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A Review on Carbon Fiber Reinforced Polymer as Wrapping Structures For Pipeline

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Abstract: To maintain the continuous product flow in the pipe, the durability of the pipe structure is achieved through pipe insulation. The composite material will be used as the main material, since it may have the combined characteristics of the constituents or have substantially different properties than the individual constituents. Replacing the damaged pipe with a new one will not only consume high cost but also will create a complication for product flow. As to alleviate such situations this research focusses on using the carbon fiber reinforced polymer (CFRP) as the wrapping material. To identify the suitable design and optimization of laminated CFRP on piping systems, the defect, leakage and imperfection on pipe shall be identified. The effect of different laminate orientation through Classical Laminate Theory CLT and experimental data too need to be considered as it changes the mechanical properties of the composite material. The microstructure of the composite too will be validated as an extra reference for the theoretical and experimental data on its effect in the microstructure after the loading.

Keywords: Carbon fiber reinforced polymer, piping system, lamination optimization, wrapping structure

1. Introduction

Among the existing infrastructural facilities pipeline system is considered a very important structure specifically in oil and gas sectors as well as other related industries whereby this system considered as the critical infrastructure (CI) [1]. In these sectors safety is given the highest priority since the risk exposure is very high. The combination of design, material and operating practices always lowers the chances of pipe failure. Natural occurrence and exposure to critical elements also contributes to the failure of pipeline system. To eliminate such failures, pipeline structure is given the highest level of priority and maintenance to maintain the continuous product flow in the pipe. Durability of the pipe structure is achieved through the pipe insulation where it provides a high mechanical strength and flexibility in a variety of applications. Defects of pipe structure shall be identified upon considering the importance of material and its wrapping structure on defected pipe. As an overall idea, composite material was chosen compared to other material as this material is known for its relative alteration on its characterization based on the requirement.

This composite material has a very unique characteristic, where depending on the manner in which the constituents are put together, the resulting composite material may have the combined characteristics of the constituents or have substantially different properties than the individual constituents [2]. That's the reason behind its high consumption in various industry sectors as it possibly could possess low density, corrosion resistance and various better mechanical properties. In present, the above-mentioned approach on piping system is applied as defect, leakage and imperfection in pipe became the critical problem that being faced in various industry as what has been illustrated in Fig. 1. Furthermore, among the group of composite materials the CFRP was decided to be used as the main material among the other type due to its specific characteristics which will be reviewed further in this paper.

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Fig. 1 - Example of pipeline problems [3,4]

2. Literature Review

A variety of methods are used to protect pipes from impact, abrasion, corrosion. Among the existing repairing method composite wrapping is gaining popularity across the decade [5]. This composite wrapping method are gaining popularity and acceptance around the globe whereby this method and procedure are guided by international engineering standards and provide an engineered, proven and durable solution to non-metallic repair works. [6]

2.1 Defects on Pipe System

All structural materials contain imperfections, and the greater their complexity the more likely flaws will be introduced during manufacturing. A defect is considered an elementary form of failure in pipes that could fail a safety system. Pipe system due to their buried and often located in areas of construction activity are susceptible to defects and anomalies. When the presence of defect is detected, normally the pipe system is restored to its original design configuration through repairs [7]. One of the critical defects in pipeline are the external corrosion which may result to pipe leakage in long term time frame. The definition of corrosion according NACE International is “The deterioration of a substance or its properties because of a reaction with its environment” [8]. As mentioned earlier since pipe structures are regularly exposed and react to the environment there the tendency for pipe failures is high. All materials can corrode if we place them in an environment that causes that particular material to deteriorate [9]. Oxidation in other words known as corrosion, that occurs on the steel pipe results in metal loss in the pipe. This will eventually cause the steel pipe to loss in strength gradually [8]. As corrosion is known as an electrochemical process, it is absolutely time-dependent. In general, corrosion is categorized either as general corrosion or localized (pitting) corrosion [10].

Pitting corrosion are defined as the corrosion with a length and width less than or equals to three times of the uncorroded wall thickness while general corrosion, defined as corrosion with a length and width greater than three times the uncorroded wall thickness [11]. Specifically, there are 7 types of corrosions that are involved in pipeline failures. The list of various corrosion types are as follows [12,13]: -

i. Galvanic corrosion
ii. Microbiologically induced corrosion
iii. AC Corrosion
iv. Differential soils
v. Differential aeration
vi. Cracking
vii. defect-free pipe
viii. corrosion
ix. gouges
x. plain dents
xi. kinked dents
xii. smooth dents on welds
xiii. smooth dents containing gouges
xiv. smooth dents containing other types of defects
xv. manufacturing defects in the pipe body
xvi. girth weld defects
xvii. seam weld defects cracking
xviii. environmental cracking

Corrosion in a pipeline is really difficult to characterise as it will have an irregular depth profile and extend in irregular pattern in both longitudinal and circumferential directions as illustrated in Figure 2. As mentioned earlier metal loss due to corrosion may occur internally or externally in the pipe surfaces, base material, seam weld or in the girth weld [14]. As this corrosion lead to metal loss substantially it leads to volumetric loss leading to leakages and failure in mechanical strength. The geometry of a typical metal loss corrosion defect on a pipeline is illustrated in Figure 3. Besides, defect type like gouges on welds, kinked dents, smooth dents and gouge which are severe defects need to be resolved with immediate actions. Gouges, cracking, plain dents, smooth dents on welds, weld defects and manufacturing defects could also lead the pipe metal loss [17]. The right choice to prevent the existing defects which will lead to leakage can be avoided by wrapping the whole leaked pipeline section. This is to maintain the continuous product flow through the pipeline system. Various pipe leakage detection methods can be used for which comprises the exterior, visual and interior scopes. Therefore, as mentioned earlier since the pipelines are extremely long-serving and critical infrastructure it is very important to protect this structure from all sorts of defects and the perseverance of the pipeline structure is best likely maintained by the wrapping structure covering the pipe.

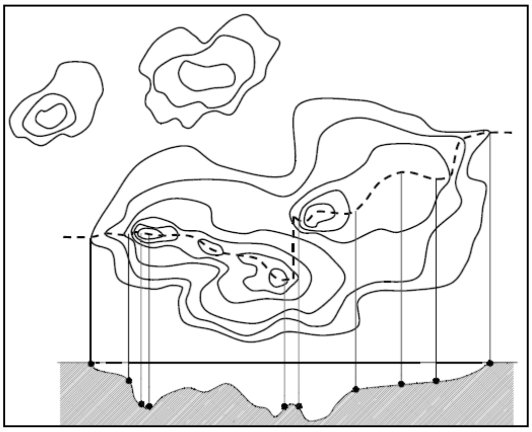


Fig. 2 - The irregular depth, width and length due to corrosion on a defected pipe [12]

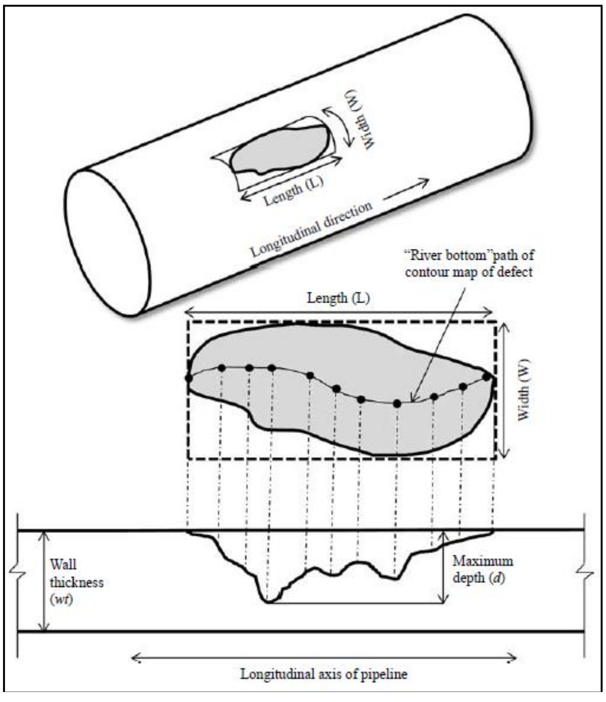


Fig. 3 - Volumetric loss due to corrosion in pipeline surface [15,16]

2.2 Composite Material

For more than 20 years, advanced composite material has been used as transmission pipeline repair methods. In general, there are four types of composites which are known as the particulate composite, flake composite, fiber reinforced composite and laminated composite [18,19]. Particulate composites are generally made up of a randomly dispersed hard particle constituent in a softer matrix [20]. Flake composites are formed by adding thin flakes to the matrix material. Fiber-reinforced composite are the most commonly used form of the constituent combinations. The fiber of such composites is generally strong and stiff and therefore serve as the primary load-carrying constituent. The last form of composite materials is thin layers of material fully bonded together to form so-called composite laminates. [21]. A composite repair has many benefits when compared to more traditional pipeline methods [19,20]. One of the key benefits is that it could wrap while the pipeline is still in-service as the pressure does not have to be raised or lowered to make the repair. [19]. Moreover, composite material is able to provide high specific strength and stiffness, resist against corrosion, and it possess low density and relatively as good dielectric material [22]. Besides, the downside of the composite needs to be considered as well to make sure that the composite material is the right material to be chosen as lamination material. In common trend there are four basic failure occurs in the composites. They are categorized under mechanical (static and cyclic) loading. These comprises matrix cracking, interfacial debonding, delamination and fiber breakage [23,24,25]. The failures need to be addressed or taken into consideration as such failure effects the strength composite properties as wrapping material. [26]

2.3 Carbon Fiber Reinforced Polymer (CFRP)

Since carbon fiber is under the fiber-reinforced composite, the possible pattern that could be formed should be identified by referring to type of pattern. Particularly, random short fibers, oriented short fibers/plain fibrous layers, continuous fibers, plain weaves, tri-axial weave/woven, fabrics and bi-plane weave are the six fiber arrangement patterns in the layer of a fiber-reinforced composite [27]. Visually, carbon fibers are very thin filaments where they are in size of 5–10µm in diameter, where they are just visible to the human eye. The visual comparison can be clearly seen in the following Figure 4. It is trusted that Thomas Edisson was the one whom invented the carbon fibers as filaments for the light bulbs in the year of 1879 and lately in the mid of the 20th century the high-performance carbon fibers were manufactured [29,30]. As rapid development was done across decades, lately the mechanical properties of the carbon fibers were very much improved compared to other type material especially materials like steel [31]. The Table 1 shows different material typed pipes that were used in oil fields and their performance. It is very necessary to get to know the existing pipe types and their performances so that the proposed wrapper will meet the requirement with existing parameters. The comparison on mechanical properties of carbon fibers and steel is tabulated in Table 2.

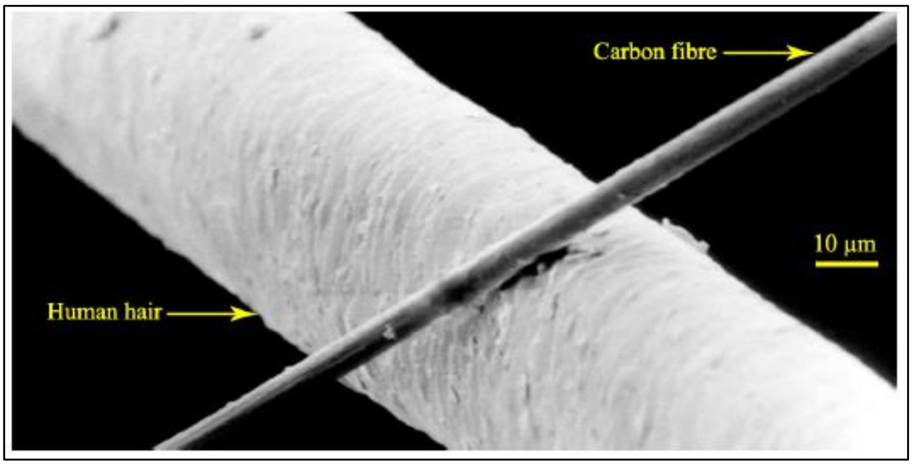


Fig. 4 - Comparison of carbon fiber with human hair [28]

Table 1 - Different pipes used in oil field and their performance [32]

Performance \ Type	Carbon Steel	Coated Carbon Steel	FRP	RTP
Corrosion resistance	Low	Medium	High	High
Maintenance cost	High	High	Low	Low
Speed of installation	Low	Very low	Medium	High
Impact resistance	High	High	Low	Medium
Maximum pressure (MPa)	>32	>32	32	25
Maximum temperature (℃)	150	65	120	65

Table 2 justifies on the necessity of carbon fiber chosen as the wrapping material as it is high in tensile strength, elastic modulus and less dense compared to the steel. Moreover, the breaking length is a good parameter to show the high strength and lightweight characteristics of certain materials. Carbon Fiber reinforced polymer seems to be met the requirement as the wrapping material even though Glass Fiber Reinforced Polymers (GFRP) and Polymer Reinforced polymers are relatively belonging to composite material group. This carbon fiber reinforced polymer has various advantages and disadvantages where it is very much needed to be discussed. This is to make sure its characteristics are compatible to the requirements to be used as wrapping material for pipeline system. Carbon fibers embedded in a polymer resin, in which the carbon fibers function as the reinforcement material and the polymer resin functions as the matrix to hold the fibers. [19]. This carbon fiber reinforced polymer has various advantages and disadvantages where it is very much needed to be discussed as to make sure its characteristics are compatible to the requirements to be used as wrapping material for pipeline system. Carbon fibers embedded in a polymer resin, in which the carbon fibers function as the reinforcement material and the polymer resin functions as the matrix to hold the fibers.

Table 2 - Mechanical properties of carbon fibers compared with steel materials [33,34]

Material Type		Density (kg/m^3)	Tensile Strength (GPa)	Elastic Modulus (GPa)	Breaking Length (km)
Carbon Fiber	Standard	1760	3.53	230	205
	High Strength	1820	7.06	294	396
	High Modulus	1870	3.45	441	188
Steel	S355	7850	0.50	210	6
	Wire	7850	1.77	210	23

Table 3 clearly states the advantages and disadvantages of the various fiber reinforced polymer so that a suitable material could be identified for the above issue. Again, it can be clearly seen that the carbon fiber comparatively meets the requirement for the research as the wrapping material in pipeline system. One of the key benefits is that it could wrap while the pipeline is still in-service as the pressure does not have to be raised or lowered to make the repair [33]. All these general benefits had made the composite to be chosen and in particular, the carbon fiber which is under the fiber-reinforced composite category was selected as the wrapping material for this research [34,35].

Table 3 - Advantages and disadvantages of various type of composites [27,28,29,30]

Advantages	Disadvantages
Carbon Fiber Reinforced Polymer	
Lightweight	Carbon fiber will break or shatter when it is compressed.
High tensile strength	Relative cost where it is high quality material with a price to match.
Low thermal expansion	
Exceptional durability	
Corrosion resistance	
Radiolucency	
Electrical Conductivity	
Ultra-violet resistant	
Glass Fiber Reinforced Polymer	
They can be easily drawn into fibers from molten state	It has poor rigidity and stiffness
Glass is cheaper and readily available	Its application is limited to a temperature below 300-degree Celsius
Glass fiber is relatively strong	
Polymer Nanocomposites	
Superior mechanical properties (modulus and strength)	Non-uniform distribution
Structural and thermal stability	High viscosity
Promising electrical conductivity	Formation of agglomeration
Noise damping	
Corrosion resistance	
Low permeability of fluids	
Low density than ceramic / metallic materials	
Low filler content	
Ease manufacturing	

2.4 Polymer Resin of CFRP

Polymer resins in the CFRP is the key reinforcement that gives the mechanical strength to the whole composite structure. Therefore, polymer resin for CFRP is categorized into two where one is the thermoplastic resin and the other one is the thermosetting resin. The usage of this resin simultaneously changes the mechanical strength of the composite structure relatively with different mechanical-thermal responses [34,36]. Although both type resins responses accordingly with thermal and mechanical exposure but both the resins differ accordingly with molecular structures and properties. Thermoplastic resin are polymers that linked with intermolecular interactions that forms branched or linear molecular structure. This molecular structure allows the thermoplastics remelt able and tractable. In the other hand, thermosetting resins are polymers that were bonded with chemical bonding, forming highly cross- linked molecular structure. This restricts the thermosets from being remelting or intractable upon heat and pressure after curing [37,38]. For visual aid the following Figure 5 illustrates the molecular structure of polymer resin for better understanding on thermosets and thermoplastics.

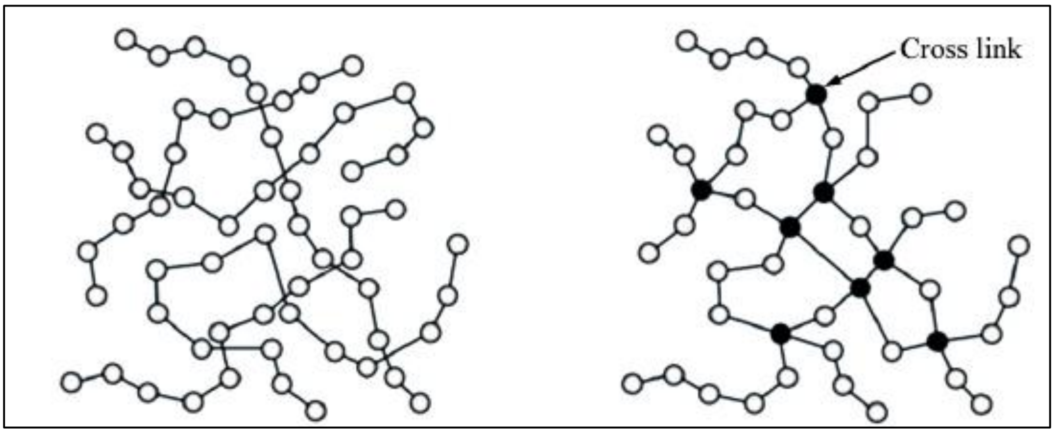


Fig. 5 - Molecular structures of (a) thermoplastic resins and; (b) thermosetting resins [39]

As mentioned earlier the polymer resin plays a very key role in deciding the mechanical properties of the CFRP. It is very necessary to get to know the mechanical properties of both the polymer resins. By referring to the Table 4 below it can be seen that the thermosetting resin is the right choice for this research upon considering its application. Since heat and pressure plays a major role in the pipe defect wrapping the thermoplastic is not suitable to be used as it could remelt. In other hand the thermosetting is advisable to be used as it could withstand the pressure and thermal stress. Among, the thermosetting resins, Epoxy is very much suitable to be used as resin. This is because by comparing both Orthophthalic polyester and Vinylester the epoxy has lower density and tensile strength even though it has lower elastic modulus. It is very much concerned that the prior modification should be used as the synergistic fashion with a polymer resin to realize their superior mechanical properties [19].

Table 4 - Mechanical properties of commonly used polymer resins [35,40]

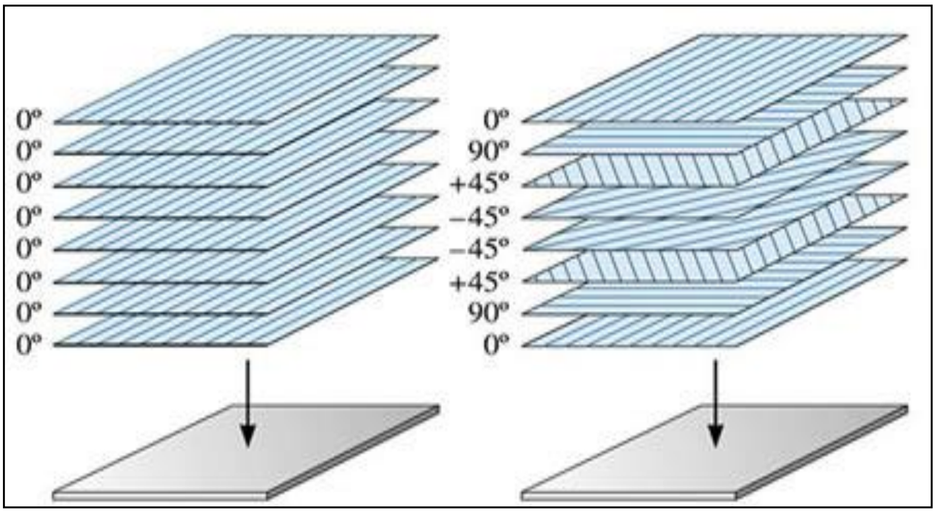
Type	Name	Density	Tensile strength	Elastic modulus
Thermoplastic	Polyethersulfone	1370	0.084	2.4
	Polyetherether ketone	1310	0.070	3.8
	Polyetherimide	1270	0.105	3.0
Thermosetting	Orthophthalic polyester	1350	0.070	3.2
	Vinylester	1250	0.075	3.3
	Epoxy	1250	0.115	3.0

2.5 Pipeline Wrapping

The lamination of leaked pipe already exists in various industry. This includes primer, inner wrap, outer wrap, plastic rock shield and hand wrapping tape. Specifically, the primer shall be a fast-drying compound, compatible with the laminated tape suitably compound to produce a liquid coating material that can be readily applied cold by brushing or spraying to produce an effective bond between the bare pipe surface and the subsequent coat of laminated tape [41]. Inner wrap, shall have a backing of stabilized polyethylene and a primer activated adhesive mass of butyl rubber while outer wrap shall be polyethylene plastic tape suitable for machine application over the inner wrap [42]. It shall give protection against mechanical damage over inner wrap during pipe lowering-in and back-fill operations. Plastic rock shield shall consist of a matrix of spaced ribs of high-density polyethylene with good impact resistance. It shall be resistant to shock, fungi, natural and artificial agents contained in soil. On the other hand, laminated plastic tape shall have a backing of highly flexible polyethylene and a mass of primer activated coat of butyl rubber [40].

2.6 Composite as A Wrapping Material

Composite material is considered a material that is very convenient to be used in hand lay-up technique as it possesses high possibility to alter the lay-up orientations. The alteration is really important to achieve the isotropic properties through quasi-isotropic lamination. Isotropic means a particular material possesses the same strength and stiffness when measured in various direction. Quasi-isotropic means a particular material possesses the isotropic properties whereby the strength and stiffness are same in all direction but only in-plane [43]. Therefore, the lamination of CFRP is considered as the quasi-isotropic as it could possess it properties that varies with planes. Figure 6 illustrates the unidirectional isotropic and cross-piled quasi-isotropic [43, 44].



(a) **(b)**

Fig. 6 - (a) Unidirectional quasi-isotropic and; (b) cross-piled quasi-isotropic lamination [44]

It is known that quasi-homogenous lamination bends and extends with similar properties but in single failure mode in longitudinal tensile loading, the failure occurs at top surface where it experiences compression while the bottom surface experiences tension. Moreover, bending occurs on laminates which were lay-up oriented in unidirectional orientation. This same orientation will eventually cause a failure in the lamination due to the weak fiber network. Classical Laminate Theory (CLT) is the most suitable technique to study the behavior of the lamination theoretically as this data will be used to correlated with the experimental data [45, 46]. Both experimentally and theoretically, 6 layers of each laminate orientation $(0)_6$, $(45)_6$, $(90)_6$, (45/-45/45) s and 8 layers of symmetric quasi-isotropic laminate orientation (± 45/0/90) s will eventually give flexural properties of the material structure. By referring to the ASTM D790 and BS 4994 125mm x 12.7mm and 200mm x 20mm specimens should be used to identify flexural properties. The following Figure 7 shows the lay-up laminate orientation of the CFRP that should be considered when testing and evaluating the lamination.

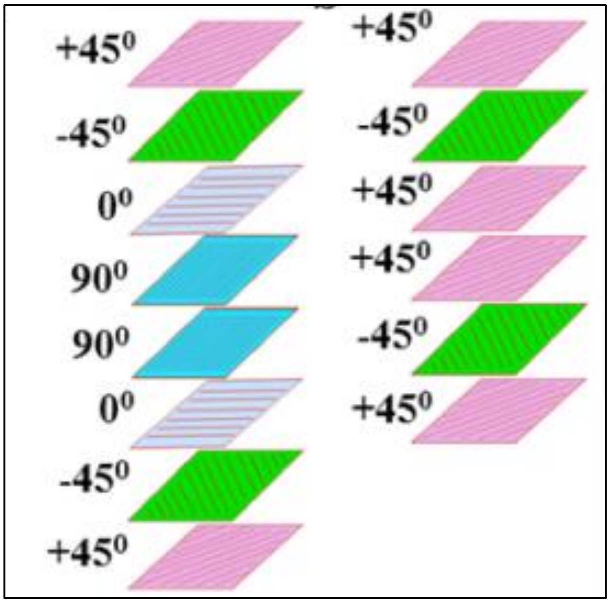
3. Theoretical Modelling

Theoretically, the laminate orientation modelling can be done through by substituting the force and moments per unit length in a plate in the following formula 1 and 2 [47]

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz \qquad (1)$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} Z \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz \qquad (2)$$

where Nx, Ny and Nxy indicates the in-plane normal and in-plane shear forces per unit length, while σ_x, σ_y and τ_{xy} are the normal and shear stresses, respectively. Mx, My and Mxy are the bending and twisting moments per unit length, respectively. h indicates the thickness of the lamination. The force and moments are related to matrices and laminate strains [A], [B] and [D] could be defined in Formula 3 [47].



(a) (b)

Fig. 7 - Schematic diagram of (a) symmetric quasi-isotropic laminate; (b) symmetric laminate [47]

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \end{bmatrix} \quad (3)$$

Where [Aij], [Bij] and [Dij] are extension and extension-bending coupling and bending stiffness matrices, respectively. The formula to calculate the respective extensions are as stated in Formula 4, 5 and 6 [47],

$$[A_{ij}] = \sum_{k=1}^{n} \left(\overline{Q_{ij}}\right)_k (h_k - h_{k-1}) \quad (4)$$

$$[B_{ij}] = \frac{1}{2} \sum_{k=1}^{n} \left(\overline{Q_{ij}}\right)_k ({h^2}_k - {h^2}_{k-1}) \quad (5)$$

$$[D_{ij}] = \frac{1}{2} \sum_{k=1}^{n} \left(\overline{Q_{ij}}\right)_k ({h^3}_k - {h^3}_{k-1}) \quad (6)$$

The extension stiffness matrix and bending matrix for a quasi-isotropic laminate are denoted as in Formula 7 and 8 [47].

$$[A_{ij}] = \begin{bmatrix} \frac{Eh}{(1-\nu^2)} & \frac{\nu Eh}{(1-\nu^2)} & 0 \\ \frac{\nu Eh}{(1-\nu^2)} & \frac{Eh}{(1-\nu^2)} & 0 \\ 0 & 0 & \frac{Eh}{2(1+\nu)} \end{bmatrix} \quad (7)$$

$$[D_{ij}] = \begin{bmatrix} \frac{Eh^3}{12(1-v^2)} & \frac{vEh^3}{12(1-v^2)} & 0 \\ \frac{vEh^3}{12(1-v^2)} & \frac{Eh^3}{12(1-v^2)} & 0 \\ 0 & 0 & \frac{Eh^3}{24(1-v)} \end{bmatrix} \quad (8)$$

Where, *E* and *v* are known as the flexural modulus and Poisson's Ration of the quasi-isotropic lamination.

4. Experimental Flexural Properties of Different Laminate Orientation Wrapping Structure With Different Composite Material

With designated experimental procedures the Mechanical Properties of the different orientation of CFRP and GFRP is tabulated in Table 5. About 5 specimens of CFRP and GFRP that have the laminations of 0°,45°, [45°/-45°/45°], [± 45°/0°/90°]$_s$ and 90° were evaluated. From the data itself it can be seen that the CFRP possess better properties for almost all the orientations than the GFRP material. The flexural strength flexural modulus or the elasticity modulus of the CFRP possess higher properties than the GFRP. Fig. 8 and Fig. 9 is the graph of the data in Table 5 which concerned on the flexural strength and flexural strain of CFRP and GFRP.

Table 5 - Mechanical properties of the different orientation of CFRP [47]

Mtrl.	Flexural properties	0	45	$(45/-45/45)_s$	$(\pm 45/0/90)_s$	90
CFRP	Flexural strength [MPa]	929 ± 33.8	101.1 ± 10.5	184.8 ± 9.45	541.9 ± 16.6	92 ± 5.11
	Flexural strain [%] at peak load	1.47 ± 0.19	1.14 ± 0.1	3.1 ± 0.3	1.98 ±0.14	0.72 + 0.05
	Flexural strain [%]	5.46 ± 0.3	1.92 ± 0.11	21 ± 1	8.64 ± 2	1.84 ± 0.15
	Flexural modulus [GPa]	73.75 ± 1.9	10.5 ± 0.7	9.5 ± 0.86	38.53 ± 1.17	6 ± 0.77
	ILSS [MPa]	61 ± 4.24	13.33 ± 0.57	41 ± 4.21	37 ± 2.82	8.75 ± 1
GFRP	Flexural strength [MPa]	878.4 ± 7.9	99.32 ± 0.95	167.39 ± 3	333.9 ± 30.9	86.57 ± 4.5
	Flexural strain [%] at peak load	3.39 ± 0.1	1.42 ± 0.1	5.6 ± 0.38	3.51 ± 0.83	2.15 ± 0.41
	Flexural strain [%]	6.08 ± 0.31	3.48 ± 0.72	31 ± 1.41	15.73 ± 3.7	3.1 ± 0.2
	Flexural modulus [GPa]	26.25 ± 0.6	8.11 ± 0.57	7.67 ± 0.29	14.31 ± 1.84	4.45 ± 0.63
	ILSS [MPa]	27.5 ± 3.5	14.5 ± 2.12	15.75 ± 2.87	27.66 ± 7.5	9.5 ± 0.7

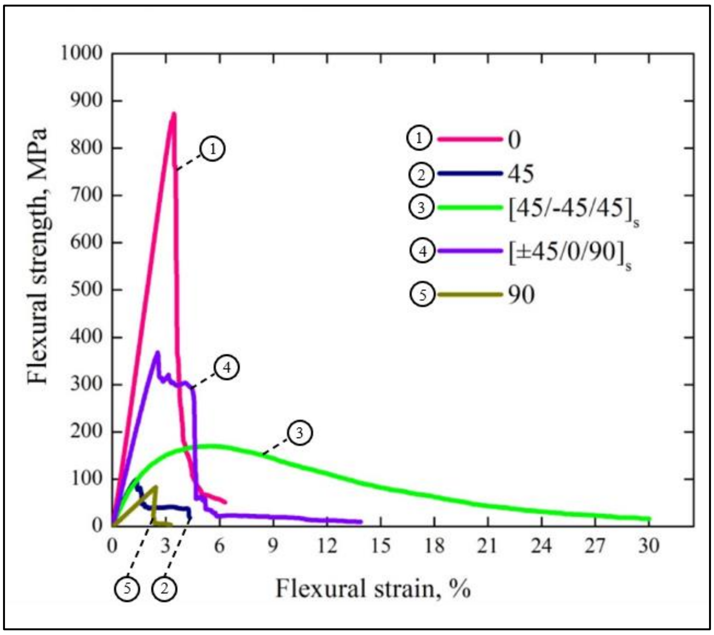


Fig. 8 - The flexural strength versus flexural strain of CFRP [47]

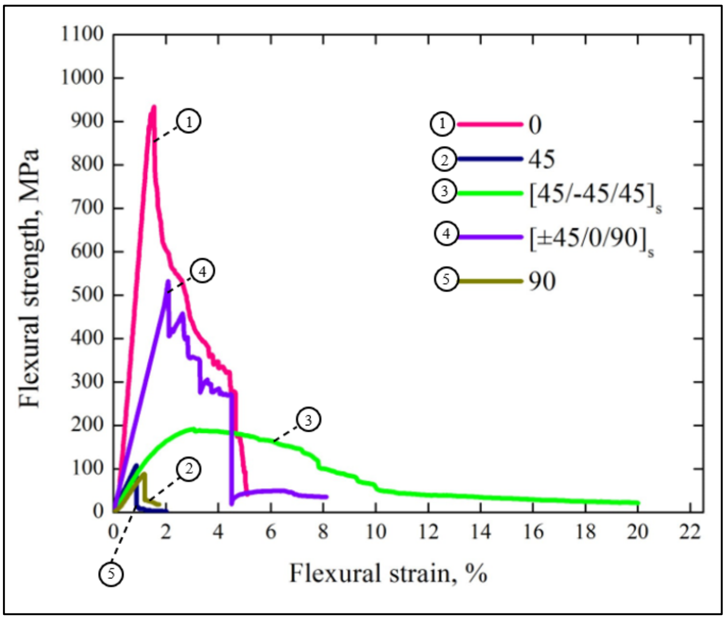


Fig. 9 - The flexural strength versus flexural strain of GFRP [47]

By comparing the flexural properties for each different lamination stacking sequences of CFRP and GFRP the 0° laminate shows the higher flexural strength and modulus compared to other orientations. But it is very necessary to understand that whenever a transverse loading is applied perpendicularly to the sample then the flexural strength with homogenous or unidirectional orientation will possess higher flexural strength. A unidirectional layer orientation will tend to react well to the stress in one direction only [11]. But in the service pipe structure the force out from a defect will exert in multiple direction. Therefore, the orientation that could sustain the loading in all direction shall be considered [1]. The application of the wrapper on the pipe structure is in different scenario where there are 3 axes of the loading shall be considered. Based on the data in Figure 8 and Figure 9, the CFRP possess a gentle failure slope while the GFRP possess a very steep failure slope. Both figures shows that the lamination orientation of 0° have a larger flexural strength but it has a sharp slop after the breaking point. This shows that this lamination has lower elasticity modulus compared others, while the $[\pm45/-45/45]_s$ seems to have a better elasticity modulus where it has much smooth slope or gradient after the breaking point. The specimen failure of $[\pm45/0/90]_s$ orientation had failed completely after some time of period upon exiting the breaking limit but the specimen that has a lamination orientation of 0° completely in just short time of period upon exiting the breaking point. Significantly, the lamination stacking sequence of $[45/-45/45]_s$ shows higher flexural strain due to the presence of the opposite layup orientation which will result in higher deformations and crack propagation [47]. Referring to the above data fiber-matrix cracking and delamination occurs easily in bending with the lamination orientation of 0°,45° and 90° due to the weak network with fibers. The five different laminate orientations give a very clear idea on the lamination should be used for pipeline structure. This significance is very much needed to optimize the lamination of CFRP in pipe structure. It should be understood that flexural strain or flexural stress may differ according to type of defect and their effect on strength of the pipe structure.

This data gives an idea that the CFRP is durable enough to withstand wear, pressure or stress upon different lamination orientation of wrapping structure. In other words, the GFRP is fragile against the wear, pressure or stress. Therefore, the CFRP gives a formidable data that this material could be used as the wrapping material on defected pipe structure. Besides the statistical data, visual inspection also plays a major role for a better conclusion. The following Figure 10 is also a visual illustration of SEM micrographs due to loading of on different laminate orientation. It clearly shows that there was fiber breakage, fiber-matrix debonding, fiber-matrix interface cracking and matrix cracking in 0°, 45° and 90° laminations.

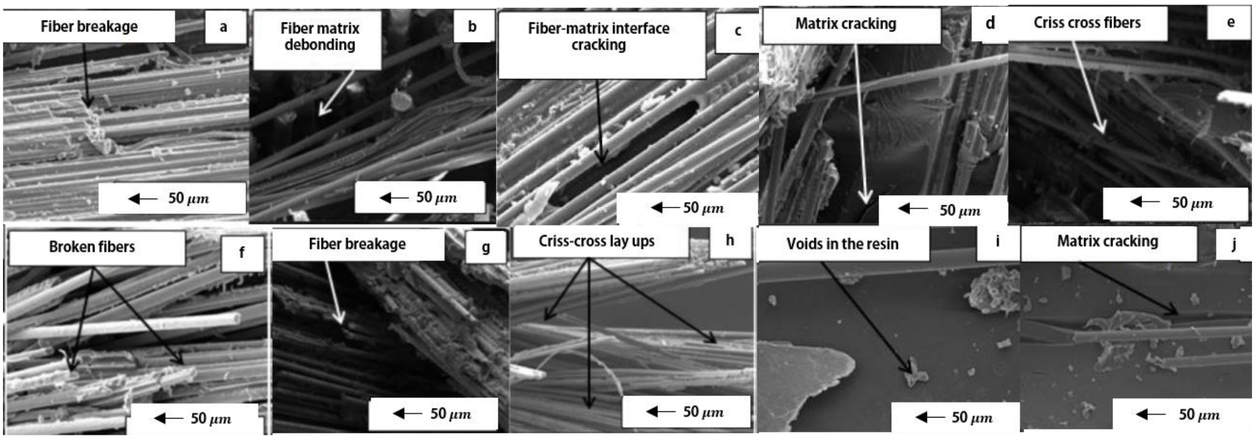


Fig. 10 - SEM micrographs for different laminate orientations: 0°– a, b; 45°– c, d; (45°/-45°/45°) s – e, f; (±45°/0°/90°) s – g, h; 90°– i, j; CFRP – a, c, e, g, i; GFRP – b, d, f, h, j in bending [47]

5. Conclusion

Theoretically it is found that CFRP composite seems to be the most suitable pipe wrapping material considering it's the greater properties that it could possess compared to GFRP which are in optimum conditions. Moreover, this material is also compatible with the lay-up lamination technique that can be easily installed around both complex and unsophisticated geometries such as elbows and bends. It is assumed that the, wrapping thickness is expected at 6-8 layers and among the 5 orientations, $[\pm 45/0/90]_s$ possess optimized properties that is suitable for defected pipe structure. But this orientation needs to be simulated, and examined practically comparing with more orientations. Particularly this paper proves that CFRP is a better material over the GFRP for wrapping purpose and among the CFRP material orientation the $[\pm 45/0/90]_s$ seems to possess better properties. The reliability, the lifetime and the durability of the wrapping structure is expected to be at optimum level and would be further verified with Monte Carlo simulation and with NDT Method. It is very much expected too that the specification and characteristics of the wrapping structure could be identified precisely by justifying through this technique. These assumptions are just based on the theoretical findings and shall be further validated with experimental approach.

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