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Hydrostatic Pressure Analysis of Yarn Composites Patch for PVC Pipes

Jamaliah Md Said[1,2], Noor Leha Abdul Rahman[1*], Aidah Jumahat[1], Zaidahtulakmal Mohd Zahib[1], Muhammad Zarief Iman Mahadzir[1]

[1]*School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, 40450, Selangor, Malaysia*
[2]*School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, Pasir Gudang Campus, Johor Branch, 81750 Masai, Johor, Malaysia*

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ABSTRACT

The globally high-demand pipeline is prone to operational issues that can be mitigated using composite materials. Damage and cracks in the pipe can lead to structural weakening, leaks, and reduced functionality. This research aims to determine the adhesion strength of polyvinyl (PV) resin through lap joint testing, assess the burst pressure of polyvinyl chloride (PVC) pipes via hydrostatic pressure testing, and evaluate the impact of various wrapping materials on the maximum hydrostatic pressure of damaged PVC pipes. The PVC pipe was introduced to a 20 mm hole diameter as a defect and then patched with woven basalt fiber. The yarn-commingled fiber mat was wrapped onto the PVC pipe surface using the hand lay-up and vacuum bagging methods. Various materials with the same stacking lay-up layer and different fiber orientations were used in this study. Hydrostatic pressure testing on the PVC pipe showed that the bare pipe (unwrapped) can withstand up to 1.5 MPa before failing. For reference materials in the woven fiber type, the highest maximum pressure achieved was approximately 2.03 MPa using the glass chopped strain mat (CSM) and woven fiber for the wrapping system. Among the commingled fiber systems, the basalt (B/B) commingled fiber demonstrated the highest maximum hydrostatic pressure of about 1.86 MPa, with a maximum hoop stress of 26.5 MPa and a strain of 1.37%. This research demonstrates that using composite materials, particularly glass chopped strain mat (CSM), woven fibers, and basalt commingled fibers, significantly enhances the structural performance of damaged PVC pipelines compared to untreated pipes. These findings provide valuable insights into the effective design and selection of fiber composite materials for pipeline repairs, offering durable and innovative solutions to mitigate operational issues in high-demand pipeline systems.

[1*] Corresponding author. *E-mail address*: noorleha3585@uitm.edu.my
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INTRODUCTION

Plastics are widely utilized in various commercial and industrial piping applications, with polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), acrylonitrile butadiene styrene (ABS), polybutylene (PB), and glass fiber reinforced polyester (GRP or FRP) being the most common. PVC, PE, and PP are the preferred polymer materials for piping systems related to drinking water supply, gas distribution, and sewage disposal (Hughes, 2023). PVC has been extensively used for gravity sewer pipes over the past decades, becoming the dominant construction material. Its cost efficiency, ease of installation, availability in a range of diameters of 40 mm - 630 mm, and reputed chemical resistance have made it a favoured choice among decision-makers in urban drainage (Makris et al., 2020). The ability of PVC pipes to withstand internal pressure is a key determinant of their suitability for various applications. This is particularly important for systems that transport fluids under pressure, such as water supply and sewage systems.

The unique response of PVC to loading conditions can be attributed to its material properties which include flexibility, chemical resistance, and durability. In most instances, internal pressure is the primary factor influencing PVC pipe design with additional considerations including temperature, loading duration, cyclic loading, and dynamic surge pressure. Dynamic surge pressure often resulting from sudden changes in fluid flow can induce transient stresses that PVC pipes must be able to absorb and dissipate effectively. These properties enable PVC pipes to maintain structural integrity and functionality even under varying and challenging conditions (Gao, 2011).

Pressurized pipes are frequently subjected to damage during operation due to internal pressure, temperature changes, and corrosion. Given the high costs associated with repairing and maintaining the pipelines, newer and more cost-effective methods such as using composites are being explored as alternatives to traditional methods like welding or replacing damaged pipeline sections. One of the newer methods is the use of fiber-reinforced polymer-based composite patches. Composite patching is the most widely used method for restoring the load-carrying capacity of weakened structures or reinforcing damaged zones, offering greater strength and stiffness than the original material (Brandtner-Hafner, 2024; Hu et al., 2024). Budhe et al. (2018) and Hart Smith et al. (2021) extensively studied the aircraft industry and found that bonded composite patch methods not only reduce weight but also extend service life. These patches provide more uniform load transfer by avoiding high-stress concentrations and offer additional benefits such as improved fatigue behaviour, restored stiffness and strength, reduced corrosion, and easy adaptation to complex aerodynamic contours. Therefore, the patching system is investigated in this study to evaluate the suitability of this method as a treatment for defective pipes.

Roberts (1995) conducted an experimental investigation on a cracked steel pressure vessel repaired with carbon fiber composite patches. Using standard tensile stress specimens, the researcher measured the effects of the repair. The cracked specimens repaired with the composite patches were subjected to static and environmental loads. The study found that the crack propagation was slowed, and the lifespan of the specimens increased. Similarly, Hu et al. (1990) studied repaired cracked steel pressure vessels using steel patches with epoxy glue. In another study, Wilson (2006) repaired a damaged steel pipe with a carbon/epoxy wrap, measuring the energy release rate at the composite wrapping/steel interface. Another study by Ayaz et al. (2016) investigated the use of composite patch repair on galvanized steel pipes using carbon fiber and acrylic adhesive. They examined the effects of patch thickness, overlap angle, and length on stress distribution, concluding that greater tangential overlap length and increased patch thickness contribute to higher failure pressure. Duell et al. (2008) studied the reinforcement and surface corrosion prevention of steel pipes using carbon/epoxy composites for repairs. They performed stress analysis on damaged pipes of varying geometries through three-dimensional finite element methods and compared these results with experimental data. Both sets of results indicated that the maximum stress is located at the centre of the damaged area Berrin Günaydın (2013) conducted an experimental investigation into the effects of composite patch repairs on the fatigue behaviour of surface-notched glass fiber reinforced plastic (GFRP)

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composite pipes. The pipes had notch size ratios of a/c = 0.2 and a/t = 0.75. They found that pipes repaired with 100 mm wide patches comprising two to seven layers have higher burst pressure than un-patched notched pipes. The study concluded that fatigue life increases with the number of patch layers. Therefore, it can be stated that applying a patching technique with fibre to the defective pipes would increase the lifespan and strengthen the pipe.

In the present work, the adhesively bonded composite fiber is utilized to extend the lifetime of a cracked steel pipeline with different inclination angles under hydrostatic pressure. There is a lack of specific research on the application of composite patches on different fiber orientations in commingled fiber mats to PVC pipes, particularly under hydrostatic pressure conditions. The main objective of this study is to investigate the effect of different wrapping materials on the maximum hydrostatic pressure of damaged PVC pipes, particularly focusing on woven basalt fiber patches and various fiber orientations in commingled fiber mats. It is expected that the current work and findings can provide guidelines for selecting and designing fiber composite material repairs for pipelines, potentially offering more durable and effective solutions for mitigating operational issues in high-demand pipeline systems.

METHODOLOGY

Materials

The raw materials utilized in this study comprise both synthetic and natural fibers. The Arenga Pinnata was chosen as natural fiber derived from palm trees and Basalt fiber while the mineral based fiber sourced from volcanic rock glass fiber was synthetic fiber. Polyvinyl (PV) resin was chosen as the matrix, bonding with the fibers to provide strong adhesion and interfacial strength. Samples were prepared using the commingling technique, based on the configurations listed in Table 1. Fig 1 shows the natural and synthetic fibers used in this research in the production of the comingle fiber system.

Table 1. Designation of fiber according to fiber system

Fiber system	Fiber	Designation
Comingle system	Arenga Pinnata/Arenga Pinnata	AP/AP
	Arenga Pinnata/Glass	AP/G
	Arenga Pinnata/ Basalt	AP/B
	Glass/Glass	G/G
	Basalt/Basalt	B/B
Woven fiber	Glass fiber	WG
	Basalt fiber	WB
	Carbon fiber	WC

(a) (b) (c)

Fig. 1. (a) Raw AP, (b) strands basalt, and (c) strands glass.

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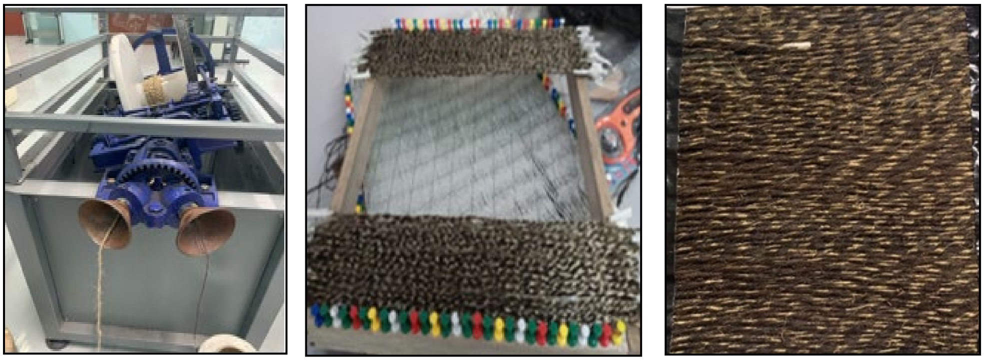
Firstly, the raw AP fibers were prepared and cleaned to remove any dirt or debris from the core. The fibers were then air-dried at room temperature for 24 hours before proceeding with commingling. After AP yarn was prepared, the commingling fiber system was ready to be made. The AP and B fibers were comingled to get into long yarn fibers. These yarn fibers were combined using a rope maker machine, with the machine's turning rate adjusted to an appropriate speed for optimal commingling. The commingled fibers were yarned within the threads interwoven among the fibers to secure them in place to form a mat material as shown in Fig 2. All the procedures were repeated for AP/AP, AP/G, G/G, and B/B systems, respectively.



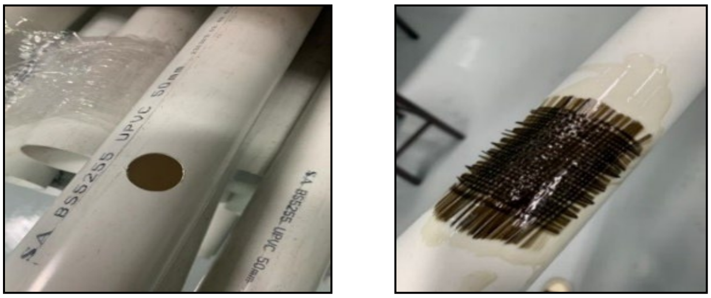
(a) (b) (c)

Fig. 2. (a) Rope maker machine, (b) yarn fibers into the thread of a square wooden frame fiber, and (c) mat fiber.

Preparation of defective patching PVC pipe

A hole was introduced into the PVC pipe to replicate a defect that is commonly encountered in real life situations that necessitate repair. A 20 mm diameter hole was drilled into the pipe's surface to create this defect. The pipe was subsequently patched with a size of 50 x 50 mm WB. Fig 3 shows the PVC pipe with the drilled hole and the patched specimen. This repair technique ensures that the wrapped material adheres firmly to a stable surface, thereby improving the overall effectiveness of the repair.

This study focuses on the hydrostatic pressure testing of wrapped woven fibers, specifically WC, WB, and WG types which assess the performance in comparison to wrapped commingle fibers. Due to extensive application in various industries, woven fibers provide a suitable reference for evaluating the newly developed commingled fibers. The experimental work involves solid PVC pipes, which will be compared with the wrapped materials.



(a) (b)

Fig. 3. (a) Defect pipe and (b) PVC pipe patching with woven basalt fiber.

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Preparation of treated patching PVC pipe

The wrapping technique was applied to strengthen the pipe and prevent further leaks, utilizing hand lay-up and vacuum bagging methods. As shown in Fig 4, the process began with a layer of chopped strand mat (CSM) glass fiber. This was followed by two layers of comingled fiber mat oriented at 0° and 90°, respectively. The outermost layer was woven basalt (WB) fiber, chosen for its compatibility with the commingled fiber and its natural properties. The fibers were layered with polyvinyl (PV) resin using hand lay-up techniques and wrapped around the patched pipe. After wrapping, the sample underwent vacuum bagging to enhance consolidation, promote resin infusion and fiber wetting, and improve the overall quality of the composite materials.

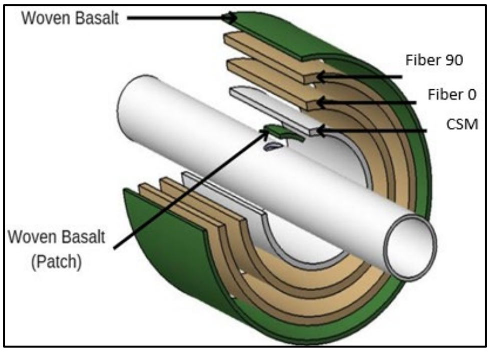

Fig. 4. Lay-up layer of composite fiber.

Hydrostatic test

Hydrostatic tests were conducted at room temperature to evaluate pressure failure following the ASTM D1599 standard. An endcap was attached to both ends of the specimen pipe to prevent slippage and minimize bubble formation during pressurization. The pipe was filled with water via a connected hose while the pump was activated, and pressure was applied uniformly until failure occurred. The treated PVC pipe was submerged in water to contain any fragments from the burst. A sensor linked to a data logger recorded the measurements on a computer throughout the testing process. Fig 5 illustrates the schematic of the hydrostatic pressure testing setup.

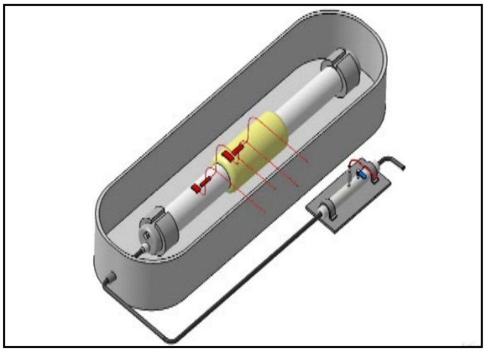

Fig. 5. Schematic hydrostatic pressure testing setup.

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Barlow's equation is employed to obtain the stress value in the stress-versus-strain graph, as it relates to determining pressure in a pipe and stress simultaneously. The equation is rearranged in terms of stress, and the known values of P, t, and D of the pipe are substituted into Equation (1).

$$p = \frac{2St}{D} \rightarrow S = \frac{PD}{2t} \tag{1}$$

where, *P* is maximum internal pressure (in MPa), *S* is material stress (in MPa), *D* is the outer diameter of pipe (in m), and *t* is the thickness of pipe (in m).

RESULTS AND DISCUSSION

Hydrostatic pressure

Woven fibers

Fig 6 and Fig 7 show the experimental results of the burst test of wrapping PVC pipe with woven types of fiber. Fig 6 shows the pressure failure of woven fiber over time. It was observed that the burst pressure of solid PVC pipes gave different results with different types of woven wrapped materials. PVC pipes wrapped with WG fiber show the highest burst pressure value, reaching 2 MPa, while solid unwrapped PVC pipes have a maximum pressure of 1.51 MPa. This represents a 29.2% increase as compared to solid unwrapped PVC pipe. These results indicate that the properties of woven glass fiber are recognized for its strong mechanical properties that may contribute effectively to pipe repairs (Gao & Li, 2016). However, while the WG wrapped fiber pipe shows the highest burst pressure value, it has a shorter burst time to failure compared to solid PVC pipe. This reduction in the pipe's flexibility is due to WG wrap, resulting in quicker failure time (Al-Mahfooz & Mahdi, 2020).

Fig 7 demonstrates the stress-strain behaviour of wrapped woven fibers. It can be observed that the WG wrapped pipe achieved the highest maximum stress of 29.42 MPa with a strain of 1.19%. In contrast, the WC-wrapped PVC pipe displayed the highest strain at 1.40% but had the lowest stress at 23.02 MPa. The solid PVC pipe showed the lowest values for both stress and strain, at 21.33 MPa and 0.67%, respectively. These results indicate differences of 31.8% and 56% compared to the maximum stress and strain of the wrapped pipes.

By comparing the pressure-time graph and the stress-strain graph, it is evident that the wrapped pipe shows a substantial improvement in pressure resistance and structural strength. This enhancement is largely due to the wrapping materials, which contribute significantly to the strength of the final samples (Kara et al., 2015). The stress-strain graph also revealed that the wrapped pipe has a higher strain percentage than the solid PVC pipe, with the wrapped pipe exhibiting a strain of 1.40%, compared to just 0.67% for the solid PVC pipe. This indicates that wrapping PVC pipes effectively enhances their overall strength.

Commingle fibers

Fig 8 shows the pressure-time relationship for wrapped commingled fiber pipes. The graph indicates that all wrapped commingled fiber pipes have higher burst pressure than the solid PVC pipe. Notably, the commingled wrapped pipe with B/B commingled reached a maximum pressure of 1.86 MPa, reflecting a 22.7% increase over the solid PVC pipe's burst pressure of 1.51 MPa. Among the wrapped pipes, the commingled G/G had the lowest maximum burst pressure at 1.55 MPa, yet it still exceeded the solid PVC pipe's burst pressure by 2.3%.

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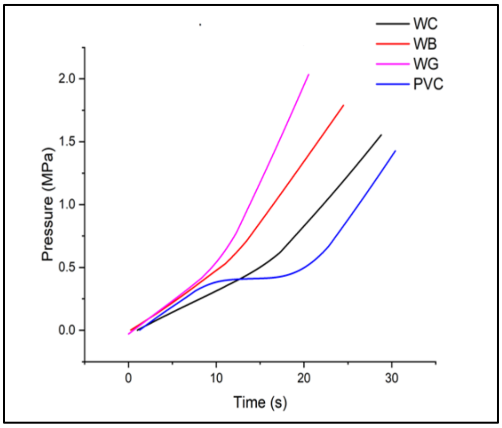

Fig. 6. Pressure failure of woven fiber wrapped PVC.

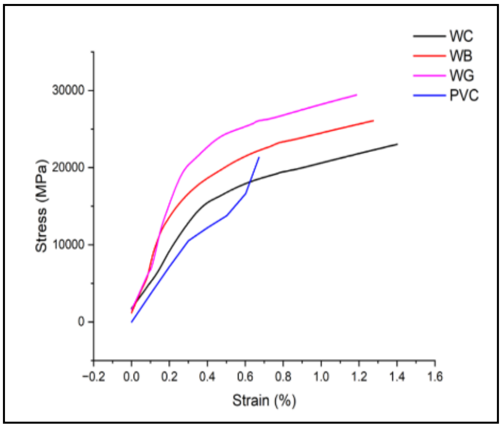

Fig.7. Typical stress-strain behaviour of woven fiber wrapped PVC.

The stress-strain relationship for pipes wrapped with commingled fiber is shown in Fig 9. The data analysis indicates that the B/B wrapped pipe exhibited the highest values for both maximum stress and maximum strain, recorded at 26.54 MPa and 1.37%, respectively. The AP/AP wrapped pipe ranked second in maximum stress, achieving 26.23 MPa. Basalt (B/B) fibers had the highest modulus of elasticity at 60 GPa compared to Arenga pinnata and glass fiber which had a modulus of 3.69 GPa and 52 GPa, respectively. Fibers with a higher modulus of elasticity have a greater impact on critical internal pressure (Alizadeh & Dehestani, 2018). However, the strain value for the AP/AP wrapped pipe was significantly lower, being 73.4% less than that of the B/B wrapped pipe. Conversely, the AP/B wrapped pipe showed only a 7% difference in strain compared to the B/B wrapped pipe and recorded the third-highest maximum stress at 24.37 MPa. Among the types of fibers, the G/G commingled fiber displayed the lowest strength and stiffness, with values of 22.17 MPa and 0.75%, respectively. Despite damage occurring in the pipes during testing, the strength values increase when commingled fibers are utilised compared to solid PVC pipes. This wrapping technique has proven effective in addressing burst damage on PVC pipe surfaces. Other studies have supported this finding, showing that conventional patching methods are insufficient for fully repairing such damages when the pipes are subjected to pressure (Kepir et al., 2022).

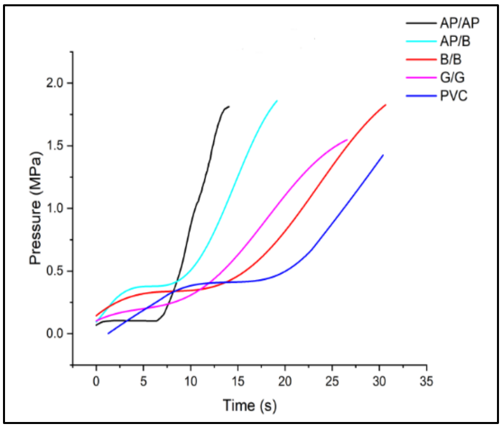

Fig.8. Failure pressure of commingled fiber wrapped PVC pipe.

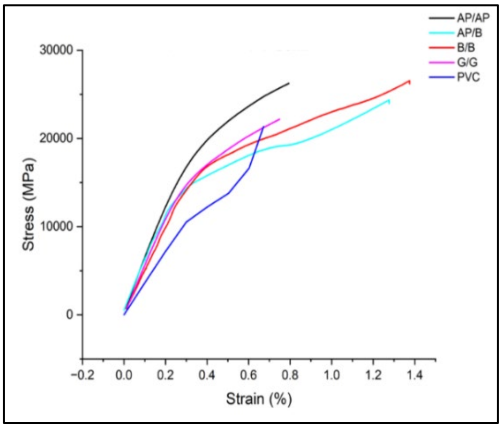

Fig.9. Typical stress strain behaviour of commingled fibers wrapped PVC pipe.

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Crack analysis

The failure mode of PVC pipes under hydrostatic pressure typically involves a process known as ductile failure. Ductile failure occurs when the material undergoes plastic deformation before rupturing. In the case of PVC pipes, when the internal water pressure exceeds the pipe's capacity, the material begins to deform plastically. This deformation initially appears as small cracks or microvoids on the surface of the pipe wall. As the pressure continues to rise, these cracks propagate and extend, creating larger cracks that may eventually lead to rupture. The cracks typically follow the direction of the applied stress, which is generally along the axial direction of the pipe.

(a) (b) (c)

Fig.10. Failure characteristic of (a) PVC pipe, (b) woven composite pipe, and (c) commingled composite pipe.

The failure mode observed in PVC pipes during hydrostatic pressure testing is characterized by the appearance of cracks on the pipe wall, which propagate and extend along the axial direction as the internal water pressure increases, as illustrated in Fig 10(a). This failure is in good agreement with previous results done by Yang & Hu (2021).

There is a significant difference between the failure mode of woven fiber composites and commingled fiber composites as shown in Fig 10(b) and Fig 10(c), respectively. The specimen showed catastrophic failure without significant expansion and deformation. The pipe broke into pieces at the fitted endcap of PVC pipes and a through crack appeared in the pipe wall. The surface of the breach was flat and smooth. These failure characteristics indicate that the failure mode of both woven and comingled-wrapped pipes is a brittle failure. The induced hole in the PVC pipe creates a weak point in the pipe where stress concentrations occur during the hydrostatic pressure test. One potential reason for the failure could be delamination or separation between the PVC pipe and the fiber composite wrapping. This delamination could weaken the structural integrity of the pipe, especially under high-pressure conditions, leading to failure at the ends where stress concentrations are typically higher (Yekani Fard et al., 2020).

Vukelic & Vizentin, (2021) in their study on composite-wrapped pipes found that bursting occurs at the value of just over 50 bar, significantly higher than the maximum allowable pressure. The bursting occurs at the edge of the patch, not in the location of the hole. Rohem et al., (2016) conducted a hydrostatic test on laminated composited repaired pipes and found that the failure occurred by delamination on the interface between the primer and the first layer of glass fiber while the leakage occurred at the edges of the laminate.

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CONCLUSIONS

In conclusion, this study has demonstrated the potential of composite materials to significantly enhance the structural integrity and performance of pipelines which are in high demand. Pipelines are prone to operational issues such as damage and cracks, leading to structural weakening and leaks. These challenges need innovative solutions like the wrapping method explored in this research. Hydrostatic pressure tests on solid PVC pipes revealed that an untreated pipe could withstand pressures up to 1.5 MPa before failure. Among the materials tested, the CSM glass layered with woven basalt fibre showed the highest hydrostatic maximum pressure resistance, reaching 2.03 MPa. Notably, the basalt (B/B) commingled fiber achieved the highest maximum hydrostatic pressure value at 1.86 MPa, which corresponded to maximum stress and strain values of 26.54 MPa and 1.37%, respectively. These findings indicate that the application of CSM, woven, and commingled wrapping significantly enhances the pressure, stress, and strain values as compared to the untreated PVC pipe, highlighting the effectiveness of these composite materials in pipeline rehabilitation.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Noor Leha Abdul Rahman: **writing and editing, conceptualization, methodology, data curation writing-original draft writing;** Jamaliah Md Said: **writing-reviewing and editing**; Aidah Jumahat: **conceptualization, methodology, validation, supervision, writing-reviewing and editing**; M. Zarief Iman: **samples characterized, writing-reviewing and editing**; Zaidatulakmal Mohd Zahib: **writing-reviewing and editing.**

REFERENCES

Al-Mahfooz, M. J., & Mahdi, E. (2020). Bending behavior of glass fiber reinforced composite overwrapping pvc plastic pipes. Composite Structures, 251(13), 112656. https://doi.org/10.1016/j.compstruct.2020.112656

https://doi.org/10.24191/jmeche.v22i1.2921

Alizadeh, E., & Dehestani, M. (2018). Analytical and numerical fracture analysis of pressure vessel containing wall crack and reinforcement with CFRP laminates. Thin-Walled Structures, 127, 210–220. https://doi.org/10.1016/j.tws.2018.02.009

Ayaz, Y., Çitil, S., & Şahan, M. F. (2016). Repair of small damages in steel pipes with composite patches. Materials Science and Engineering Technology, 47(5–6), 503–511. https://doi.org/10.1002/mawe.201600526

Brandtner-Hafner, M. (2024). Evaluating the bonding effectiveness of CFRP patches in strengthening concrete structures. Construction and Building Materials, 436(6), 136966. https://doi.org/10.1016/j.conbuildmat.2024.136966

Duell, J. M., Wilson, J. M., & Kessler, M. R. (2008). Analysis of a carbon composite overwrap pipeline repair system. International Journal of Pressure Vessels and Piping, 85(11), 782–788. https://doi.org/10.1016/j.ijpvp.2008.08.001

Fard, M. Y., & Raji, B. (2022). Hydrostatic and cyclic pressure testing of small-scale composite pipes and vessels. Journal of Aerospace Engineering, 35(1), 04021114. https://doi.org/10.1061/(asce)as.1943-5525.0001368

Fard, M. Y., Raji, B., Doan, B., Brooks, M., Woodward, J., & Foster, C. (2020). An experimental study of the mechanical properties of seamless and overlapped stitched composite tubes under hydrostatic pressure, lateral compression, and impact. The Journal of Strain Analysis for Engineering Design, 55(7–8), 212–221. https://doi.org/10.1177/0309324720922749

Gao, G., & Li, Y. (2016). Mechanical properties of woven glass fiber-reinforced polymer composites. Emerging Materials Research, 5(2), 201–208. https://doi.org/10.1680/jemmr.16.00018

Gao, Y. (2011). Computational and experimental analysis of composite overwrap repair of butt-joint pvc pipes. [Master dissertation, University of California]. Retrieved from http://surl.li/jbohkf

Günaydın, B., Dağhan, B., & Avci, A. (2013). Fatigue behavior of surface-notched composite pipes repaired by composite patches. International Journal of Damage Mechanics, 22(4), 490–498. http://dx.doi.org/10.1177/1056789512450596

Hu, J., Kang, R., Fang, J., Chen, S., Xuan, S., Zhou, J., & Tian, W. (2024). An experimental and parametrical study on repair of cracked titanium airframe structures with single-side bonded carbon fiber-reinforced polymer prepreg patches. Composite Structures, 338(6), 118102. https://doi.org/10.1016/j.compstruct.2024.118102

Hu, Y. Q., Li, P. N., Ju, D. Y., & Pan, H. L. (1990). Experimental investigation on a cracked body with adhesive bonded reinforcement. International Journal of Pressure Vessels and Piping, 41(2), 193–206. https://doi.org/10.1016/0308-0161(90)90041-F

Kara, M., Uyaner, M., & Avci, A. (2015). Repairing impact damaged fiber reinforced composite pipes by external wrapping with composite patches. Composite Structures, 123, 1–8. https://doi.org/10.1016/j.compstruct.2014.12.017

Kepir, Y., Gunoz, A., & Kara, M. (2022). Repairing of damaged composite materials and self-healing composites. Turkish Journal of Engineering, 6(2), 149–155. https://doi.org/10.31127/tuje.866955

Makris, K. F., Langeveld, J., & Clemens, F. H. L. R. (2020). A review on the durability of PVC sewer pipes: research vs. practice. Structure and Infrastructure Engineering, 16(6), 880–897. https://doi.org/10.1080/15732479.2019.1673442

https://doi.org/10.24191/jmeche.v22i1.2921

Rohem, N. R. F., Pacheco, L. J., Budhe, S., Banea, M. D., Sampaio, E. M., & De Barros, S. (2016). Development and qualification of a new polymeric matrix laminated composite for pipe repair. Composite Structures, 152, 737–745. https://doi.org/10.1016/j.compstruct.2016.05.091

Vukelic, G., & Vizentin, G. (2021). Composite wrap repair of a failed pressure vessel — Experimental and numerical analysis. Thin-Walled Structures, 169, 108488. https://doi.org/10.1016/j.tws.2021.108488

Wilcox, M. (2023). The perils of PVC Plastic Pipes. Beyond Plastics, Bennington College. [Online] Available:https://static1.squarespace.com/static/5eda91260bbb7e7a4bf528d8/t/6491ce414930f2385aedb80c/1687277125680/The_Perils_of_PVC_Plastic_Pipes-April_2023_Digital.pdf (Accessed Dec 30,2024)

Wilson, J. M. (2006). Characterization of a carbon fiber reinforced polymer repair system for structurally deficient steel piping. [Doctoral dissertation, University of Tulsa]. Retrieved from http://surl.li/fjlkyf

Yang, J., & Hu, S. (2021). Estimation of burst pressure of pvc pipe using average shear stress yield criterion: Experimental and numerical studies. Applied Sciences, 11(21), 10477. https://doi.org/10.3390/app112110477

https://doi.org/10.24191/jmeche.v22i1.2921