Polímeros
ISSN 1678-5169 (Online)

https://doi.org/10.1590/0104-1428.20220111

ORIGINAL ARTICLE

Effect of hybridisation and nano reinforcement on repairing cracked pipeline

Payman Sahbah Ahmed[1*]

[1]Strength of Materials Laboratory, Manufacturing & Industrial Engineering Department, Faculty of Engineering, Koya University, Koya, Kurdistan Region, Iraq

***payman.suhbat@koyauniversity.org**

Abstract

Composite materials are used to repair cracks in pipelines that appear after a period of time. This study investigates the effect of hybridisation on the blister behaviour of composite repair by using the finite element method. The behaviour of the best hybridised stacking sequence is compared with the experimental results to validate the numerical outcomes. The effect of adding multiwall carbon nanotubes (MWCNTs) to the epoxy resin, used to stick the composite repair with the steel pipeline, is explored by combining the MWCNT and the epoxy through high shear mixing. The results showed that hybridisation has a great effect on improving the blistering behaviour of the composite repair. The preparation of nano-reinforced adhesive by shear mixing did not show noticeable improvement. Predicting the composite repair behaviour through blister test by using the finite element method can be used as a good indication of pipeline protection.

Keywords: *hybridisation, blister test, MWCNTs, shear mixing process, composite repair.*

How to cite: Ahmed, P. S. (2023). Effect of hybridisation and nano reinforcement on repairing cracked pipeline. *Polímeros: Ciência e Tecnologia*, *33*(1), e20230010. https://doi.org/10.1590/0104-1428.20220111

1. Introduction

Composite materials are used to repair pipeline issues, such as rifts and fissures due to weathering and large temperature differences between summer and winter[1,2]. They are used for this purpose due to their capability to overcome the generated stresses in the pipes and to retain the bending and tensile stiffness of the pipelines caused by high internal pressure[3].

Recently, the demand for high-strength and good performance composites is increasing due to their outstanding toughness under various thermal and chemical conditions, as a result of generation composite hybridisation[4,5]. Two or more types of fibre can be mixed in the resin by composite hybridisation to utilise the good properties of fibres and to overcome the weaknesses of the individual fibres[4,6,7].

Mechanical properties are greatly influenced by hybrid composite stacking sequence[4] where the appropriate types and sequence of fibres are used and mixed. Considering the required application and its specific requirements of particular properties can greatly improve the behaviour of the composite material. The selection of fibre type depends on how many plies will be used in addition to the density and thickness of each ply[8].

The use of a hybrid combination of glass fibre with other types can improve the mechanical and impact properties[9]. Although carbon-reinforced polymer composites have extremely high strength, they have high cost, low toughness and strain to failure, which restricts their use in applications that require high compressive and flexural strength. The addition of glass fibre to carbon-reinforced polymer composites can greatly improve the strain of failure and lower the cost[10,11].

Blister test[12] is used to evaluate the sticking of composite repair to the pipeline. The composite repair is stuck with an adhesive over a steel plate with a hole at the centre. A shaft is placed across the hole as opposed to the bottom of the coating, resulting in composite repair delamination from the steel plate and creating a blister[3].

Zugliani et al.[13] developed a method of repairing pipes with bonded joints by wrapping a composite around the pipe became standard practice in the sector. To determine the energy release rate of different specimens made of the same material as the most frequent repairs (steel/glass fiber reinforced polymer), double cantilever beam (DCB) and width tapered double cantilever beam (WTDCB) tests were conducted. It is possible to anticipate a value of failure pressure using the results of the energy release rate calculations for the DCB and WTDCB using the design equation published in Standards ISO/PDTS 24817 and ASME PCC-2. Analysis was done by comparing the prophesied failure pressure value to the outcomes of the experimental hydrostatic tests and the comparison should a good agreement, which indicates that this methodology can be utilized to foretell the failure pressure in bonded repaired pipes.

A shaft blister test was utilized by Barros et al.[3] to evaluate the projected failure pressure of glass reinforced Epoxy composite repairs. An investigation on the interfacial debonding of a composite plate bonded to steel substrate included blister tests. The pipeline repair used on the blister test specimen is composite material. It is possible to foretell the failure pressure using the outset debonding load. The debonding propagation has been tracked, and the blister shape had been assessed, using a 3D digital image correlation (DIC). To simulate the loaded shaft blister test, a 3D finite element model with a cohesive zone model has been used. The results showed a good correlation between blister testing and finite element simulations[3].

The full-scale pipeline burst tests and finite element calculations on a damaged pipe and a composite-repaired pipe were explored by Lim et al.[14]. The findings demonstrated that the composite-repaired pipe's burst pressure increased by 23% while its strain in the defect area was greatly reduced. Detailed information on the burst pressure and strain reading over the whole applied pressure range was recorded for each component of the burst-test specimens, and their behavior was analyzed. These results were helpful in optimizing the current composite repair design processes[14].

Kong et al.[15] utilized CFRP to repair defects in pipes with various hoop lengths, and various putties to cover the flaws. The impacts of defect diameters and putty mechanical characteristics on the burst performances of the repaired pipes were examined through burst test and finite element (FE) Analysis. For example, if the defect's hoop length is less than 20% of the pipe's diameter and the putty failed before the CFRP, the CFRP continued to support the load. However, if the length was longer, it became inactive. To prevent the putty from failing first, the rupture strain of the material should be higher than that of CFRP. The design approaches based on acceptable stress in the pipe substrate or allowable strain of the repair laminates in ISO/TS 24817 were quantitatively compared based on the burst performances of the repaired faulty steel pipe with CFRP. Based on the failure mechanism of the repaired pipes, a method to estimate the burst pressure of the pipes was put forth[15].

Zhang et al.[16] used tests to investigate the durability of Carbon Fiber Reinforced Polymer (CFRP) which was used to repair corroded maritime pipes with the bending moment and seawater immersion. The elements affecting durability were investigated, and the attenuation of the restored structure was divided into that of CFRP and that of the interface between CFRP and steel. The Finite Element Analysis method (FEM) was used to create a numerical damage model of CFRP-repaired pipes based on the attenuation law. Numerical methods were used to obtain the mechanical characteristics of the restored pipelines. These characteristics were nearly identical to those found in the experimental findings[16].

To assess the failure behavior and capacity of grouted composite repair systems, Shamsuddoha et al.[17] created a three-dimensional (3D) Finite Element Analysis (FEA) of a full-scale pipe with varying amounts of metal loss. Using two infill grout systems reinforced with carbon and glass sleeves of various thicknesses, steel pipes with a localized fault ranging from 20% to 80% metal loss were considered. The outcomes showed that the infill grout's tensile cracking controls how well the repair technique performs. Higher tensile strength grout and a thicker sleeve result in greater pipe capacity in the repair system. A high modulus grout, on the other hand, offers a more efficient load transfer from steel to sleeve[17].

As can be seen from the aforementioned earlier studies, researchers either utilized glass or carbon alone but never attempted to combine the two to improve behavior, highlighting the gap in the literature and the importance of the present study.

The behaviour of the adhesives is weak and imperfect due to their low strength compared with the composite repair and the steel plate. The use of nanoparticle reinforcement can solve this problem and improve the mechanical properties of structural adhesive. Nano–reinforced polymers have exhibited the preferred physical and mechanical properties over polymer-matrix composites and their corresponding conventional fillers, such as fibres or micro reinforcement in the last decades. The addition of small amounts of nano reinforcement can lead to a huge improvement in the polymer properties[18].

Manufacturing of nanoparticle-reinforced composite is difficult due to the need of nano reinforcement for functionalisation. This process requires a surface modification of the nanoparticles to make them chemically compatible with the matrix, and a special chemical preparation process is needed in addition to careful dealing with the nanopowder due to its high hazardous effects. Many processes, such as the use of ultrasound energy, solvent evaporation, ball mills, 3-roll mill and high shear mixing, have been proposed by authors to disperse the nanoparticle in the matrix and to ensure an effective functionalisation[19].

This work investigates the effect of the hybridisation of woven glass with carbon fibres in 12 different stacking sequences on the blister behaviour of composite repair by using the FEM. The behaviour of the best stacking sequence was compared with the experimental results to validate the numerical outcomes. The effect of adding multiwall carbon nanotubes (MWCNTs) to the epoxy resin that is used to stick the composite repair with the steel pipeline is explored by combining the MWCNTs and the epoxy through high shear mixing.

2. Theoretical and Numerical Model

Shaft-loaded blister tests, in which the shaft stimulates the created load from the petroleum flow and the resulting pressure on the composite repair, can be used to determine the strength of the adhesive bonding between the composite repair and pipeline.

The energy release rate G_T can be calculated in terms of the load of failure F, as shown in Equation 1[3].

$$G_T \quad \frac{F^2}{32\pi^2 D} \tag{1}$$

where D represents the stiffness of bending measured depending on the characteristics of the laminate, E is young's modulus, ν is Poisson's ratio, and t is the plate thickness, as shown in Equation 2[3].

$$D = \frac{Et^3}{12\left(1-\nu^2\right)} \tag{2}$$

Failure pressure P of the utilised composites to repair the pipes can be calculated by using Equations 3[20,21]:

$$P = \sqrt{\frac{G_T}{\frac{\left(1-v^2\right)}{E_{ac}}\left(\frac{3}{512t^3}d^4 + \frac{1}{\pi}d\right) + \frac{3}{64Gt}d^2}} \qquad (3)$$

where $E_{ac} = \sqrt{E_1 E_2}$ [22], d represents the diameter of the hole, and G is the shear modulus.

By creating a model using FEM in the ANSYS workbench, the cohesive zone model (CZM) is utilized to depict the interface between the pipeline and the composite repair through the blister test. The foundation of the CZM approach is a zone where the material can bear traction stresses just in front of a fracture tip[23]. When the surface thickness is zero, surface cohesive behaviour can be used to model CZM as an alternative to the cohesive element technique[24].

A traction separation law (Figure 1) that consists of three parts (the first of which is the linear elastic region before damage initiation and before the separation starts δin and σmax in Figure 1 and the second of which is the damage evolution from initial separation δin until final separation δf. σmax represents the behavior of the adhesive zone to mode I of fracture. The adhesive binding strength is shown by the symbol max in Figure 1. The third part is the after-damage initiation region, sometimes referred to as the softening region or the release site for fracture energy (Gc)[23,25,26].

In this investigation, traction stress of 8 MPa and interface displacement of 0.06 mm were used as CZM parameters. Figure 2 depicts the mesh and boundary conditions for the quad/tri free face sweep meshing method. To cut down on run time, one-fourth of the model is utilised. To show the shaft, a displacement in a vertical direction is applied to the disc's upper face[3]. The woven, unidirectional carbon and glass-reinforced epoxy mechanical characteristics employed in the numerical model were acquired from the Ansys library.

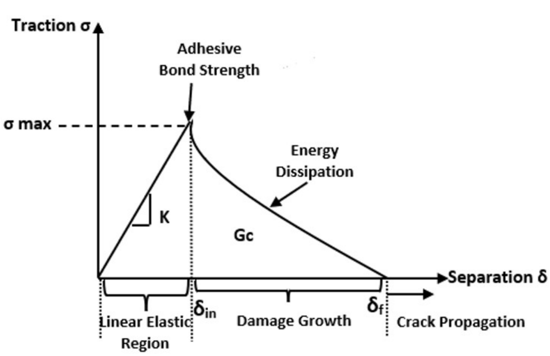

Figure 1. Traction-separation law represents the behavior of the adhesive zones.

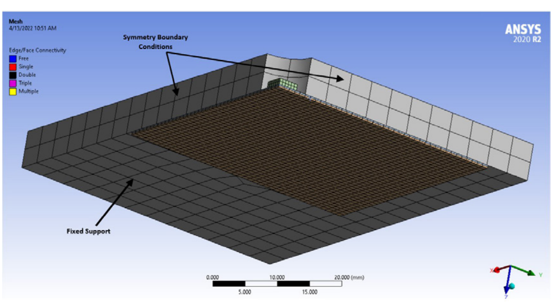

Figure 2. Meshing and boundary conditions of the finite element model used in simulating blister test.

Twelve stacking sequences are used in this research (Table 1) to investigate the effect of hybridisation on the blister test behaviour of composite used for pipeline repair.

3. Methodology

3.1 Materials

Epoxy resin (Sikadur-52, Sika Company) is used as the matrix and consists of two components, namely, low viscosity resin and hardener, where three parts of resin are mixed with one part of hardener. The properties of the epoxy matrix are listed in Table 2.

Steel plates with 6 mm thickness, a maximum tensile strength of 470 MPa and yield tensile strength of 355 MPa are used as a base, and their chemical composition is 0.23% carbon, 1.6% manganese, 0.05 silicon, 0.05% sulphur and 0.05% phosphorus.

The properties of woven carbon and glass fibres are listed in Table 3.

MWCNTs (Henan Huier Nano Technology Company) have 3–12 nm tube length, 12.9 nm tube outer diameter, 4.1 mm tube wall thickness, and 5 to 12 layers.

3.2 Preparation of composite repair and nano-reinforced adhesive

3.2.1 Preparation of composite repair

Vacuum bagging is used to prepare the carbon and glass hybrid composite, as shown in Figure 3. Four plies are placed together between two nylon sheets to form the vacuum bag. The vacuum bag is connected to a vacuum motor by a hose from one side, and another hose connects the vacuum bag with the epoxy resin-hardener mix from the other side. A resin trapper is placed between the vacuum bag and the vacuum motor to prevent the epoxy from going into the vacuum motor.

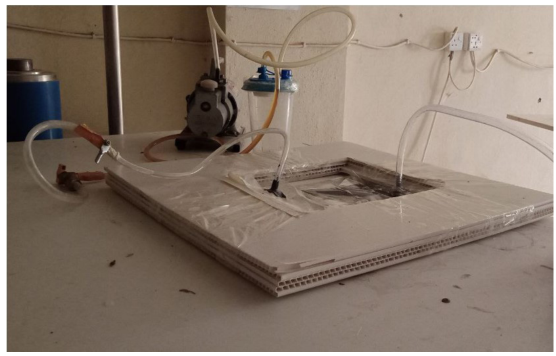

Figure 3. Vacuum bagging technique.

Table 1. Stacking sequence of hybrid composite repair.

No.	Abbreviation	No. of Layers	Stacking Sequence
1	CG	2 Layers	Woven Carbon + Woven Glass
2	GC		Woven Glass + Woven Carbon
3	2G		2 Woven Glass
4	2C		2 Woven Carbon
5	2G2C	4 Layers	2 Woven Glass+2 Woven Carbon
6	GCGC		Woven Glass + Woven Carbon+ Woven Glass + Woven Carbon
7	CGGC		Woven Carbon +Woven Glass + Woven Glass + Woven Carbon
8	GCCG		Woven Glass +Woven Carbon +Woven Carbon+ Woven Glass
9	GUCUCG		Woven Glass +Unidirectional Carbon Unidirectional Carbon+ Woven Glass
10	UGCCUG		Unidirectional Glass +Woven Carbon +Woven Carbon+ Unidirectional Glass
11	UCGGUC		Unidirectional Carbon +Woven Glass + Woven Glass + Unidirectional Carbon
12	CUGUGC		Woven Carbon + Unidirectional Glass + Unidirectional Glass + Woven Carbon

Table 2. Properties of epoxy matrix (provided by the supplier).

Compression Strength	Flexural Strength	Tension Strength	Modulus of Elasticity
53 N/mm^2	50 N/mm^2	25 N/mm^2	1.06 KN/mm^2

Table 3. Properties of woven carbon and glass fibers (provided by the supplier).

Fiber	Woven Carbon	Woven Glass	Unidirectional Carbon	Unidirectional Glass
Longitudinal Modulus of Elasticity (GPa)	29	20	45	169
Transvers Modulus of Elasticity (GPa)	5.52	13.96	12	9
Shear modulus (GPa)	2.51	3.1	5.5	6.5
Poisson's ratio	0.15	0.22	0.19	0.21
Density (gm/cm^3)	1.22	1.83	2.076	1.646

A mesh sheet is placed over the fibre layers to guarantee a homogeneous distribution of the resin inside the fibre layers. The vacuum bag is tightly sealed to ensure no leakage occurs before pumping the resin into the vacuum bag. When all fibre layers are completely covered with the resin, the two hoses are closed tightly, and the composite is left to cure at room temperature for 24 h. The cured composites are cut to the repair dimensions of 80 mm*80 mm, and they are ready to be stuck on the steel plate.

3.2.2 Preparation of nano-reinforced adhesive

The MWCNT is mixed with the epoxy resin and left overnight at 80 °C. The mixture is mixed manually until the nanopowder was visibly dispersed into the resin. MWCNT samples are prepared at 0.8% by weight according to[27]. Mille shear mixer was used on the previously mixed composite at 1800 RPM for 60 min[19], and then the mixture is used to stick the composite repair to the steel plate.

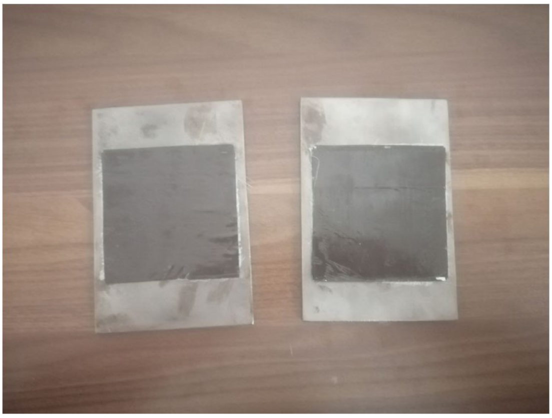

Figure 4. Hybrid woven glass and carbon reinforced epoxy blister test samples with and without nano reinforced adhesives.

3.3 Blister sample and test

The blister test sample is made of a steel plate with 95 mm width, 140 mm length and a hole with a 5 mm radius in the centre where the shaft will pass through. The lower surface of the steel plate is cleaned by using a sand jet to obtain a clear and rough surface, and acetone is used to remove dirt. A waxy material is utilised to fill up the hole in the steel plate to precluding the adhesive to go in the hole. The epoxy and MWCNT-reinforced epoxy are used to agglutinate the composite repair on the steel plates. Hybrid woven carbon and glass-reinforced epoxy plates are agglutinated on the steel plates and cured for a week at room temperature (Figure 4). The waxy material should be removed after curing.

A cylindrical part with a 4 mm radius and 4 mm height is agglutinated on the composite repair inside the hole of the steel plate to ensure an axisymmetric formation during the test.

An Instron machine is utilised to test the samples by blister test. The steel plate with the composite repair is placed horizontally, and the composite direction is placed downward and fixed in the machine by two holders. The cross-head velocity is set to 2 mm/min, and force is applied on the shaft and the small disc to ensure that the load will be distributed uniformly on the composite repair[22]. The blister sample and test are shown in Figure 5.

3.4 SEM images

A MIRA 3 field emission scanning electron microscope is used to find out the effectiveness of high shear mixing in dispersing the MWCNT in the epoxy adhesive.

4. Results and Discussion

This study investigates the effect of hybridisation and nano-reinforced adhesive on the blistering behaviour of 12 composites having different stacking sequences, as mentioned in Table 1.

To reduce the amount of time and money spent on the experiment, the effect of hybridizing glass with carbon woven fibers is studied using the FEM. In contrast to utilizing either carbon or glass alone, using two layers of woven glass and carbon fibers raises the load and improves the blistering behavior, as demonstrated in Table 4 and Figure 6. This results in a higher failure pressure value. A better result may be obtained by placing glass in front of carbon as opposed to carbon in front of glass. The reason for this behavior is that the composite maintains its strength under the load and pressure of the shaft, and its back is shielded by the high-strength carbon fiber. This behavior is caused by the high strain of glass in the composite. The composite is unable to bend and cannot maintain its strength under pressure when the carbon is placed in front of the low strain carbon fiber. The low-strength glass in its rear is unable to provide the composite with the necessary level of protection, which causes the composite repair to prematurely delaminate from the pipe.

When compared to the two layers of GC, where the failure pressure of 2G2C is four times higher than GC, the employment of four woven layers improved the blistering behavior. according to Table 4. It is preferable to place two layers of woven glass fiber in front of two layers of woven carbon fiber rather than alternate layers of glass and carbon, placing the glass and carbon on the exterior surfaces, or

Figure 5. Sample of blister test in Instron machine.

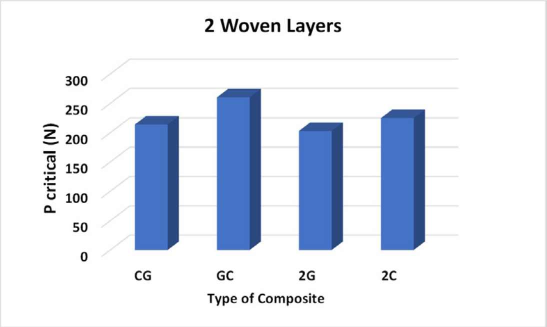

Figure 6. Effect of composite type on critical load (by using 2 woven layers).

Table 4. FEM results of blister test for varying stacking sequence of hybrid composite repair.

	Sample	P critical (N)	G_T (N/mm)	P (MPa)
2 Woven Layers	CG	214	0.5488	5.00154
	GC	260	0.8101	6.0761
	2G	203	0.5961	4.8376
	2C	225	0.51869	5.1442
4 Woven Layers	2G2C	825	1.0194	24.6789
	GCGC	655	0.6425	19.5931
	CGGC	564	0.4764	16.871
	GCCG	175	0.0458	5.2348
2 Woven & 2 Unidirectional Layers	GUCUCG	215	0.0177	2.5349
	UGCCUG	183	0.0333	2.7243
	UCGGUC	211	0.0170	2.4876
	CUGUGC	603	0.3626	8.9767

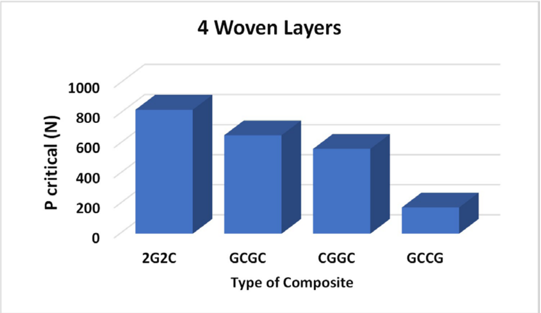

Figure 7. Effect of composite type on critical load (by using 4 woven layers).

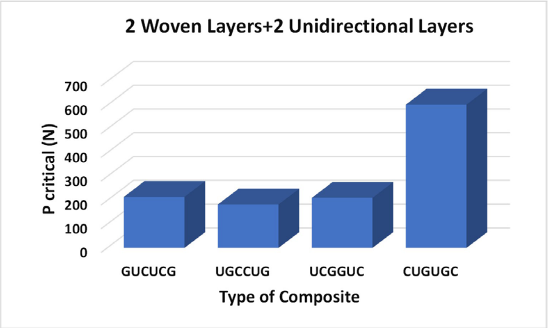

Figure 8. Effect of composite type on critical load (by using 2 woven layers+2 unidirectional layers).

placing the glass and carbon inside the core, as shown in Figure 7. The bending force pressures the composite during the blistering test, creating tension and compression stresses. Due to its high strain to failure, glass will endure compression pressures, and carbon will withstand tension strains because to its great strength.

The inclusion of four layers significantly raises the failure pressure of composite repairs, with 2G2C having a failure pressure that is four times higher than GC. The failure pressure of the composite repair is improved by the inclusion of alternating layers made of woven carbon and glass fibers, where the failure pressure of GCGC is three times higher than that of the GC composite. The pipeline repair composite's strength is significantly increased with the addition of fibers with higher stiffness, such carbon[28]. It works better to place woven carbon fibers on the outside than woven glass fibers. This circumstance results from the outer layer's fundamental control of stiffness[28], which suggests that the delamination load is mostly dependent on the outer layer's strength. Adding carbon to the outside When compared to GC, CGGC increases failure pressure by 2.8 times, and the failure pressure of GCCG composite falls to 5.2348 MPa from 6.0761 MPa for GC composite.

Table 4 demonstrates that there is a significant reduction in blistering behavior when unidirectional fibers are hybridized with woven fibers. The unidirectional fibers will resist the load from one direction when it is applied to the center of the composite during the blistering test, but the composite will be unprotected from the other direction due to the non-isotropic structure of the composite layer[28]. Due to the low load value, delamination will take place before failure, which lowers the failure pressure. as depicted in Figure 8. Higher load values are achieved when employing woven carbon fibers on the outside than when using woven glass fibers, unidirectional carbon fibers, or unidirectional glass fibers.

According to the FEM findings, the 2G2C composite performed the best in the blister test. The numerical computation is verified through a series of experimental blister testing. The composites are prepared by vacuum bagging to conserve the mechanical properties of the composite[29]. As shown in Figure 9. a close delamination behaviour is observed but the numerical value of the load is higher, and this is logically right due to the ideal behaviour of the FEM model.

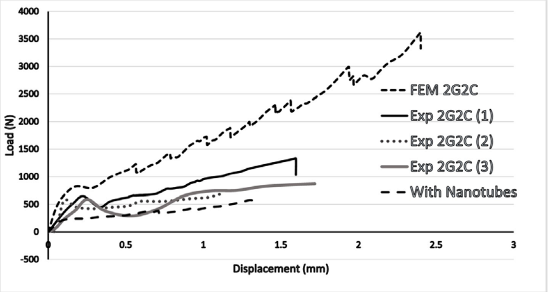

Figure 9. Experimental and numerical load – displacement curve of 2G2C composite repair with and without the MWCNT reinforced adhesive.

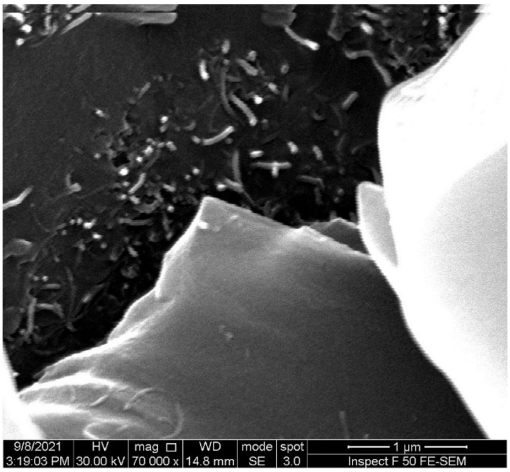

Figure 10. FE-SEM image of the MWCNT reinforced adhesive.

The addition of the MWCNTs to the epoxy adhesive by shear mixing does not give an improvement in the blister behaviour (Figure 9). This condition is due to the huge agglomeration and nonuniform distribution of the nanotubes, as shown Figure 10. The use of other preparation methods may solve the agglomeration problem and result in better behaviour, such as 3-roll milling as suggested by Collinson et al.[19] or ultrasonic dispersion as demonstrated by Oliveira et al.[30].

5. Conclusions

Hybridisation has a great effect on improving the blistering behaviour and increasing the failure pressure of the composite repair, where using two layers of woven glass and carbon fibres increases the load and improves the blistering behaviour leading to an increase in the failure pressure value compared with using either carbon or glass alone. Putting the glass in front of carbon can give a better effect than putting the carbon in front of glass.

The use of four woven layers enhanced the blistering behaviour compared with the two layers of GC where the failure pressure of 2G2C is four times higher than GC. Putting two layers of woven glass fibre in front of two woven carbon fibres is better than putting alternating layers of glass and carbon or putting the glass and carbon on the outer surfaces or in the core. The use of unidirectional fibres is not beneficial in composite repair.

The incorporation of higher stiffness fibres, such as carbon, leads to a remarkable improvement in the strength of the pipeline repair composite. Putting woven carbon fibres on the outer sides has a better effect than putting the woven glass fibres.

The addition of the MWCNTs to the epoxy adhesive by shear mixing does not give an improvement in the blister behaviour due to the huge agglomeration.

The preparation of nano-reinforced adhesive by high shear mixing is not recommended.

Predicting the composite repair behaviour under blister test by using the FEM can give a good indication about the pipeline protection.

6. References

1. Budhe, S., Banea, M. D., Barros, S., & Silva, L. F. M. (2017). An updated review of adhesively bonded joints in composite materials. *International Journal of Adhesion and Adhesives*, *72*, 30-42. http://dx.doi.org/10.1016/j.ijadhadh.2016.10.010.
2. Saeed, N. (2015). *Composite overwrap repair system for pipelines - onshore and offshore application* (Doctoral thesis). The University of Queensland, St. Lucia.
3. Barros, S., Fadhil, B. M., Alila, F., Diop, J., Reis, J. M. L., Casari, P., & Jacquemin, F. (2019). Using blister test to predict the failure pressure in bonded composite repaired pipes. *Composite Structures*, *211*, 125-133. http://dx.doi.org/10.1016/j.compstruct.2018.12.030.
4. Azlin, M. N. M., Sapuan, S. M., Zuhri, M. Y. M., & Zainudin, E. S. (2022). Effect of stacking sequence and fiber content on mechanical and morphological properties of woven kenaf/polyester fiber reinforced polylactic acid (PLA) hybrid laminated composites. *Journal of Materials Research and Technology*, *16*, 1190-1201. http://dx.doi.org/10.1016/j.jmrt.2021.12.046.
5. Rajak, D. K., Pagar, D. D., Menezes, P. L., & Linul, E. (2019). Fiber-reinforced polymer composites: manufacturing, properties, and applications. *Polymers*, *11*(10), 1667. http://dx.doi.org/10.3390/polym11101667. PMid:31614875.
6. Safri, S. N. A., Sultan, M. T. H., Jawaid, M., & Jayakrishna, K. (2018). Impact behavior of hybrid composites for structural applications: a review. *Composites. Part B, Engineering*, *133*, 112-121. http://dx.doi.org/10.1016/j.compositesb.2017.09.008.
7. Bunsell, A. R., & Harris, B. (1974). Hybrid carbon and glass fiber composites. *Composites*, *5*(4), 157-164. http://dx.doi.org/10.1016/0010-4361(74)90107-4.
8. Shesan, O. J., Stephen, A. C., Chioma, A. G., Neerish, R., & Rotimi, S. E. (2019). *Improving the mechanical properties of natural fiber composites for structural and biomedical applications*. In A. B. Pereira & F. Fernandes (Eds.), *Renewable and sustainable composites* (pp. 130-141). Croatia: IntechOpen. http://dx.doi.org/10.5772/intechopen.85252.
9. Jusoh, M. S. M., Santulli, C., Yahya, M. Y. M., Hussein, N. S., & Ahmad, H. A. I. (2016). Effect of stacking sequence on the tensile and flexural properties of glass fibre epoxy composites hybridized with basalt, flax or jute fibres. *Material Science and Engineering with Advanced Research*, *1*(4), 19-25. http://dx.doi.org/10.24218/msear.2015.19.
10. Ikbal, M. H., Wang, Q. T., & Li, W. (2015). *Effect of glass/carbon ratios and laminate geometry on flexural properties of glass/carbon fiber hybrid composites*. In *2015 International Conference on Materials Chemistry and Environmental Protection (MEEP-15)* (pp. 114-118). China: Atlantis Press.
11. Mishnaevsky, L. Jr, & Dai, G. (2014). Hybrid carbon/glass fiber composites: micromechanical analysis of structure–damage resistance relationships. *Computational Materials Science*, *81*, 630-640. http://dx.doi.org/10.1016/j.commatsci.2013.08.024.
12. Dannenberg, H. (1961). Measurement of adhesion by a blister method. *Journal of Applied Polymer Science*, *5*(14), 125-134. http://dx.doi.org/10.1002/app.1961.070051401.
13. Zugliani, P. A., Banea, M. D., Budhe, S., Carbas, R. J., Silva, L. F. M., Rohem, N. R. F., & Barros, S. (2019). Bonded composite repair of metallic pipeline using energy release rate method. *Journal of Adhesion Science and Technology*, *33*(19), 2141-2156. http://dx.doi.org/10.1080/01694243.2019.1632537.
14. Lim, K. S., Azraai, S. N. A., Yahaya, N., Noor, N. M., Zardasti, L., & Kim, J.-H. J. (2019). Behaviour of steel pipelines with composite repairs analysed using experimental and numerical approaches. *Thin-walled Structures*, *139*, 321-333. http://dx.doi.org/10.1016/j.tws.2019.03.023.
15. Kong, D., Huang, X., Xin, M., & Xian, G. (2020). Effects of defect dimensions and putty properties on the burst performances of steel pipes wrapped with CFRP composites. *International Journal of Pressure Vessels and Piping*, *186*, 104139. http://dx.doi.org/10.1016/j.ijpvp.2020.104139.
16. Zhang, Y., Liu, Z., Xin, J., Wang, Y., Zhang, C., & Zhang, Y. (2021). The attenuation mechanism of CFRP repaired corroded marine pipelines based on experiments and FEM. *Thin-Walled Structures*, *169*, 108469. http://dx.doi.org/10.1016/j.tws.2021.108469.
17. Shamsuddoha, M., Manalo, A., Aravinthan, T., Islam, M. M., & Djukic, L. (2021). Failure analysis and design of grouted fibre-composite repair system for corroded steel pipes. *Engineering Failure Analysis*, *119*, 104979. http://dx.doi.org/10.1016/j.engfailanal.2020.104979.
18. Tutunchi, A., Osouli-Bostanabad, K., Eskandarzadeasl, M., Kamali, R., & Chavoshian, M. (2015). *Steel-epoxy composite joints bonded with nano reinforced structural acrylic adhesive*. In *5th International Biennial Conference on Ultrafine Grained and Nanostructured Materials - UFGNSM15* (pp. 663-676). Amsterdam: Elsevier.
19. Collinson, M., Hayes, S., & Petropoulos, S. (2019). *The effect of type of mechanical processing on electrical conductivity and piezoresistive response of CNT and graphite composites*. In *2nd CIRP Conference on Composite Material Parts Manufacturing (CIRP-CCMPM 2019)* (pp. 314-320). Amsterdam: Elsevier. http://dx.doi.org/10.1016/j.procir.2019.10.001.
20. International Organization for Standardization – ISO. (2017). *ISO 24817:2017: petroleum, petrochemical and natural gas*

industries. Composite repairs for pipework — qualification and design, installation, testing and inspection. Geneva: ISO.

21. American Society of Mechanical Engineers – ASME. (2015). *ASME PCC-2-2015. Repair of pressure equipment and piping with supplement*. New York: ASME.
22. Köpple, M. F., Lauterbach, S., & Wagner, W. (2013). Composite repair of through-wall defects in pipework – analytical and numerical models with respect to ISO/TS 24817. *Composite Structures*, *95*, 173-178. http://dx.doi.org/10.1016/j.compstruct.2012.06.023.
23. Caro, S., Masad, E., Bhasin, A., Little, D., & Sanchez-Silva, M. (2010). Probabilistic modeling of the effect of air voids on the mechanical performance of asphalt mixtures subjected to moisture diffusion. *Electronic Journal of the Association of Asphalt Paving Technologists*, *79*, 221-252.
24. Liravi, F., Das, S., & Zhou, C. (2014). *Separation force analysis based on cohesive delamination model for bottom-up stereolithography using finite element analysis*. In *2014 International Solid Freeform Fabrication Symposium* (pp. 1432-1451). Austin: Laboratory for Freeform Fabrication/ University of Texas at Austin.
25. Xue, J., Wang, W.-X., Zhang, J.-Z., Wu, S.-J., & Li, H. (2015). Experimental and numerical study on the tensile behaviour of UACS/Al fibre metal laminate. *Applied Composite Materials*, *22*(5), 489-505. http://dx.doi.org/10.1007/s10443-014-9419-y.
26. Daggumati, S., Sharma, A., Kasera, A., & Upadhyay, N. (2020). Failure analysis of unidirectional ceramic matrix composite lamina and cross-ply laminate under fiber direction uniaxial tensile load: cohesive zone modeling and brittle fracture mechanics approach. *Journal of Materials Engineering and Performance*, *29*(4), 2049-2060. http://dx.doi.org/10.1007/s11665-020-04724-x.
27. Ahmed, P. S., Kamal, A. A., Abdulkadir, N. J., Fadhil, B. M., & Khoshnaw, F. M. (2022). Blister test reliability to evaluate bonding of MultiWall Carbon Nanotubes (MWCNT) on woven carbon fiber reinforced epoxy used for repairing pipelines. *Multidiscipline Modeling in Materials and Structures*. In press.
28. Ahmed, P. S., Fadhil, B. M., & Mohamed, A. A. K. (2016). Effect of unidirectional and woven fibers on impact properties of epoxy. *Research Journal of Applied Sciences, Engineering and Technology*, *12*(2), 197-205. http://dx.doi.org/10.19026/rjaset.12.2321.
29. Sałasińska, K., Cabulis, P., Kirpluks, M., Kovalovs, A., Kozikowski, P., Barczewski, M., Celiński, M., Mizera, K., Gałecka, M., Skukis, E., Kalnins, K., Cabulis, U., & Boczkowska, A. (2022). The effect of manufacture process on mechanical properties and burning behavior of epoxy-based hybrid composites. *Materials*, *15*(1), 301. http://dx.doi.org/10.3390/ma15010301. PMid:35009447.
30. Oliveira, M. M., Forsberg, S., Selegård, L., & Carastan, D. J. (2021). The influence of sonication processing conditions on electrical and mechanical properties of single and hybrid epoxy nanocomposites filled with carbon nanoparticles. *Polymers*, *13*(23), 4128. http://dx.doi.org/10.3390/polym13234128. PMid:34883631.

Received: Nov. 17, 2022
Revised: Apr. 13, 2023
Accepted: Apr. 13, 2023