ENERGY ABSORPTION PERFORMANCES OF GLASS-FIBRE REINFORCED POLYMER CYLINDRICAL STRUCTURES UNDER HOOP TENSILE LOADING

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DEDICATION

This thesis is dedicated to my wife and family, who continuously support me directly or indirectly.

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ABSTRACT

Composite structure creates lightweight with a high strength-to-weight ratio material. This structure allows design flexibility in fibre orientation and the number of plies. Leveraging the design and performance of glass-fibre reinforced polymer (GFRP) pipes is essential to increase their competitiveness against metallic structures. However, GFRP has a wide range of failure modes and is less intuitive in the design phase than isotropic materials. A lack of practical design and analysis in composite materials directly compromises operational safety, especially when subjected to extreme internal loading conditions. The primary objective of this study was to determine the energy absorption performance of GFRP cylindrical structures under hoop tensile loading through experimental and numerical methods. The split disc test was conducted to determine the hoop tensile stress of various-sized GFRP pipe rings. The numerical results were compared to the experimental ones to validate the finite element method (FEM) model in terms of force-displacement curves, and deformation mode. The comparison showed an acceptable correlation in numerical analysis. The validated FEM model was then used to conduct a series of parametric studies. These studies showed that increasing the core thickness and winding angle significantly affects energy absorption performance under hoop tensile loading. A 171% increase in specific energy absorption (SEA) capacity can be seen when the core thickness was increased from 5.23 mm to 15 mm. A superior performance was obtained by involving a greater amount of material in energy absorption process. On the one hand, a 61% increase in SEA was observed when increasing the winding angles from ±54.5° to ±75° due to the parallel high angle with the force direction. On the other hand, increasing the layer counts from 14 to 25 layers yielded a 0.7% decrease in SEA. Increasing the number of layers reduces the ply thickness-to-resin ratio, leading to stiffer structure with increasing microcracks. Above all, the current research makes a critical contribution by developing a validated FEM model as a design tool for evaluating the performance of GFRP by varying controllable parameters prior to fabrication. This contribution would significantly reduce manufacturing time and material waste while optimizing design efficiency.

ABSTRAK

Struktur rencam menghasilkan bahan ringan dengan nisbah kekuatan kepada berat yang tinggi. Struktur ini membenarkan kebolehlenturan rekabentuk dalam orientasi gentian dan bilangan lapisan. Memanfaatkan reka bentuk dan prestasi paip polimer bertetulang gentian kaca (GFRP) adalah penting untuk meningkatkan daya saingnya terhadap struktur logam. Namun, GFRP mempunyai pelbagai mod kegagalan dan kurang intuitif dalam fasa rekabentuk berbanding bahan isotropik. Kekurangan rekabentuk dan analisis praktikal dalam bahan komposit secara langsung menjejaskan keselamatan operasi, terutamanya apabila tertakluk kepada keadaan pembebanan dalaman yang melampau. Objektif utama kajian ini adalah untuk menentukan prestasi penyerapan tenaga bagi struktur silinder GFRP di bawah pembebanan tegangan lilitan melalui kaedah eksperimen dan berangka. Ujian cakera pemisah telah dijalankan untuk menentukan tegasan tegangan lilitan bagi gegelang paip GFRP pelbagai saiz. Hasil keputusan analisis berangka telah dibandingkan dengan hasil eksperimen untuk mengesahkan model kaedah unsur terhingga (FEM) dari segi lengkung daya-anjakan dan mod ubah bentuk. Perbandingan tersebut menunjukkan keputusan hasil analisis berangka boleh diterima. Model FEM yang disahkan kemudiannya digunakan untuk menjalankan satu siri kajian berparametrik. Kajian ini menunjukkan bahawa peningkatan ketebalan teras dan sudut belitan sangat mempengaruhi prestasi penyerapan tenaga di bawah pembebanan tegangan lilitan. Peningkatan 171% dalam keupayaan penyerapan tenaga tentu (SEA) boleh dilihat apabila ketebalan teras ditingkatkan daripada 5.23 mm kepada 15 mm. Prestasi unggul diperoleh dengan melibatkan lebih banyak bahan dalam proses penyerapan tenaga. Manakala peningkatan 61% dalam SEA diperhatikan apabila meningkatkan sudut belitan daripada ±54.5° kepada ±75° disebabkan sudut tinggi selari dengan arah daya. Sebaliknya, meningkatkan kiraan lapisan daripada 14 kepada 25 lapisan menghasilkan penurunan 0.7% dalam SEA. Meningkatkan bilangan lapisan mengurangkan nisbah ketebalan lapisan kepada resin, menjadikan struktur lebih kaku dengan penambahan retakan mikro. Di atas segalanya, penyelidikan semasa memberikan sumbangan kritikal dengan membangunkan model FEM yang disahkan sebagai alat rekabentuk untuk menilai prestasi GFRP dengan mengubah parameter-parameter kawalan sebelum pembikinan. Sumbangan ini akan mengurangkan masa pengilangan dan sisa bahan dengan ketara sambil mengoptimumkan kecekapan rekabentuk.

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LIST OF ABBREVIATIONS

FE	-	Finite Element
FEM	-	Finite Element Model
GFRP	-	Glass-Fibre Reinforced Polymer
ECGS	-	Exhaust Gas Cleaning Systems
UV	-	Ultra-Violet
ASTM	-	American Society for Testing and Materials
FWM	-	Filament Winding Method
RCW	-	Rotary Centrifugal Winding
HLM	-	Hand Lay-up Method
CCM	-	Centrifuged Continuous Method
HTS	-	Hoop Tensile Strength
EA	-	Absorbed Energy
SEA	-	Specific Energy Absorption
UD	-	Unidirectional
PFA	-	Progressive Failure Analysis
CFRP	-	Carbon-Fibre Reinforced Polymer
FPF	-	Progressive Failure Analysis
ILSS	-	Inter-Laminar Shear Strength
DGEBA	-	Diglycidyl Ester Bisphenol A

LIST OF SYMBOLS

D - Average diameter

F - Transverse compressive load

F_c - Constant load

F_{mean} - Average load

F_{peak} - Maximum load for first peak

g - Acceleration due to gravity

L - Length

OD - Outer diameter

ID - Internal diameter

t - Reinforcement thickness of the pipe

σ - Stress

CHAPTER 1

INTRODUCTION

1.1 Introduction

As the global energy sector transitions away from fossil fuels toward more environmentally friendly energy production, the industry is making strenuous efforts to reduce its operational carbon dioxide (CO_2) footprint. Many major operators are taking this a step further by accounting for the CO_2 footprint of their products throughout their life cycle, intending to achieve "net-zero" carbon emissions. The glass-fibre reinforced polymer (GFRP) would be the material of choice to contribute to this critical work as it is lightweight, reducing the need for energy-consuming transportation and installation processes. Due to their superior properties, such as excellent corrosion resistance compared to traditional carbon steel pipes, GFRP composite pipes are widely used in various applications, obviating the need for costly mitigation measures such as corrosion inhibitors and cathodic protection [1, 2]. Since the 1950s, demand for GFRP composite pipes in manufacturing and a wide variety of applications has increased, as illustrated Figure 1.1 [3-5].

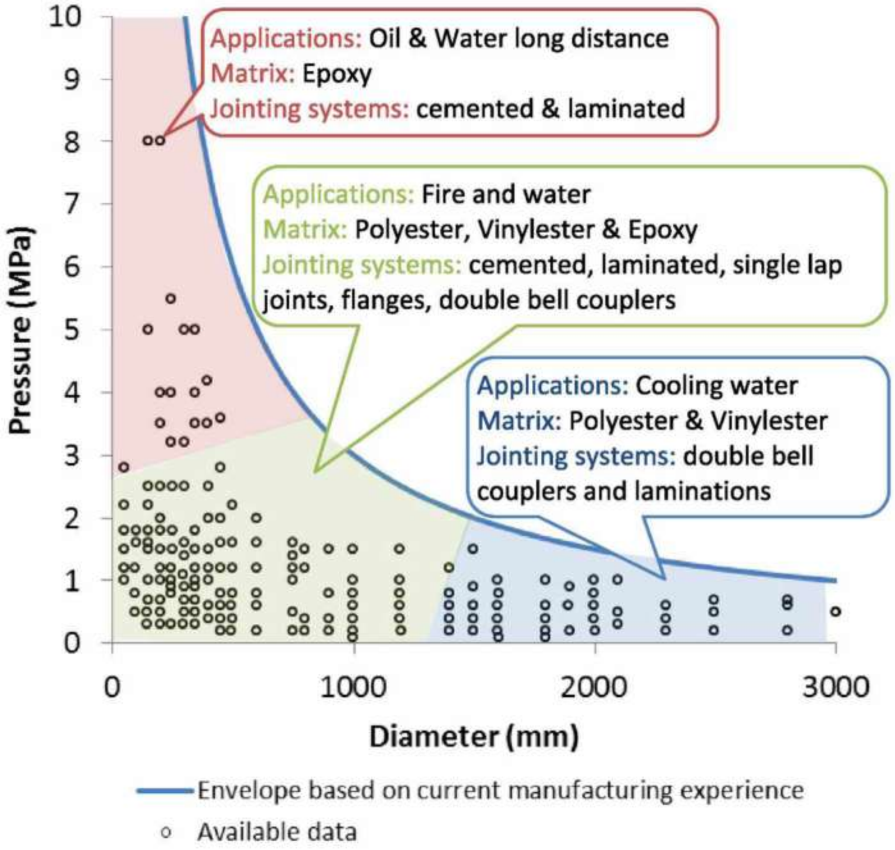

Figure 1.1 Dissemination of GFRP composite pipes [5]

Internal corrosion of traditional piping materials such as carbon steel can clog firewater sprinklers, jeopardizing the system's safe operation. GFRP popularity is primarily due to the outstanding advantage of low weight to high specific strength. Due to the reinforcements and polymer matrices, GFRP composite materials are widely used in lightweight structural components [6-11]. Additionally, GFRPs in composite pipes are becoming more appealing, owing to their higher moduli, reduced weight, and lower installation costs. [12, 13]. As a result, these pipes are used in various engineering applications, including aerospace, automotive, marine, agriculture, and wind turbines. [14-16].

Properties such as high specific strength, sufficient fatigue strength, and superior corrosion resistance are required to transport hot mediums [17-19]. It is critical in these circumstances to leverage additional knowledge about the design and performance of GFRP composite pipes to achieve enhanced properties. To improve quality, concurrent engineering on material, design, and fabrication must be addressed [20]. As a result, a better understanding of the fabrication processes and their state-of-the-art technology is critical. These benefits, however, come at a higher material cost. The lower installation and maintenance costs associated with replacing metallic piping systems in marine and offshore assets can compensate for the higher material costs [21, 22].

1.2 Problem Statement

The increased adoption of composite materials spurs significant research, particularly in composite mechanics and failure prediction under various loading conditions. Most metallic structures require repair and maintenance during their service life due to deterioration, particularly without proper control and mitigation regimes. This issue causes a series of unnecessary asset shutdowns, compromising the integrity of other equipment and increasing operating costs. Using advanced composite materials to replace costly steel components has been heavily disputed to ensure their suitability and durability in subsea conditions.

Despite the numerous advantages of GFRP, the disadvantages need to be addressed appropriately. One of the most prominent disadvantages is hoop stress resistance [23]. The optimal solution for isotropic materials would be to increase the pipe thickness. However, increasing the pipe thickness alone might not be optimal for orthotropic materials since it will drastically defeat the weight advantage of the composite materials. Despite their excellent in-plane properties, composite structures' failure is still an area of long-standing confusion, especially in the marine and offshore industries. This unresolved problem is often a complicated process and requires a significant amount of time to examine and understand. Composite materials have a wide range of failure modes and are less intuitive in the design phase than isotropic materials. Lack of practical design and analysis in composite materials will directly compromise operational safety, especially when subjected to extreme internal loading conditions. Therefore, it is essential to optimize the laminate design to increase the hoop strength and the direction of most of the loads for piping systems to meet the desired performance. The design parameters include winding angle, core thickness, and the number of layers.

Energy absorption potential is an essential composite parameter because there is a relationship between energy absorption and failure mechanisms. It is also helpful to think about how the composite constituent variable affects the energy absorption capacity of the composite structure. With a thorough understanding of the damage mechanisms and powerful simulation tools, designs with accurate failure prediction for higher resistance can be achieved without 'over-design,' which will drastically defeat the weight advantage of composite materials while maintaining the product's safety and integrity. The material model can then reduce the number of required experimental tests, resulting in a lower total design cost. The constitutive relations can then be inputted into a non-linear Finite Element Software to simulate the composite response numerically. Various strength metrics must be examined because of this. Therefore, a parametric study must be conducted using the validated finite element method (FEM) of the composite cylindrical structures. An extensive simulation with different pipe properties would provide an in-depth understanding of GFRP pipes under different failure modes, leading to an optimized design for a specific application.

Numerous studies [24-27] have been conducted to determine the mechanical properties of GFRP composite pipes. Although numerous papers have been published on the effect of GFRP pipe parameters on the performance of composite pipes, very minimal single study has addressed the effect of winding angles, layer number, and core thickness on the Hoop Tensile strength (HTS) of E-glass/Epoxy composite rings in a study.

1.3 Research Questions

(a) How accurate is a FEM in representing the experimental result?

(b) How would the varying parameters increase the energy absorption performances of the GFRP pipe?

1.4 Research Objectives

The objectives of the research are:

(a) To evaluate the energy absorbance of the hoop tensile test.

(b) To study the influence of geometrical parameters capacity on the hoop tensile loading.

(c) To analyze the failure mechanism under hoop tensile loading.

1.5 Scope of The Study

The study focuses on evaluating the energy absorption behaviour of GFRP composite pipes subjected to hoop tensile loading. The scopes of this study are as follows.

(a) The composite materials are:

  a. Fibre System: Unidirectional Continuous E-Glass
  b. Matrix System: Epoxy
  c. Hardener System: Aromatic Amine
  d. Manufacturing Method: Filament Winding method (FWM) with a Helical Angle of ± 54.5

(b) The test conducted is Split-Disk loading test in accordance with American Society for Testing and Materials (ASTM) D2290-19a.

(c) The numerical model development employed a commercial LS-DYNA using the material properties from the manufacturer's datasheet and literature.

(d) The damage model of the material is based on existing damage-based formulations.

(e) The numerical model was validated using the results obtained from the hoop tensile test in the form of a load-displacement curve.

(f) A series of parametric studies is carried out to evaluate the influence of controllable parameters on the cylindrical structure.

1.6 Significance of Research

The outcome of this research would be beneficial for Research and Development (R & D) for industrial application. Unlike the isotropic nature of steel and metals, composite material properties are essential for fast-growing industries, such as the marine, oil, and gas industries [28]. The current material characterization of GFRP for industrial applications typically involves physical and destructive tests with no specific requirement for Finite Element application to reduce physical tests, product development, and project qualification [29, 30]. The outcome of this study is in the form of a validated model, acted as a preliminary study to examine the performances of GFRP with varying parameters. From this preliminary study, only selected design parameters are expected to be proceeded to the fabrication stage, reducing costs and minimizing waste significantly. The result of tested fabricated samples validated the model to improve its efficiency. The same model can be used to troubleshoot damage occurrences in the field application. This action would remove the need for the damaged pipe to be transferred back to manufacturing plants/testing laboratories for further evaluation. Besides, the model provides the basis for pipe support designs for GFRP pipes. The current design adaptations are mainly from the steel piping design. Optimization of GFRP piping support could provide better energy absorption performances over the design life.

1.7 Thesis Outline

Chapter 2 includes a comprehensive review of the literature relevant to the thesis's objectives and scope. The chapter began by summarizing the fundamental concept of GFRP's energy absorption properties. Following this review, a comprehensive examination of prior and ongoing research on GFRP pipes is discussed. This section discusses the analysis and experimental testing of such materials and the finite element modeling of GFRP pipes.

Chapter 3 describes the split-disk test per ASTM D2290 as an experimental method for determining the hoop tensile strength. Additionally, the development and validation of the finite element model used to simulate GFRP pipes subjected to hoop tensile loading were discussed. The methodology used to develop the model and to simulate quasi-static loading conditions is introduced.

Chapter 4 discusses the experimental results, theoretical model, and prior research that were used to validate the hoop tensile loading FEM. Following this, the experimental load-deflection response and deformation profiles of the GFRP pipes are compared to the numerical model predictions. The validated finite element model developed in this chapter served as the foundation for parametric studies on the GFRP pipe hoop tensile loading response.

Chapter 5 summarises the thesis's main conclusions and their practical implications.

REFERENCES

[1] M. Stamenović, S. Putić, M. Rakin, B. Medjo, and D. Čikara, "Effect of alkaline and acidic solutions on the tensile properties of glass–polyester pipes," *Materials & Design,* vol. 32, no. 4, pp. 2456-2461, 2011/04/01/ 2011, doi: https://doi.org/10.1016/j.matdes.2010.11.023.

[2] P. Feng, J. Wang, Y. Wang, D. Loughery, and D. Niu, "Effects of corrosive environments on properties of pultruded GFRP plates," *Composites Part B: Engineering,* vol. 67, pp. 427-433, 2014/12/01/ 2014, doi: https://doi.org/10.1016/j.compositesb.2014.08.021.

[3] L. Patrick, "Use of Composite Pipe Materials in the Transportation of," *Natural Gas.,* vol. vol, p. 64, 1990

[4] N. N. M. Nordin, Z. Ahmad, S. I. S. Abdullah, and Z. A. Ahmad, "An Overview of Buckling, Burst and Corrosion Analyses on Pre-Stressed Thermosetting Glass Fiber-Reinforced Polymer Tubular Structures," in *Materials Science Forum*, 2020, vol. 1015: Trans Tech Publ, pp. 82-88.

[5] M. M. Prabhakar *et al.*, "An overview of burst, buckling, durability and corrosion analysis of lightweight FRP composite pipes and their applicability," *Composite Structures,* vol. 230, p. 111419, 2019.

[6] G. Nagel and D. Thambiratnam, "A numerical study on the impact response and energy absorption of tapered thin-walled tubes," *International journal of mechanical sciences,* vol. 46, no. 2, pp. 201-216, 2004.

[7] R. Rafiee and M. R. Habibagahi, "On the stiffness prediction of GFRP pipes subjected to transverse loading," *KSCE Journal of Civil Engineering,* vol. 22, no. 11, pp. 4564-4572, 2018.

[8] R. Alipour, A. F. Nejad, and S. Izman, "The reliability of finite element analysis results of the low impact test in predicting the energy absorption performance of thin-walled structures," *Journal of Mechanical Science and Technology,* vol. 29, no. 5, pp. 2035-2045, 2015.

[9] F. P. Paulin, "failures and lessons to be," *learned,* pp. 1-40, 2008.

[10] J. T. W. Jappes, I. Siva, and N. Rajini, "Fractography Analysis of Naturally Woven Coconut Sheath Reinforced Polyester Composite: A Novel Reinforcement," *Polymer - Plastics Technology and Engineering,* vol. 51, no. 4, pp. 419-424, 2012, doi: 10.1080/03602559.2011.639838.

[11] K. Mayandi, N. Rajini, P. Pitchipoo, V. S. Sreenivasan, J. W. Jappes, and A. Alavudeen, "A comparative study on characterisations of Cissus quadrangularis and Phoenix reclinata natural fibres," *Journal of Reinforced*

Plastics and Composites, vol. 34, no. 4, pp. 269-280, 2015, doi: 10.1177/0731684415570045.

[12] R. Rafiee, "On the mechanical performance of glass-fibre-reinforced thermosetting-resin pipes: A review," *Composite Structures,* vol. 143, pp. 151-164, 2016, doi: 10.1016/j.compstruct.2016.02.037.

[13] M. Shamsuddoha, M. M. Islam, T. Aravinthan, A. Manalo, and K. T. Lau, "Effectiveness of using fibre-reinforced polymer composites for underwater steel pipeline repairs," *Composite Structures,* vol. 100, pp. 40-54, 2013, doi: 10.1016/j.compstruct.2012.12.019.

[14] I. A. Guz, M. Menshykova, and J. K. Paik, "Thick-walled composite tubes for offshore applications: an example of stress and failure analysis for filament-wound multi-layered pipes," *Ships and Offshore Structures,* vol. 12, no. 3, pp. 304-322, 2017, doi: 10.1080/17445302.2015.1067019.

[15] B. Sundén, J. Fu, B. Sundén, and J. Fu, 0000.

[16] A. B. M. Supian, S. M. Sapuan, M. Y. M. Zuhri, E. S. Zainudin, and H. H. Ya, "Hybrid reinforced thermoset polymer composite in energy absorption tube application: A review," *Defence Technology,* vol. 14, no. 4, pp. 291-305, 2018, doi: 10.1016/j.dt.2018.04.004.

[17] H. Boussetta, M. Beyaoui, A. Laksimi, L. Walha, and M. Haddar, "Study of the filament wound glass/polyester composite damage behavior by acoustic emission data unsupervised learning," *Applied Acoustics,* vol. 127, pp. 175-183, 2017, doi: 10.1016/j.apacoust.2017.06.004.

[18] T. Jaipurkar, P. Kant, S. Khandekar, B. Bhattacharya, and S. Paralikar, "Thermo-mechanical design and characterization of flexible heat pipes," *Applied Thermal Engineering,* vol. 126, pp. 1199-1208, 2017, doi: 10.1016/j.applthermaleng.2017.01.036.

[19] R. Rafiee, "Stochastic fatigue analysis of glass fiber reinforced polymer pipes," *Composite Structures,* vol. 167, pp. 96-102, 2017, doi: 10.1016/j.compstruct.2017.01.068.

[20] Z. Z. Dai and B. Harris, "Acoustic emission study of impact-damaged GRP pipes," *NDT International,* vol. 21, no. 4, pp. 259-265, 1988, doi: 10.1016/0308-9126(88)90339-2.

[21] A. Brent Strong, "Fundamentals of Composites Manufacturing: Materials, Methods and Applications," *Fundamentals of Composites Manufacturing: Materials, Methods, and Applications,* 2008.

[22] Iso, "14692–1. Petroleum and natural gas industries – Glass-reinforced plastics (GRP) piping – Part 1: Vocabulary, symbols, applications and," *materials,* p. 67, 2017.

[23] P. Shabani, F. Taheri-Behrooz, S. Maleki, M. Hasheminasab, "Life prediction of a notched composite ring using progressive fatigue damage models," *Composites Part B: Engineering,* vol. 165, pp. 754-763, 2019, https://doi.org/10.1016/j.compositesb.2019.02.031

[24] Ş. Çitil, Y. Ayaz, Ş. Temiz, and M. D. Aydın, "Mechanical behaviour of adhesively repaired pipes subject to internal pressure," *International Journal of Adhesion and Adhesives,* vol. 75, pp. 88-95, 2017, doi: 10.1016/j.ijadhadh.2017.02.015.

[25] G. Meijer and F. Ellyin, "A failure envelope for ±60° filament wound glass fibre reinforced epoxy tubulars," *Composites Part A: Applied Science and Manufacturing,* vol. 39, no. 3, pp. 555-564, 2008, doi: 10.1016/j.compositesa.2007.11.002.

[26] M. Manoj Prabhakar *et al.*, "An overview of burst, buckling, durability and corrosion analysis of lightweight FRP composite pipes and their applicability," *Composite Structures,* vol. 230, p. 111419, 2019/12/15/ 2019, doi: https://doi.org/10.1016/j.compstruct.2019.111419.

[27] N. N. M. Nordin, Z. Ahmad, S. I. S. Abdullah, and Z. A. Ahmad, "An Overview of Buckling, Burst and Corrosion Analyses on Pre-Stressed Thermosetting Glass Fiber-Reinforced Polymer Tubular Structures," *Materials Science Forum,* vol. 1015, pp. 82-88, 2020, doi: 10.4028/www.scientific.net/MSF.1015.82.

[28] F. Taheri, "18 - Advanced fiber-reinforced polymer (FRP) composites for the manufacture and rehabilitation of pipes and tanks in the oil and gas industry," in *Advanced Fibre-Reinforced Polymer (FRP) Composites for Structural Applications*, J. Bai Ed.: Woodhead Publishing, 2013, pp. 662-704.

[29] S. David Müzel, E. P. Bonhin, N. M. Guimarães, and E. S. Guidi, "Application of the Finite Element Method in the Analysis of Composite Materials: A Review," (in eng), *Polymers (Basel),* vol. 12, no. 4, p. 818, 2020, doi: 10.3390/polym12040818.

[30] Bsi, "BS EN ISO 14692 Petroleum and Natural Gas Industries - Glass-Reinforced Plastic (GRP) Piping - Part 2: Qualification and Manufacture," 2017.

[31] F. C. Shen, "A filament-wound structure technology overview," *Materials Chemistry and Physics,* vol. 42, no. 2, pp. 96-100, 1995/11/15/ 1995, doi: https://doi.org/10.1016/0254-0584(95)01554-X.

[32] P. K. Gupta and R. K. Srivastava, "Fabrication of Ceramic Reinforcement Aluminium and Its Alloys Metal Matrix Composite Materials: A Review," *Materials Today: Proceedings,* vol. 5, no. 9, Part 3, pp. 18761-18775, 2018/01/01/ 2018, doi: https://doi.org/10.1016/j.matpr.2018.06.223.

[33] E. I. Croitoru, G. Oancea, and N. Constantin, "Impact testing on composite panels of fiberglass, carbon and kevlar-carbon," *Materiale Plastice,* Article vol. 54, no. 4, pp. 700-707, 2017. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85038875389&partnerID=40&md5=9dafcb10408540c3a6896f694978d05a.

[34] *ISO. 14692–1. Petroleum and natural gas industries – Glass-reinforced plastics*. European Committee for Standardization, 2017.

[35] M. Garg, S. Sharma, and R. Mehta, "Carbon nanotube-reinforced glass fiber epoxy composite laminates exposed to hygrothermal conditioning," *Journal of Materials Science,* vol. 51, no. 18, pp. 8562-8578, 2016/09/01 2016, doi: 10.1007/s10853-016-0117-z.

[36] M. Farshad, "2 - Failure investigation of plastic pipes," in *Plastic Pipe Systems*, M. Farshad Ed. Oxford: Elsevier Science, 2006, pp. 28-52.

[37] J. Mistry, A. G. Gibson, and Y. S. Wu, "Failure of composite cylinders under combined external pressure and axial loading," *Composite Structures,* vol. 22, no. 4, pp. 193-200, 1992/01/01/ 1992, doi: https://doi.org/10.1016/0263-8223(92)90055-H.

[38] A. Kinsey, D. E. J. Saunders, and C. Soutis, "Post-impact compressive behaviour of low temperature curing woven CFRP laminates," *Composites,* vol. 26, no. 9, pp. 661-667, 1995/09/01/ 1995, doi: https://doi.org/10.1016/0010-4361(95)98915-8.

[39] G. C. Grim, *Shipboard experience with glass-reinforced plastic pipes in Shell fleet*. London: Composite Materials in Maritime Structures: Volume 2, Practical Considerations, 1991.

[40] H. S. da Costa Mattos, J. M. L. Reis, L. M. Paim, M. L. da Silva, F. C. Amorim, and V. A. Perrut, "Analysis of a glass fibre reinforced polyurethane composite repair system for corroded pipelines at elevated temperatures," *Composite Structures,* vol. 114, pp. 117-123, 2014/08/01/ 2014, doi: https://doi.org/10.1016/j.compstruct.2014.04.015.

[41] J. G. Teng, T. Yu, and D. Fernando, "Strengthening of steel structures with fiber-reinforced polymer composites," *Journal of Constructional Steel Research,* vol. 78, pp. 131-143, 2012/11/01/ 2012, doi: https://doi.org/10.1016/j.jcsr.2012.06.011.

[42] K. L. Alderson and K. E. Evans, "Low velocity transverse impact of filament-wound pipes: Part 1. Damage due to static and impact loads," *Composite Structures,* vol. 20, no. 1, pp. 37-45, 1992/01/01/ 1992, doi: https://doi.org/10.1016/0263-8223(92)90010-A.

[43] A. Hawa *et al.*, "Burst strength and impact behaviour of hydrothermally aged glass fibre/epoxy composite pipes," *Materials & Design,* vol. 89, pp. 455-464, 2016/01/05/ 2016, doi: https://doi.org/10.1016/j.matdes.2015.09.082.

[44] H. Arikan, "Failure analysis of (±55°)3 filament wound composite pipes with an inclined surface crack under static internal pressure," *Composite Structures,* vol. 92, no. 1, pp. 182-187, 2010/01/01/ 2010, doi: https://doi.org/10.1016/j.compstruct.2009.07.027.

[45] L. Gemi, M. Kara, and A. Avci, "Low velocity impact response of prestressed functionally graded hybrid pipes," *Composites Part B: Engineering,* vol. 106, pp. 154-163, 2016/12/01/ 2016, doi: https://doi.org/10.1016/j.compositesb.2016.09.025.

[46] J. A. Peck, R. A. Jones, S.-S. Pang, G. Li, and B. H. Smith, "UV-cured FRP joint thickness effect on coupled composite pipes," *Composite Structures,* vol. 80, no. 2, pp. 290-297, 2007/09/01/ 2007, doi: https://doi.org/10.1016/j.compstruct.2006.05.009.

[47] F. Eggers, J. H. S. Almeida, C. B. Azevedo, and S. C. Amico, p. 105951, 2019.

[48] H. Mahdavi, G. H. Rahimi, and A. Farrokhabadi, "Failure Analysis of (± 55°)9 Filament-Wound GRE Pipes Using Explicit Finite Element Method: A Comparison with the Experimental Method," *Journal of Failure Analysis and Prevention,* vol. 18, no. 6, pp. 1526-1533, 2018, doi: 10.1007/s11668-018-0550-1.

[49] H. R. Mahdavi, G. H. Rahimi, and A. Farrokhabadi, "Failure Analysis of Glass-Reinforced Epoxy Pipes under Internal Hydrostatic Pressure: A Comparison with the Split Disk Test Method," *Journal of Pressure Vessel Technology, Transactions of the ASME,* vol. 140, no. 1, 2018, Art no. 014501, doi: 10.1115/1.4038484.

[50] G. Perillo, R. Vacher, F. Grytten, S. Sørbø, and V. Delhaye, "Material characterisation and failure envelope evaluation of filament wound GFRP and CFRP composite tubes," *Polymer Testing,* vol. 40, pp. 54-62, 2014, doi: 10.1016/j.polymertesting.2014.08.009.

[51] R. Rafiee, "Experimental and theoretical investigations on the failure of filament wound GRP pipes," *Composites Part B: Engineering,* vol. 45, no. 1, pp. 257-267, 2013, doi: 10.1016/j.compositesb.2012.04.009.

[52] R. Rafiee, "Apparent hoop tensile strength prediction of glass fiber-reinforced polyester pipes," *Journal of Composite Materials,* vol. 47, no. 11, pp. 1377-1386, 2013, doi: 10.1177/0021998312447209.

[53] W. Toh *et al.*, "Material characterization of filament-wound composite pipes," *Composite Structures,* vol. 206, pp. 474-483, 2018, doi: 10.1016/j.compstruct.2018.08.049.

[54] D. ASTM, "2290-12,“," *Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe”, American Society for Testing and Materials, ASTM International, West Conshohocken, PA,* 2012.

[55] R. Rafiee, M. Maleki, and S. Rahnama, "Experimental study on the effect of hygrothermal environments combined with the sustained mechanical loads on the strength of composite rings," *Composite Structures,* vol. 258, p. 113397, 2021.

[56] P. Jakubczak, J. Bienias, and B. Surowska, "The influence of fibre orientation in aluminium-carbon laminates on low-velocity impact resistance," *Journal of Composite Materials,* vol. 52, no. 8, pp. 1005-1016, Apr 2018, doi: 10.1177/0021998317719569.

[57] J. T. W. Jappes, I. Siva, and N. Rajini, "Fractography Analysis of Naturally Woven Coconut Sheath Reinforced Polyester Composite: A Novel Reinforcement," *Polymer-Plastics Technology and Engineering,* vol. 51, no. 4, pp. 419-424, 2012 2012, doi: 10.1080/03602559.2011.639838.

[58] D. M. Jerome and C. A. Ross, "Simulation of the dynamic response of concrete beams externally reinforced with carbon-fiber reinforced plastic," *Computers & Structures,* vol. 64, no. 5-6, pp. 1129-1153, Sep 1997, doi: 10.1016/s0045-7949(97)00022-9.

[59] R. Zhu, F. Li, and D. Zhang, "Overall buckling behaviour of laminated CFRP tubes with off-axis ply orientation in axial compression," *Science and Engineering of Composite Materials,* vol. 26, no. 1, pp. 230-239, Jan 2019, doi: 10.1515/secm-2019-0007.

[60] B. Bogner and B. Curry, "FRP pipe meets power plant requirements," *Reinforced Plastics,* vol. 52, pp. 32-35, 2008.

[61] P. Mertiny, F. Ellyin, and A. Hothan, "An experimental investigation on the effect of multi-angle filament winding on the strength of tubular composite structures," *Composites Science and Technology,* vol. 64, no. 1, pp. 1-9, Jan 2004, doi: 10.1016/s0266-3538(03)00198-2.

[62] M. H. Lapena and G. Marinucci, "Mechanical Characterization of Basalt and Glass Fiber Epoxy Composite Tube," *Materials Research,* vol. 21, 2018. [Online]. Available: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1516-14392018000100110&nrm=iso.

[63] S. W. Tsai and E. M. Wu, "A general theory of strength for anisotropic materials," *Journal of composite materials,* vol. 5, no. 1, pp. 58-80, 1971.

[64] F.-K. Chang and K.-Y. Chang, "A progressive damage model for laminated composites containing stress concentrations," *Journal of composite materials,* vol. 21, no. 9, pp. 834-855, 1987.

[65] Z. Hashin, "Failure criteria for unidirectional fiber composites," 1980.

[66] S. T. Pinho, P. Robinson, and L. Iannucci, "Fracture toughness of the tensile and compressive fibre failure modes in laminated composites," *Composites*

Science and Technology, vol. 66, no. 13, pp. 2069-2079, 2006/10/01/ 2006, doi: https://doi.org/10.1016/j.compscitech.2005.12.023.

[67] L.-D. K. U. s. Manual, "Volume II Material Models," *Livermore Software Technology Corporation,* 2017.

[68] J. Gu and P. Chen, "Some modifications of Hashin's failure criteria for unidirectional composite materials," *Composite Structures,* vol. 182, pp. 143-152, 2017/12/15/ 2017, doi: https://doi.org/10.1016/j.compstruct.2017.09.011.

[69] J. Zhang and X. Zhang, "An efficient approach for predicting low-velocity impact force and damage in composite laminates," *Composite Structures,* vol. 130, pp. 85-94, 2015, doi: 10.1016/j.compstruct.2015.04.023.

[70] Z. Hashin and A. Rotem, "A Fatigue Failure Criterion for Fiber Reinforced Materials," *Journal of Composite Materials,* vol. 7, no. 4, pp. 448-464, 1973, doi: 10.1177/002199837300700404.

[71] S. Long, X. Yao, and X. Zhang, "Delamination prediction in composite laminates under low-velocity impact," *Composite Structures,* vol. 132, pp. 290-298, 2015, doi: 10.1016/j.compstruct.2015.05.037.

[72] M. R. Abir, T. E. Tay, M. Ridha, and H. P. Lee, "Modelling damage growth in composites subjected to impact and compression after impact," *Composite Structures,* vol. 168, pp. 13-25, 2017, doi: 10.1016/j.compstruct.2017.02.018.

[73] A. Qiu, K. Fu, W. Lin, C. Zhao, and Y. Tang, "Modelling low-speed drop-weight impact on composite laminates," *Materials and Design,* vol. 60, pp. 520-531, 2014, doi: 10.1016/j.matdes.2014.04.041.

[74] C. Zhang, E. A. Duodu, and J. Gu, "Finite element modeling of damage development in cross-ply composite laminates subjected to low velocity impact," *Composite Structures,* vol. 173, pp. 219-227, 2017, doi: 10.1016/j.compstruct.2017.04.017.

[75] F. Caputo, A. De Luca, G. Lamanna, R. Borrelli, and U. Mercurio, "Numerical study for the structural analysis of composite laminates subjected to low velocity impact," *Composites Part B: Engineering,* vol. 67, pp. 296-302, 2014, doi: 10.1016/j.compositesb.2014.07.011.

[76] H. Tang *et al.*, "Computational micromechanics model based failure criteria for chopped carbon fiber sheet molding compound composites," *Composites Science and Technology,* vol. 200, p. 108400, 2020, doi: 10.1016/j.compscitech.2020.108400.

[77] M. Xia, H. Takayanagi, and K. Kemmochi, "Analysis of transverse loading for laminated cylindrical pipes," *Composite Structures,* vol. 53, no. 3, pp. 279-285, 2001.

[78] R. Guedes, "Stress analysis of transverse loading for laminated cylindrical composite pipes: An approximated 2-D elasticity solution," *Composites science and technology,* vol. 66, no. 3-4, pp. 427-434, 2006.

[79] R. Guedes, "Stress–strain analysis of a cylindrical pipe subjected to a transverse load and large deflections," *Composite structures,* vol. 88, no. 2, pp. 188-194, 2009.

[80] M. Farshad and A. Necola, "Effect of aqueous environment on the long-term behavior of glass fiber-reinforced plastic pipes," *Polymer testing,* vol. 23, no. 2, pp. 163-167, 2004.

[81] H. Q. d. Faria, "Failure analysis of GRP pipes under compressive ring loads," 2005.

[82] P. Tse, S. Reid, and S. Ng, "Spring constants of filament-wound composite circular rings," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* vol. 215, no. 2, pp. 211-226, 2001.

[83] M. Kara, M. Uyaner, A. Avci, and A. Akdemir, "Effect of non-penetrating impact damages of pre-stressed GRP tubes at low velocities on the burst strength," *Composites Part B: Engineering,* vol. 60, pp. 507-514, 2014/04/01/ 2014, doi: https://doi.org/10.1016/j.compositesb.2014.01.003.

[84] Z. Khan, M. Naik, F. Al-Sulaiman, and N. Merah, "Low Velocity Impact of Filament-Wound Glass-Fiber Reinforced Composite Pipes," *J Material Sci Eng.,* vol. 5, no. 4, pp. 1-5, 2016.

[85] C. Colombo and L. Vergani, "Optimization of filament winding parameters for the design of a composite pipe," *Composites Part B: Engineering,* vol. 148, pp. 207-216, 2018/09/01/ 2018, doi: https://doi.org/10.1016/j.compositesb.2018.04.056.

[86] A. Onder, O. Sayman, T. Dogan, and N. Tarakcioglu, "Burst failure load of composite pressure vessels," *Composite Structures,* vol. 89, no. 1, pp. 159-166, 2009/06/01/ 2009, doi: https://doi.org/10.1016/j.compstruct.2008.06.021.

[87] C. Venkateshwar Reddy, P. Ramesh Babu, R. Ramnarayanan, and D. Das, "Mechanical Characterization Of Unidirectional Carbon And Glass/Epoxy Reinforced Composites For High Strength Applications," *Materials Today: Proceedings,* vol. 4, no. 2, Part A, pp. 3166-3172, 2017/01/01/ 2017, doi: https://doi.org/10.1016/j.matpr.2017.02.201.

[88] L. A. L. Martins, F. L. Bastian, and T. A. Netto, "Structural and functional failure pressure of filament wound composite tubes," *Materials & Design (1980-2015),* vol. 36, pp. 779-787, 2012/04/01/ 2012, doi: https://doi.org/10.1016/j.matdes.2011.11.029.

[89] L. A. L. Martins, F. L. Bastian, and T. A. Netto, "The effect of stress ratio on the fracture morphology of filament wound composite tubes," *Materials & Design,* vol. 49, pp. 471-484, 2013/08/01/ 2013, doi: https://doi.org/10.1016/j.matdes.2013.01.026.

[90] L. A. L. Martins, F. L. Bastian, and T. A. Netto, "Reviewing some design issues for filament wound composite tubes," *Materials & Design,* vol. 55, pp. 242-249, 2014/03/01/ 2014, doi: https://doi.org/10.1016/j.matdes.2013.09.059.

[91] J. D. Diniz Melo, F. Levy Neto, G. De Araujo Barros, and F. N. De Almeida Mesquita, "Mechanical behavior of GRP pressure pipes with addition of quartz sand filler," *Journal of Composite Materials,* vol. 45, no. 6, pp. 717-726, 2011, doi: 10.1177/0021998310385593.

[92] R. Rafiee and F. Reshadi, "Simulation of functional failure in GRP mortar pipes," *Composite Structures,* vol. 113, pp. 155-163, 2014/07/01/ 2014, doi: https://doi.org/10.1016/j.compstruct.2014.03.024.

[93] H. S. Benabdallah, "Static friction coefficient of some plastics against steel and aluminum under different contact conditions," *Tribology International,* vol. 40, no. 1, pp. 64-73, 2007/01/01/ 2007, doi: https://doi.org/10.1016/j.triboint.2006.02.031.

[94] J. F. Chen, S. Q. Li, L. A. Bisby, and J. Ai, "FRP rupture strains in the split-disk test," *Composites Part B: Engineering,* vol. 42, no. 4, pp. 962-972, 2011/06/01/ 2011, doi: https://doi.org/10.1016/j.compositesb.2010.12.015.

[95] Ö. Özbek, N. F. Doğan, and Ö. Y. Bozkurt, "An experimental investigation on lateral crushing response of glass/carbon intraply hybrid filament wound composite pipes," *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* vol. 42, no. 7, pp. 1-13, 2020.

[96] S. Li, X. Guo, Q. Li, D. Ruan, and G. Sun, "On lateral compression of circular aluminum, CFRP and GFRP tubes," *Composite Structures,* vol. 232, p. 111534, 2020.

[97] M. T. Demirci, N. Tarakçıoğlu, A. Avcı, A. Akdemir, and İ. Demirci, "Fracture toughness (Mode I) characterization of SiO2 nanoparticle filled basalt/epoxy filament wound composite ring with split-disk test method," *Composites Part B: Engineering,* vol. 119, pp. 114-124, 2017/06/15/ 2017, doi: https://doi.org/10.1016/j.compositesb.2017.03.045.

[98] E. Mahdi, B. B. Sahari, A. M. S. Hamouda, and Y. A. Khalid, "An experimental investigation into crushing behaviour of filament-wound laminated cone–cone intersection composite shell," *Composite Structures,* vol. 51, no. 3, pp. 211-219, 2001/03/01/ 2001, doi: https://doi.org/10.1016/S0263-8223(00)00132-X.

[99] P. D. Soden, R. Kitching, P. C. Tse, Y. Tsavalas, and M. J. Hinton, "Influence of winding angle on the strength and deformation of filament-wound composite tubes subjected to uniaxial and biaxial loads," *Composites Science*

and Technology, vol. 46, no. 4, pp. 363-378, 1993/01/01/ 1993, doi: https://doi.org/10.1016/0266-3538(93)90182-G.

[100] A. W. Wharmby and F. Ellyin, "Damage growth in constrained angle-ply laminates under cyclic loading," *Composites Science and Technology,* vol. 62, no. 9, pp. 1239-1247, 2002/07/01/ 2002, doi: https://doi.org/10.1016/S0266-3538(02)00075-1.

[101] A. Ismail and M. Sahrom, "Lateral crushing energy absorption of cylindrical kenaf fiber reinforced composites," *International Journal of Applied Engineering Research,* vol. 10, no. 8, pp. 19277-19288, 2015.

[102] Z. I. Khan, A. Arsad, Z. Mohamad, U. Habib, and M. A. A. Zaini, "Comparative study on the enhancement of thermo-mechanical properties of carbon fiber and glass fiber reinforced epoxy composites," *Materials Today: Proceedings,* vol. 39, pp. 956-958, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.matpr.2020.04.223.

[103] H. Rahmani, S. H. M. Najafi, and A. Ashori, "Mechanical performance of epoxy/carbon fiber laminated composites," *Journal of Reinforced Plastics and Composites,* vol. 33, no. 8, pp. 733-740, 2014.

[104] D. a. Cai, G. Zhou, and V. V. Silberschmidt, "Effect of through-thickness compression on in-plane tensile strength of glass/epoxy composites: Experimental study," *Polymer Testing,* vol. 49, pp. 1-7, 2016/02/01/ 2016, doi: https://doi.org/10.1016/j.polymertesting.2015.10.015.