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ORIGINAL ARTICLE

Novel modified blister test to evaluate composites used in repairing cracked pipeline

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Abstract

The traditional method of fixing cracked pipes by welding needs stopping the production. In this study, a composite material is used to repair pipelines without interrupting production, saving both time and money. Hand Layup and vacuum infusion techniques were used to prepare glass strand mat and intra-ply hybrid glass - carbon fibers composites repairs. To show the composites' strength, blister, double cantilever beam, and peel tests were conducted. A novel modified blister test was utilized to show effectiveness of laboratory tests on real pipeline. The results indicate that vacuum infused intra-ply hybrid composite exhibited the highest strength. The experimental results of the best composite were compared with the finite element model under blister test, and the results were found to be identical. The modified blister test on the real pipe provides a better indication about the good strength of the composite repair compared to previous researches.

Keywords: *cracked pipe repair, hand lay up, intra-ply hybrid composite, modified blister test, vaccum infusion.*

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1. Introduction

Pipelines are one of the safest modes of transporting oil from fields to consumers, operating under significant pressure, any issue must be fixed cautiously to prevent explosions, and potential harm to; people, equipment and the environment. Among the various problems that can occur, cracks in the pipe pose the biggest concern and can result from corrosion, stress, or vandalism. Several repair methods exist for corroded pipe such as; welding, clamping and replacement of the damaged section with a new pipe[1]. The process of fixing the cracked pipe via welding is not safe in the oil and gas industries and expensive. This issue is an interesting topic for mechanical researchers for a long time, in particular, repair the fractures using safe, fast and economical method. The use of polymer-based composite systems to repair damaged pipes has been widely used in the offshore and onshore units, due to their suitability and cost-effectivness compared to other to other maintenance options[2]. The advantages of composite over metallic repairs or a full replacement of pipe sections included a better corrosion resistance, higher flexibility for the repair of complex structures, no production shut down or hot work and a minimal lead time[3]. The design of composite repairs of corroded oil and gas pipelines must take into account the strength of the interface adhesion between composite and metal[4]. The degradation of adhesion with time is the main problem[5]. The toughness of composite laminates can be improved by the addition of multi-layers[6]. Although, critical water content and relative humidity could decrease the cohesive strength of composite[7], it is possible, under the right conditions, that composite materials be used to repair offshore risers[8].

Researchers in the previous studies; de Barros et al.[2] utilized a composite of fiber glass and epoxy resin with different densities to fix a corroded pipe. Abdelouahed et al.[9] investigated the use of three different composites, graphite with epoxy, boron with epoxy and glass with epoxy. Linden et al.[3] used only the blister test for the composite and CFD package for validation. Liland et al.[10] only carried out the blister test in the study. Cao et al.[11] did a blister test for a graphene/photoresist composite film. Linden et al.[4] investigated blister test on thick fiber-reinforced plates bonded on steel disk. Tan et al.[7] analyzed the effect of humidity on the composite adhesive with blister test. Barros et al.[12] studied the failure pressure of composite repair using only the blister test and hydrostatic test. Borowski et al.[6] examined the fracture toughness of carbon fiber reinforced polymer (CFRP) using double cantilever beam (DCB) and delaminate tests. Alexander[8] developed a guideline to help the operators and manufacturers in using composite for fixing offshore risers.

As a result of generation composite hybridization, the demand for high-strength and high-performance composites has recently increased due to their exceptional toughness under diverse thermal and chemical circumstances. Composite hybridzation involves combining tow or more typs of fibers with resin, leveraging the strengths of each fiber while addressing thier limitations. The hybrid composite stacking sequence, where the right types and sequence of fibers are employed and combined, has a significant impact on mechanical properties. The behavior of the composite material can be significantly improved by taking into account the necessary application and its particular needs for certain features. The number of plies that will be utilized, together with their density and thickness, all affect the fiber type that is chosen[13]. The mechanical and impact properties can be improved by employing a hybrid combination of glass fiber with other types. The usage of carbon-reinforced polymer composites is limited by their high cost, low toughness, and strain to failure, despite the fact that these materials have an extraordinarily high strength. Glass fiber can significantly reduce the cost and strain of failure of carbon-reinforced polymer composites[13]. In the literature, four primary types of hybrid composites are discussed: "interply hybrid composites," which are made up of different fiber types arranged in different sequences; "intraply hybrid composites," which are made up of two or more different types of fibers used in the same ply; "interply-intraply hybrid composites," which are made up of interply and intraply laminates stacked in a specific order; as well as "resin hybrid composites," which can be created by combining two or more resins rather than changing the type of fiber[14]. The objective of the current study is to employ a composite for reparing fractured pipeline. The study aims to conduct a comperhanesive laboratory test on multi layers composite. The novelties of this work lies in utilizing intra-ply hybridizing and different manufacturing processes to repair cracked composites, along with modifying the original blister test to better simulate realistic conditions in petroleum fields.

2. Experimental

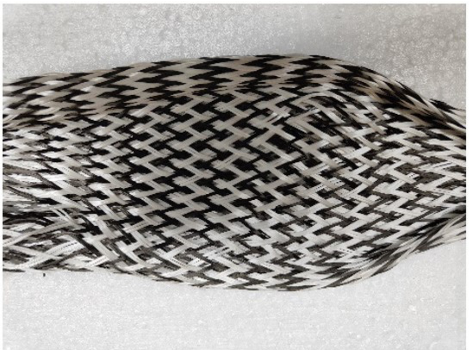
2.1 Materials

Epoxy resin (Sikadur-52, Sika Company) is employed 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 can be found in Table 1. Glass strand mat and Intraply carbon+glass fibres (Figure 1) were used as reinforcement, the properties of fibres are listed in Table 2.

Two Manufacturing Processes were used to prepare composite materials repairs: Hand lay-up and vacuum Infusion Technique as listed in Table 3. Figure 2 shows that the layers of the fibers are placed on a piece of glass, followed by adding the epoxy matrix to each layer then another glass piece is placed over the composite layers to push the bubbles outside the composite plate and then fixed tightly by 4 clamps. The samples were cured as a final preparation step at 112 °C for 4 hrs[15]. Vacuum Infusion is used to prepare the carbon and glass hybrid composite, as shown in Figure 3. Four plies are placed together between

Table 1. 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



(a)

(b)

Figure 1. (a) Intra-Ply Hybrid Glass+Carbon; (b) Chopped Strand Mat Glass used in this Study.

Table 2. Properties of fibers (provided by the supplier).

Fiber Type	Young's Modulus (GPa)	Tensile Strength (MPa)	Elongation (%)	Density (gm/cm^3)
Intra-Ply Hybrid Glass+Carbon	151	3625	2.8	2.18
Chopped Strand Mat Glass	7.5	111	3.5	1.6

Table 3. Composites of this study.

Symbol of Composite Material	Type of fiber	No. of Layers	Type of Manufacturing Process
6GCH	Intra-Ply hybridized glass and carbon	6	Hand lay-up
4GCH	Intra-Ply hybridized glass and carbon	4	Hand lay-up
4RGH	chopped strand mat glass plies	4	Hand lay-up
4GCV	Intra-Ply hybridized glass and carbon	4	Vacuum infusion technique

Figure 2. Hand lay-up method.

Figure 3. Vacuum Infusion technique.

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. 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 houses are closed tightly, and the composite is left to cure at 112°C for 4 hrs. The molds were cut to be ready for the mechanical tests: peel (ASTM D 3330)[16] double cantilever beam (DCB) (ASTM D5528)[17], and blister test[12].

2.2 Tests

2.2.1 Peel test

Peel test specimens were manufactured with 140 mm length substrate and 95 mm width, 150 mm length rigid substrate and 20 mm width. The rigid substrate is made of composite repair sticked on the substrate which is made from carbon steel by two adhesive epoxy glue from Tepusi and Sikadur 52, as shown in Figure 4. Tests were performed by a universal tensile machine with a capacity of 100kN and the testing speed was 5 mm/min, the test standard is ASTM D3330[16].

2.2.2 Double Cantilever Beam (DCB) test

DCB specimens were manufactured and evaluated in accordance with the ASTM D5528[17] standard test technique to ascertain the composite's Mode I interlaminar fracture toughness. The composite laminate's thickness, h, and initial delamination length, a0, were created to meet the requirements of the standard. The configuration of the DCB specimen are shown in Figure 5. Two piano hinges were bonded to the delaminated arms of the DCB specimen after the test coupons were cut to the required sizes (163 mm in length*22 mm in width and 63 mm distance of the open end from the edge). This was done to apply the tensile opening load and cause a Mode I delamination fracture. The Instron

Figure 4. Peel test.

Figure 5. DCB test.

machine used for the DCB tests (ASTM D5528) has a load cell with a 100 kN capacity. Crosshead speed was maintained at 3 mm/min when loading the specimens[18].

2.2.3 Blister test

A universal tensile machine with a capacity of 100kN was used to perform the blister test. The specimen was fixed horizontally and the repaired face by the composite was faced down (to produce tensile stresses) and fixed by two holders. The used cross-head velocity was 2 mm/min and the force was exerted on the shaft which was placed on a small disc to make sure that the load will transfer uniformly to the composite repair. Figure 6 shows the blister test arrangements[19].

2.2.4 Modified blister test

The modified blister test consists of wrapping the composite repair directly then adding Epoxy by vacuum infusion technique on 10 mm diameter cracked pipeline as can be seen in Figure 7 and test it by a shaft to resemble the fluid pressure on the composite repair.

3. Numerical Analysis of Blister Test

To determine a material's effective qualities from knowledge of its basic rules and the spatial distribution of its constituent parts is one of the main objectives of heterogeneous material physics. The techniques utilized for homogenization have advanced significantly in sophistication and efficacy, particularly when it comes to mechanical characteristics and thermal conductivity. There is also numerical homogenization

Figure 6. Blister test.

(a)

(b)

Figure 7. (a) Vacum Infusion of composite repair around the pipe; (b) Modified pipe blister test.

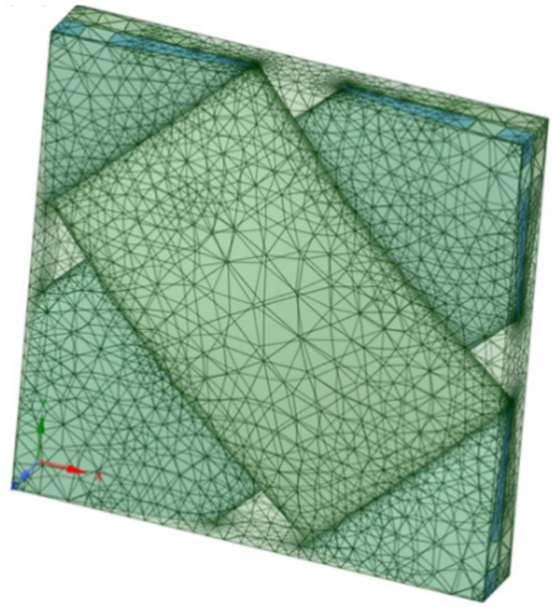


Figure 8. RVE of Intraply woven fiber composite.

Table 4. Properties of 4GCV calculated by materials designer.

Property	Value	Unit
E1	6.1077E+08	Pa
E2	6.1077E+08	Pa
E3	3.7208E+09	Pa
G12	1.9271E+10	Pa
G23	3.4679E+08	Pa
G31	3.4679E+08	Pa
nu12	0.98815	
nu13	0.0066025	
nu23	0.0066025	

for the macroscopic effective characteristics. They consist of the popular finite element techniques or the quick Fourier transform. The term “homogenization” describes the process of taking into account a Representative Volume Element RVE, a statistically homogenous representation of a heterogeneous material[20]. Glass and carbon woven fiber composites were modeled in three dimensions using FEA utilizing the ANSYS Material Designer program and a homogenization strategy. The effective characteristics of materials or composites having periodic architectures were calculated using homogenization theory. The simulations were run under the presumption that the structure is made up of an endless network of unit cells. The boundary conditions for FEA utilizing homogenization theory are symmetrical in all planes.

Figure 8 depicts the application of the composite material’s 3D model based on homogenization theory. For the purpose of creating a virtual RVE and setting the volume to Matrix epoxy, epoxy composites with intraply glass and carbon textiles were modelled in three dimensions. The epoxy RVE contained the glass and carbon fibers.

The volume occupied by the of 4GCV was 75.5% and it’s calculated by the set of equations mensioned by Abdalla et.al[21].

Based on the volume fraction used to structure the oriented glass and carbon textiles in the epoxy matrix, the basic modeling criteria were established. SOLID187 elements with a mesh size of 2 mm were the element type utilized for FEA. The implementation of secondary displacement is supported by SOLID187, making it the best tool for building meshes inside structures with odd shapes. The components utilized for the epoxy matrix and glass and carbon fibers were set to the same size in order to lessen the sensitivity of forecasting physical attributes based on mesh size[22]. The calculated properties are listed in Table 4.

The strength of the adhesive bonding between the composite repair and pipeline can be assessed using shaft-loaded blister tests (Figure 5), in which the shaft stimulates the produced load from the petroleum flow and the consequent pressure on the composite repair. The cohesive zone model (CZM) is used to represent the interface between the pipeline and the composite repair through the blister test by building a model using FEM in the ANSYS workbench. A zone where the material can withstand traction loads immediately in front of a fracture point forms the basis of the CZM method. Surface cohesive behavior can be employed as an alternative to the cohesive element technique to simulate CZM when the surface thickness is zero[19].

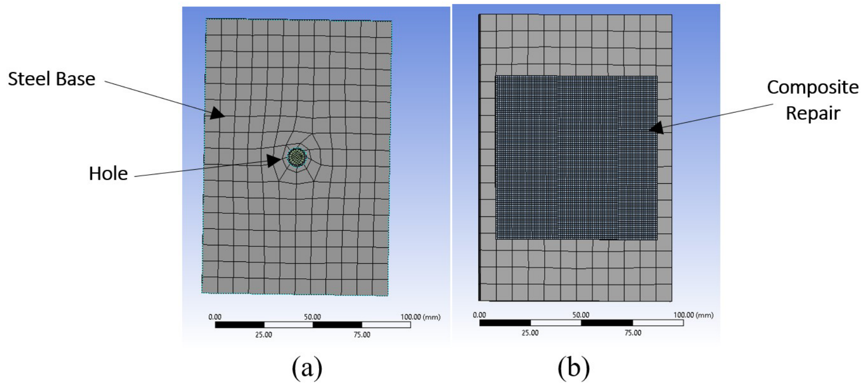


Figure 9. Composite repair and the steel base (a) front view; and (b) back view.

The CZM parameters employed in this experiment were traction stress of 8 MPa and interface displacement of 0.06 mm. The quad/tri free face sweep meshing method's mesh and boundary conditions are shown in Figure 9. The upper face of the disc is given a displacement in the vertical direction to reveal the shaft[13].

4. Results and Discussions

4.1 Peel test

Epoxy matrix resins are applied to wrapped composite repairs consists of carbon or glass fiber reinforcements. Performance and behavior of composite repairs are significantly influenced by interfacial characterization. The most significant failure mode between layers in the repair/metal substrate interface occurs after the transferred fluid cracks the pipeline wall and forms a blister, which is known as delamination. Peel tests have been developed to measure a thin film's ability to stick firmly to adjacent surfaces[11].

Its clearly obvious from Figure 10 that Sikadure-52 gives a better strength than that of comercial Epoxy glue (Tepusi). This result lead to the use of Sikadure-52 to stick the composite repair on the steel base for this study.

4.2 DCB test

The force-load point extension is the primary outcome of the DCB tests (Figure 11). The vacuum infusion technique plays a significant effect in strengthening the bonding between the composite layers, which increases the load value needed to open the crack tip, as can be seen from these curves. The impact of vacuum in eliminating voids and improving the interface between the fiber and epoxy is evident when comparing the load values of 4GCV and 4GCH.

Due to the compression force it experiences during the process, vacuum infusion exhibits better mechanical qualities and can prolong the time it takes for the resin to fully cure. The procedure is also carried out in a vacuum environment to get rid of the gases inside the mold. The ambient pressure will indirectly shrink the voids or empty space inside the sample. The mechanical characteristics can be improved if the sample's internal voids and space are minimized[23].

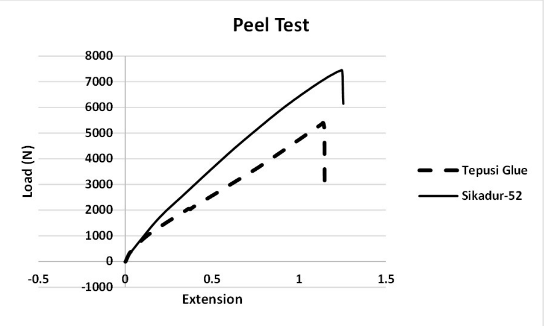


Figure 10. Load-Extension curves for the composites under peel test.

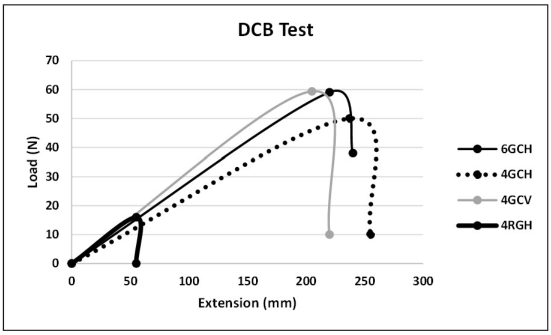


Figure 11. Load-Extension curves for the composites under DCB test.

Additionally, when comparing the 4GCV and 6GCH, it is noticeable that using a 4-layer vacuum-infused composite results in a weight savings advantage over a 6-layer hand-laid composite. The advantage of woven fiber over random strand mat is plainly visible when comparing the 4GCV and 4RGH, where the load value increases by 4 times.

The effect of fiber orientation, which plays a crucial role in the mechanical behavior of the composite, may be responsible for this large improvement. Due to insufficient interface strength between the fiber and matrix and poor stress transfer efficiency, which favors crack initiation, random glass composites have worse mechanical properties.

In woven laminates, crack leaping and fiber bridging have a significant impact on the load value in DCB test. Crack hopping, in which the delamination crack spreads through a nearby ply or into the other interface, is a common failure mechanism seen in woven composites. As a result, it appears that crack leaping and fiber bridging have been reduced[24].

The complex weave of woven fabrics used in woven fiber composites, where the fiber bundles are aligned in the force direction and can therefore hold more load, can slow or stop fiber debonding. In other words, the weaved fibers resist tensile stress until they break because they do not separate like randomly distributed fibers. Although the forces may cause the woven threads to stretch, they might not be strong enough to completely break the fibers. Additionally, the polymer matrix can be damaged and separated from the woven fibers[23]. In order to integrate the greatest qualities of each reinforcement ingredient, intraply fibers composites are created. "Intraply hybrid composites" are materials made up of two or more types of fibers combined into a single ply. Additionally, some of the unfavorable reinforcements can be removed. For instance, by combining the benefits of carbon and glass fiber textiles' high modulus and high strain, a novel hybrid composite material can be created[14].

4.3 Blister test

Since the delamination in the test only occurs under small strains, the blister test results are more important when studying the adhesion of the composite repair[11]. Figure 12 shows the load-displacement curves of the blister test for the four composites, first the curve is increased until the point of the critical load which indicates that the initial debonding of the repair is taking place. Then the interfacial debonding grew as a second stage, and finally, the tearing of the composite repair occurred. Figure 12 shows that 4GCV improves the behavior of the composite repair and increases the value of the critical load to 368 N which the highest value compared with other composites.

Vacuum infusion has greater mechanical properties and can extend the time it takes for the resin to fully cure because of the compression force it experiences during the process. To remove the gases from the mold, the technique is also carried out in a vacuum atmosphere. The voids or empty space inside the sample will indirectly contract due to ambient pressure. If the sample's internal voids and space are reduced, the mechanical properties can be enhanced[23]. This significant improvement can be attributable to the effect of fiber orientation, which is important for the composite's mechanical behavior. Random glass composites have poor mechanical properties when compared to woven fiber due to insufficient interface strength between the fiber and matrix and poor stress transfer efficiency, which promotes fracture initiation.

Fiber debonding can be slowed down or prevented by the intricate weave of woven fabrics used in woven fiber composites, where the fiber bundles are aligned in the force direction and can therefore hold greater load. In other words, because the woven fibers do not separate like randomly distributed fibers, they resist tensile force until they break. The woven fibers could stretch as a result of the stresses, yet the fibers may not totally break even if they are strong enough to do so[23]. As shown in Figure 8, using intraply woven glass and carbon fibers increases the load and improves the blistering behaviour in comparison to using either carbon or glass alone used by previous researchers[13] and[11] with taking into account weaving and stitching pattern. A larger critical load value is the effect of this. Placing glass with carbon within the same layer may produce better results due to the high-strength carbon fiber and the high strain of the glass in the composite, the composite maintains its strength under the load and pressure of the shaft. While in the case of 4RGH, the composite is unable to keep its strength under pressure because the random glass cannot offer the composite the required amount of protection due toits low strength, which results in the composite repair delaminating prematurely from the pipe[13].

Figure 13 shows the identical behavior of FEM and the practical blister Load-Displacement curve in the critical load value. This shows that the CZM zone of blister test can be successfully presented utilizing the RVE method and the bilinear traction separation law. Due to its simplicity and adaptability, the bilinear cohesive traction-separation rule is widely employed in finite element modeling. According to ISO/TS 2481[25], this law is divided into three regions: firstly: an elastic zone up to full strength, secondly: a softening region, and a third region with full nodal pair separation on zero tractions[25]. However, the fact that FEM evaluates the ideal behavior of the materials without taking into consideration issues in the lab work like improper bonding or the occurrence of gaps is what causes the disparity between the experimental and numerical behavior[20] in the second with 7% difference and third region with 10% difference of the curve.

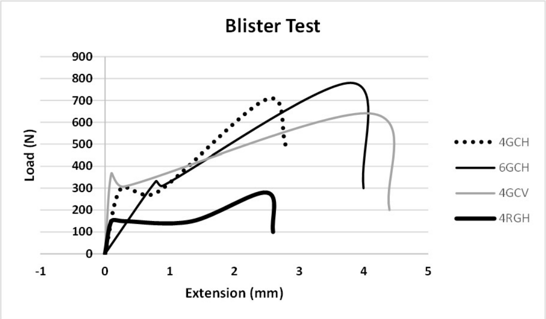


Figure 12. Load-Displacement curves for the composites under blister test.

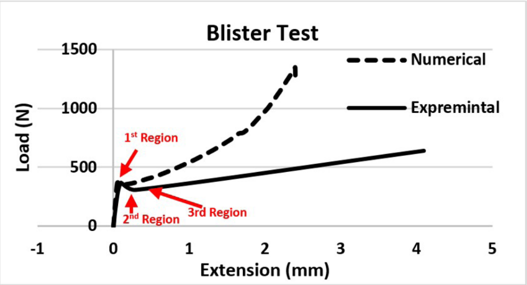


Figure 13. Expremintal and numerical Load-Extension curves for 4GCV composite under blister test.

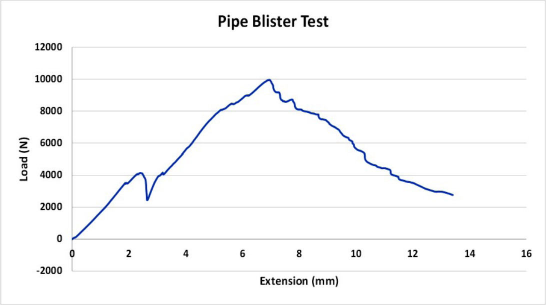


Figure 14. Load-Extension curve for 4GCV composite under pipe modified blister test.

4.4 Modified blister test

The modified blister test consists of wrapping the composite repair directly on cracked pipeline and test it by a shaft to resemble the fluid pressure on the composite repair. As can be seen in the below Load-Extension curve (Figure 14). First, the curve is raised till the critical load point, which denotes the beginning of the repair's debonding. The interfacial debonding developed as a secondary step after that, and the composite repair eventually tore. But when comparing the load value (4154N) with that of plain blister test (368.177N), it can be concluded that the plain blister test gives an initial indication about the adhesion strength but the modified blister test can give the real data about the adhesion strength.

5. Conclusions

The vacuum infusion technique has a significant impact in strengthening the bonding between the composite layers compared to the hand lay up method. 4-layer vacuum-infused composite results in a weight savings advantage over a 6-layer hand-laid composite. The advantage of woven fiber over random strand mat is plainly visible when comparing the 4GCV and 4RGH, where the load value increases by 4 times. The utilization of intraply woven glass and carbon fibers leads to increase the load and improves the blistering behaviour compared to using either carbon or glass alone. Furthermore, there is a close correspondence between the behavior of the Finite Element Model FEM and the practical blister Load-Displacement curve in the critical load value. This shows that the CZM zone of blister test can be successfully presented utilizing the RVE method and the bilinear traction separation law. Plain blister test gives an initial indication about the adhesion strength but the modified blister test can give the real data about the adhesion strength. Using natural fibers in repairing cracked piplines may be a potential future perspectives to reduce repairing costs and lowering the harmful effect of using synthetic materials.

6. Author's Contribution

- **Conceptualization** – Payman Sahbah Ahmed; Jafar Abdullah Ali.
- **Data curation** – Payman Sahbah Ahmed.
- **Formal analysis** – Payman Sahbah Ahmed.
- **Funding acquisition** - NA.
- **Investigation** – Payman Sahbah Ahmed; Jafar Abdullah Ali.
- **Methodology** – Payman Sahbah Ahmed; Jafar Abdullah Ali; Serwan Sarbast Mohammed Talabani.
- **Project administration** – NA.
- **Resources** – Payman Sahbah Ahmed; Jafar Abdullah Ali.
- **Software** – Payman Sahbah Ahmed; Serwan Sarbast Mohammed Talabani.
- **Supervision** – NA.
- **Validation** – Payman Sahbah Ahmed.
- **Visualization** – Payman Sahbah Ahmed; Jafar Abdullah Ali; Serwan Sarbast Mohammed Talabani.
- **Writing – original draft** – Payman Sahbah Ahmed; Jafar Abdullah Ali.
- **Writing – review & editing** – Payman Sahbah Ahmed; Jafar Abdullah Ali; Serwan Sarbast Mohammed Talabani.

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