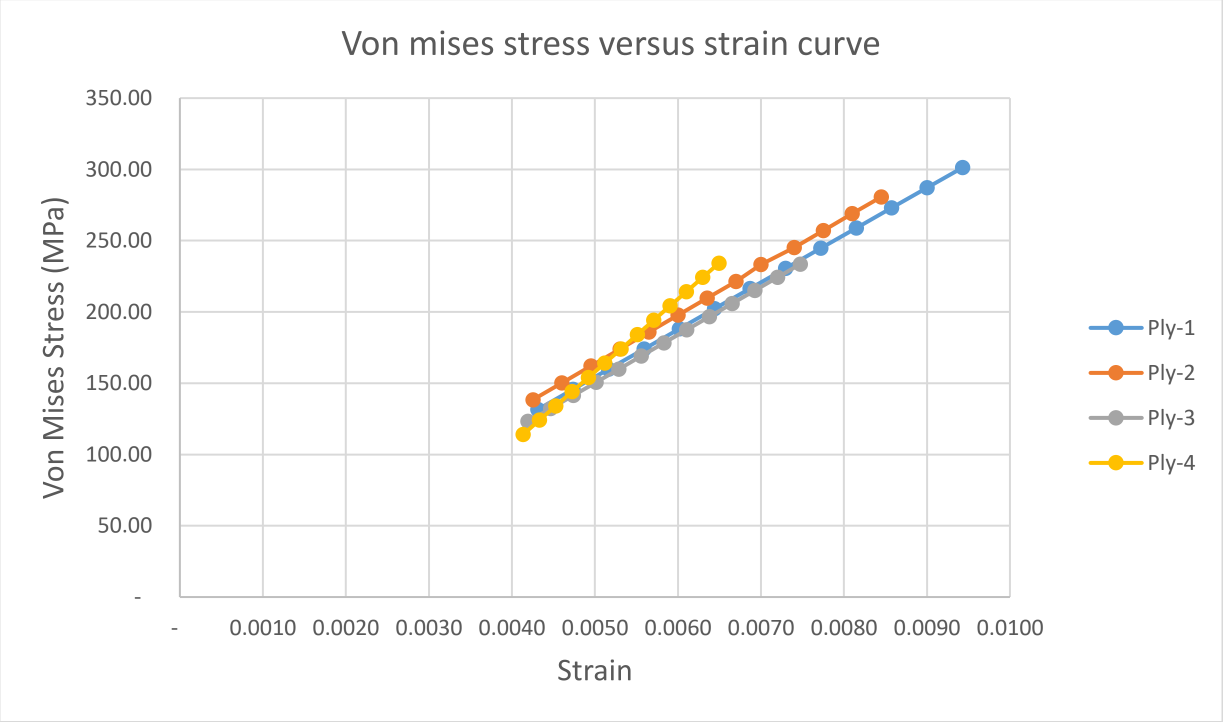


Figure 34: Von mises stress versus strain curve for critical load

In the analysis of a 10-ply GFRP composite pipe under combined load using Abaqus CAE, the stress-strain response further evaluated to understand the pipe is mechanical to estimate the performance of the pipe. The simulated tensile loading along the axial direction of the pipe reveals a linear stress-strain response up to failure initiation. The composite pipe resisted the critical load applied, the maximum von mises stress result is 301MPa, and it is on ply 1. Moreover, after consideration of moisture the maximum von mises stress rises to 331.2MPa.

4.9. Damage Initiation Criterion

In the analysis of GFRP composite pipes using Abaqus CAE, Hashin's failure criteria are commonly employed to predict fiber damage initiation under tensile and compressive loading. With the selected standard loading, the damage behavior was analyzed using hashin failure criteria. According to the result extracted from the FEA for the standard loading condition the pipe can operate with a large safety factor. The largest value Hashin's matrix tensile damage initiation criterion result obtained from the analysis is 0.005 (dry condition) and 0.04 (after moisture consideration).

4.9.1. Hashin's Fiber tensile and compressive damage initiation criterion for critical load

Hashin's Fiber Tensile criterion identifies damage when the longitudinal stress exceeds the fiber tensile strength, typically in the direction of the fibers, while the Compressive criterion addresses failure when compressive stress surpasses the material's fiber compressive strength. These criteria are implemented in Abaqus through user-defined material models or built-in damage initiation options for composite layups, allowing accurate simulation of damage progression in layered composite structures subjected to complex loading conditions.

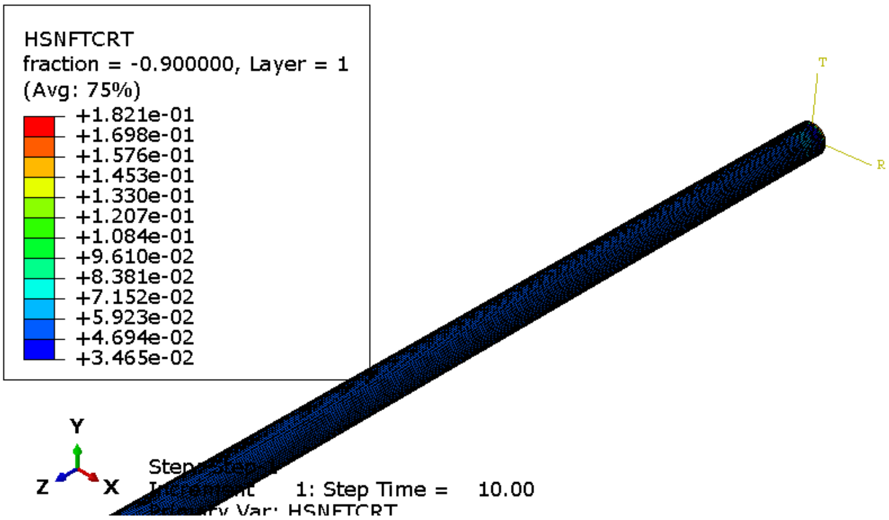


Figure 35: Hashin's fiber tensile damage initiation result (Ply-1)

4.9.2. Hashin's matrix tensile and compressive damage initiation criterion for critical load

The matrix tensile criterion activates when transverse tensile or shear stresses exceed the matrix tensile strength, indicating the onset of micro cracking. The compressive matrix criterion identifies failure caused by compressive stresses in the direction transverse to the fibers, leading to matrix crushing or shear damage. If these criteria are used for all 10 plies that make up the composite layup, the simulation gains a true understanding of the development of matrix damage as a function of multifaceted loads, enhancing structural integrity assessment accuracy.

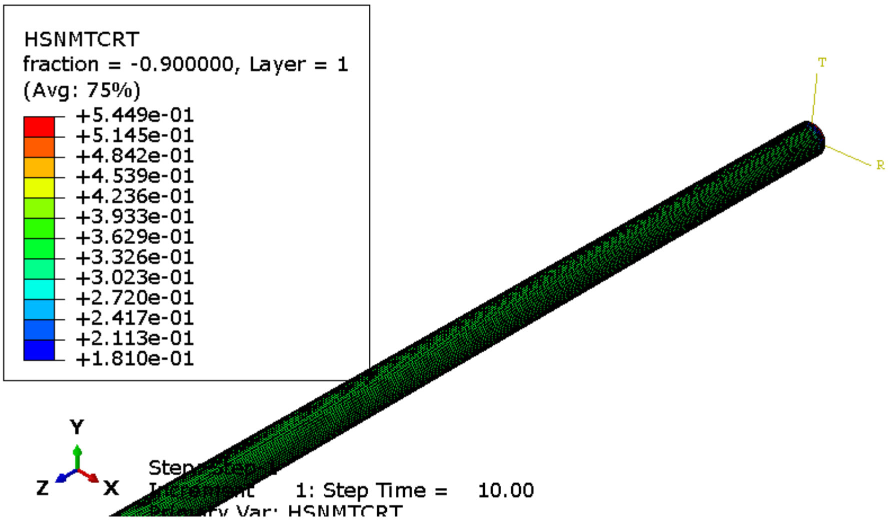


Figure 36: Hashin’s matrix tensile damage initiation result (Ply-1)

4.10. Damage Progression Analysis for critical load

4.10.1. First Ply Failure (FPF)

In the first ply failure analysis of 10-ply GFRP composite pipe using Abaqus CAE, the focus is given to the identification of initial damage initiation point upon application of applied loading conditions such as pressure or axial load. Each ply is simulated using given material properties and orientation in a way that the simulation can track stress distribution and damage development through the laminate.

In the first ply failure analysis of a 10-ply GFRP composite pipe with a (55/-55/30/-30/0)s layup using Abaqus CAE, under critical load consideration we will evaluate the damage initiation using Hashin failure criteria. For the applied critical load case (without moisture), the maximum value of hashin matrix tensile damage indicates 0.55 and it is for ply 3. While, the maximum value of hashin fiber tensile damage is 0.182 and it is for ply-1. Furthermore, after consideration of moisture for critical load case hashin matrix tensile damage become 2.76, While, the maximum value of hashin fiber tensile damage is 0.43 for ply 1.

4.10.2. Progressive Damage Simulation

As the load increased, the damage propagated radially inward. The [0°] plies sustained the longest without failure, highlighting their significance in load bearing along the pipe axis. Damage evolution followed a sequence typical for unidirectional composites under tensile and bending stresses: Matrix cracking occurred first, especially in the transverse and off-axis plies, due to lower matrix tensile strength, Delamination followed, mainly at ply interfaces with different fiber orientations, driven by interlaminar shear and normal stresses and Fiber breakage occurred last, signifying ultimate failure, and was confined to the high-stress zones aligned with the loading axis.

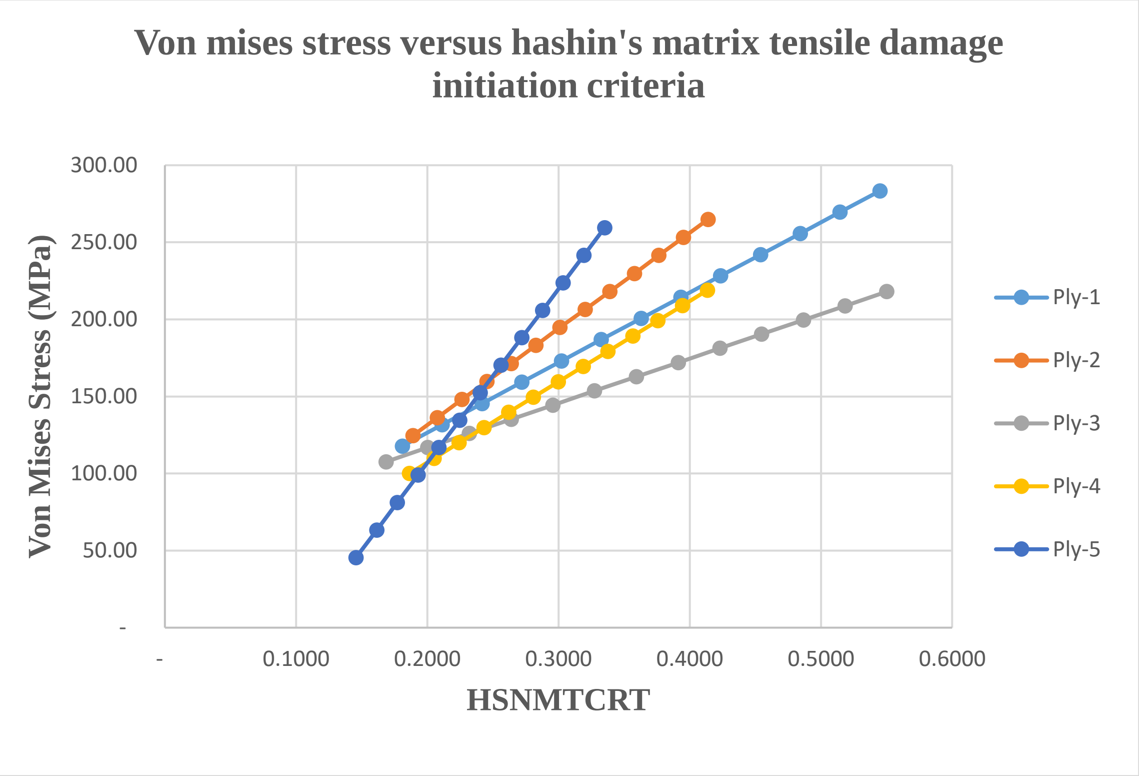


Figure 37: Von mises stress versus Hashin’s matrixr tensile damage initiation criteria

Using Hashin’s criteria, the damage initiation index for matrix tension indicates highest value of 0.55 for ply 1 and 3 with their respective stress value. Similarly, the highest value of hashin fiber tensile damage index is observed on ply 1.

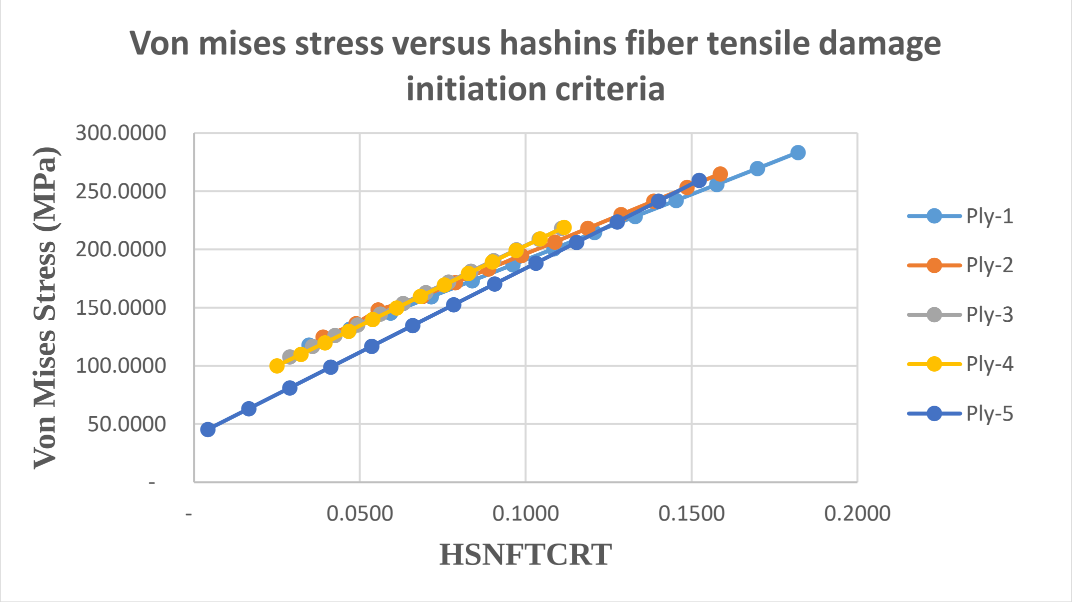
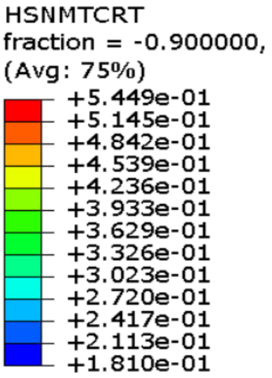
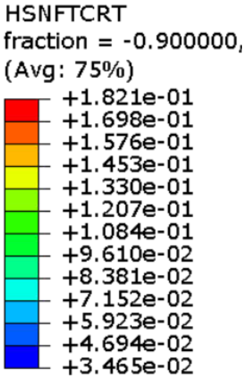
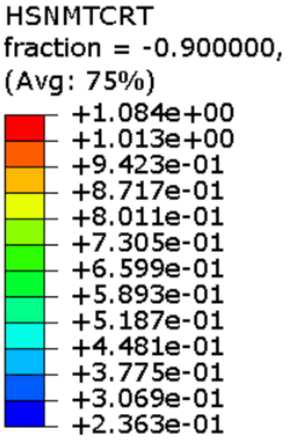
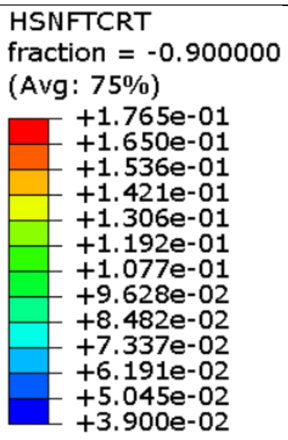


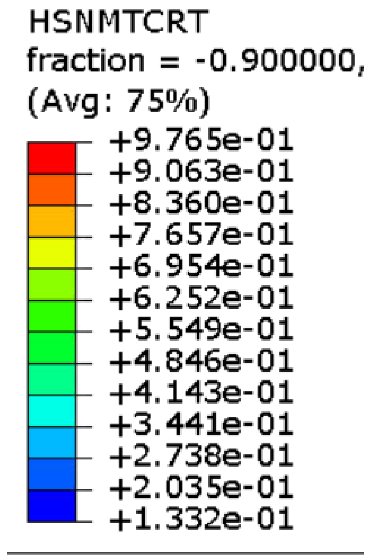
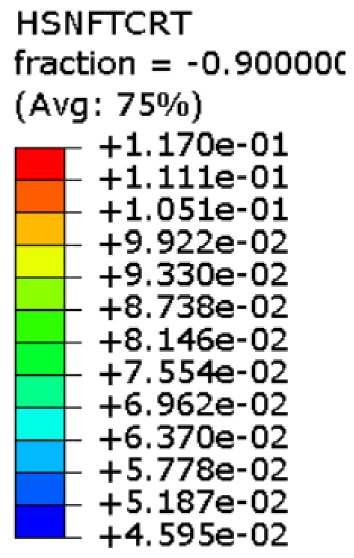
Figure 38: Von mises stress versus Hashin’s fiber tensile damage initiation criteria

4.11. Influence of Ply Orientation

In the detailed analysis of 10-ply GFRP composite pipes using Abaqus CAE, the influence of alternative ply orientations specifically (45/-45/45/-45/45)s and (30/-30/60/-60/0)s is evaluated against the optimized baseline layup of (55/-55/30/-30/0)s. The baseline configuration is designed to provide a balanced structural response, combining hoop strength from the ±55° plies, shear resistance from ±30°, and axial stiffness from the 0° layers. When replaced with the (45/-45)s layup, the structure exhibits enhanced shear performance and better torsional resistance, but will show reduced axial and hoop stiffness due to the absence of strong axial or hoop-dominant fibers.

Table 19 : Pipe matrix and fiber hashin failure index result for different ply stacking angle

Pipe thickness and Applied loads		
Wall thickness (mm)	3mm	
Axial load (KN)	40KN	
Internal pressure (MPa)	30MPa	
External pressure (MPa)	10MPa	
Ply stacking sequence	**HSNMTCRT**	**HSNFTCRT**
(55/-55/30/-30/0)s		
(45/-45/45/-45/45)s		

(30/-30/60/-60/0)s		

Simulation results reveal that the (55/-55/30/-30/0)s layup provides a more optimized balance for combined internal pressure and axial loading, highlighting the importance of strategic fiber placement in composite pipe design. Hashin failure index result of the above mentioned ply orientation for critical loading condition for dry case indicates minimum value of hashin matrix and fiber tensile damage value for the selected ply orientation.

4.12. Summary

The numerical outcomes reveal that the proposed 10-layer symmetric layup achieves a sufficient performance for groundwater riser pipe applications. The analysis confirms that the multi-angle symmetric layup enhances the capacity of multidirectional load, delaying damage initiation and sustaining structural integrity. The ±55° plies significantly improve the tensile and hoop strength, which are essential in groundwater riser pipes subject to internal pressure and axial load.

Progressive failure also is matrix-dominated, with emphasis on the shearing and transverse strength in design. Damage happens long before final structural failure, and it is, therefore, detectable early in the field. Simulation also substantiates that composite pipes like these can be operated safely with sufficient margin under normal groundwater conditions (1–5 MPa).

Chapter Five

5. Conclusions and Recommendations

5.1. Conclusion

This study aims at Glass Fiber Reinforced Polymer composite stress and damage analysis for groundwater riser pipes. Using ABAQUS CAE, a model was created from glass epoxy lamina of 50 mm internal diameter, 1.5 meter length, and 3 mm wall thickness, having a symmetric 10-layer layup sequence of [55°, -55°, 30°, -30°, 0°]s. The simulation accounted for mechanical loading conditions relevant to field operations such as internal pressure and axial load. The following two critical load cases were evaluated Case 1 (2.403 MPa Internal Pressure + 4.183 kN Axial Load) under dry and 2% moisture saturation and Case 2 (30 MPa Internal Pressure, 40 kN Axial Load, 10MPa external pressure) under dry and moisture conditions.

For case 1(dry case) the pipe exhibited linear elastic behavior with highest axial stress of approximately 27.1MPa (on ply 1), strain of approximately 0.00111 and deformation of 0.3mm in the longitudinal direction. The highest radial stresses reached 22.36MPa were experienced primarily by the ±30° plies. Hashin failure analysis ensured safe operation and failure indices were below 0.6, since there was no damage initiation. However, when subjected to 2% moisture, there was degradation of matrix-dominated properties particularly in matrix tensile strength and transverse modulus. As a result, strain increased to approximately 0.00213 with the same load.

In Case 2, a high-stress operation condition (30 MPa internal pressure, 40KN axial load and 10MPa external pressure), the pipe experienced enormous combined stresses. Von mises stress went up to nearly 301.2 MPa with a strain of 0.0094 for dry case and after moisture consideration von mises stress become 331.2MPa with strain of 0.017. Hashin analysis revealed increased value of matrix tensile index of 0.55 < 1.0) in inner ±30° plies for dry case and it became 2.76 for moist case. Such findings prove that both damage of the matrix and fiber damage can be provoked under unfavorable circumstances, as well as progressive failure. Although shell elements do not model delamination explicitly, interlaminar shear stress gradients suggest risk zones for ply separation. The results underline the importance of accounting for environmental degradation in composite design.

Thus, the composite pipe with a (55, −55, 30, −30, 0)s layup demonstrates excellent mechanical performance when subjected to dry service loads and extreme conditions. However, environmental effects such as moisture absorption place an evident reduction of safety margins. The combination of Abacus shell element modeling and Hashin failure criteria offers a robust and predictive means of determining stress, strain and damage behavior. Therefore, the proposed composite pipe can be suitable for pipe application for moderate loading conditions of ground water.

5.2. Recommendations

Based on the result obtained from the finite element simulations and Hashin failure analysis, the following recommendations are proposed to enhance the structural reliability of the glass epoxy composite borehole pipe under multi-axial loading and varying environmental conditions.

- To mitigate the effects of moisture, which accelerates matrix degradation, the application of a suitable moisture barrier or surface coating should be considered and analyzed.
- The numerical analysis indicates stress variation through plies. Hence, other researcher might try alternative layup to get optimum stress variation between plies of pipe
- Ply stacking sequence has greater effect on stress handling capacity of pipes. Although the current $(55, -55, 30, -30, 0)_s$ layup provides good multi-directional stiffness, further ply-angle optimization may enhance performance under higher loading conditions.

5.3. Future Work

Hashin failure index and stress strain result from numerical analysis of GFRC pipe indicates suitability of glass epoxy pipe for water well application for moderate loading conditions of shallow depth ground water. However, to further advance, the understanding and reliability of glass epoxy composite borehole pipes subjected to combined loading conditions the following areas of future research are recommended.

- The numerical analysis result for both dry and moist condition have to be validated by experiment.
- Investigating the influence of varying fiber volume fractions and alternative fiber orientations on the composite’s multi-axial performance.

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