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Numerical comparison between single layer woven flexible pipe and reinforced thermoplastic pipe

A. Akram[1], Z. Mustaffa[1], T. M. B. Albarody[2] and J. E. Edmund[1]

[1]Civil and Environmental Engineering Department, Universiti Teknologi PETRONAS (UTP), 32610 Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia,
[2]Mechanical Engineering Department, Universiti Teknologi PETRONAS (UTP), 32610 Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia,
Phone: +6053688000; Fax: +6053654088
*Email: aliakram92@gmail.com

ABSTRACT

The weight of a conventional flexible pipe and corrosion poses a major challenge for pipelines at significant water depths, making composite material an ideal alternative for steel in the armor layers. A woven configuration was developed for the armour layer by utilising glass epoxy, namely the woven flexible pipe. However, the performance of the woven flexible pipe in deep water conditions are unknown, thus the need for a numerical analysis. In this paper, an initial comparison was conducted for the woven flexible pipe with a typical bonded flexible pipe called the thermoplastic reinforced pipe, where one layer of the woven flexible pipe is considered to show its performance. The results showed higher stress experienced by the woven flexible pipe as compared to the reinforced thermoplastic pipe, where the lowest difference was 50.8%. It was also shown that the woven flexible pipe can withstand the 6 MPa internal pressure at a thickness of 6 mm and above. The result is still inconclusive as an experiment test is required to validate the results. However, it serves as a good estimation of the expected result for future experimental test.

Keywords: Flexible pipeline; composite material; woven.

INTRODUCTION

Unbonded flexible pipe has been successfully used as a dynamic riser and static flowline for over 30 years. This performance is due to the configuration of the unbonded flexible pipe which consists of multiple layers, each with their own unique function [1, 2]. However, as the amount of hydrocarbon from shallow water reservoir continue to dwindle, attention has been diverted to deep water and ultra-deep water for more supply. This poses a challenge in terms of the pipeline weight due to the metal armour layers [3-6]. Although this can be solved by using buoyancy modules [6], the deployment of buoyancy modules also leads to an increase in overall installation costs [7]. In addition to that, corrosion also becomes an issue due to the presence of water and corrosive gasses, such as carbon dioxide (CO_2) and hydrogen sulphide (H_2S), which can permeate through the internal sheath into the annulus area [8-12]. This condition is further aggravated in the event that the external sheath is breached or damaged, allowing seawater to mix with the gas to produce a corrosive environment [2, 9, 13]. Considering this matter, extensive research was made in replacing the steel armour layer with composite materials which were proven to be lighter and has more resistance towards corrosion [6, 7, 14, 15]. In addition to that, a woven configuration was proposed, combining the hoop layer and tensile layers into a single layer. This design allows the hoop layer to contribute in resisting tensile forces and likewise, the tensile layer contributes in resisting hoop stresses due to the interlocking mechanism of the woven configuration. However, given the high-pressure conditions of deep water environment, the woven configuration of thermosetting tapes is yet to be tested under high pressure loads, thus the need for a numerical analysis and experimental test for verification purposes.

The proposed non-metallic flexible pipe is a woven flexible pipe made from glass epoxy tapes woven in the hoop and axial direction, all of which are unbonded to allow movement of the tapes, thus increasing overall flexibility of the pipe. An experimental study would require a sophisticated equipment to weave the tapes according to the desired direction, much like the filament winding machine. The only difference is that the weaving tapes are all unbonded, which proves to be a great challenge in fabricating such a flexible pipe. Therefore, a numerical analysis was performed by using ANSYS for the woven flexible pipe and the results were compared with a typical bonded flexible pipe, called the thermoplastic reinforced pipe, to compare their performance. The objective is to study the performance of a single layer woven flexible pipe by using varying thickness. A typical unbonded flexible pipe consists of several layers, where each layer serves a specific function. The key layers as well as their function are shown in Figure 1 and Table 1. The performance of the sheath depends on the material used, which are usually high density polyethylene (HDPE), polyamide 11, and polyvinylidene fluoride (PVDF). Among these materials, PVDF polymers present the best chemical compatibility and highest continuous sustainable temperature of 130^{o}C and above [16]. Other layers are also applied when needed, such as anti-wear tape between the layers, and aramid fibres which are wrapped around the armour layers to prevent birdcaging. However, in view of corrosion and weight issues, different materials are sought for replacement which are composite materials.

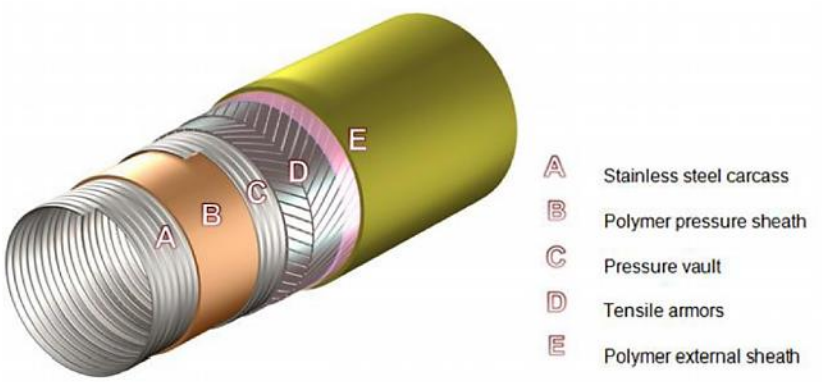


Figure 1. Typical flexible pipe construction with main layers [16].

Composite material is seen as an attractive alternative in the offshore industry due to its high strength to weight ratio. The properties are largely dependent on its components, namely the matrix and the reinforcement where the matrix discussed will be a thermosetting resin owing to its higher mechanical properties. In offshore applications, Gibson [17] simplified the selection criteria for resins into three, which are cost, flammability and mechanical properties. However, chemical resistance should also be considered due to the presence of corrosive substances. The matrix is selected from the most common thermoset used for structural purposes, that is polyester, vinyl ester, and epoxy. These materials are known for their good mechanical strength and chemical resistance. Among these resins, epoxy is the popular choice as it is regarded for its superior mechanical property and low degradation from water absorption [18].

Table 1. Key layers and functions of unbonded flexible pipe [10].

Layer	Function
Carcass	Resists hydrostatic pressure and prevents collapse in the event of rapid depressurisation.
Internal sheath	Contains flow of product.
Pressure armour	Provides hoop resistance from internal pressure and external hydrostatic pressure.
Tensile armour	Provides tensile resistance
External sheath	Protects internal parts from seawater and external impacts.

In terms of reinforcement, carbon fibre and glass fibre are usually chosen due to their strength. There are also cases where aramid fibre is used. Table 2 shows the generalisation of their mechanical property as well as cost and toxicity in fire [17], while Table 3 shows a comparison of fibre strength [19]. However, it is difficult to provide an accurate figure as it varies with different manufacturers, although it could still serve as a good reference. Thus, Table 4 provides a qualitative approach for comparison between polymers reinforced with the mentioned fibres [20]. Based on the material properties shown, the matrix and reinforcement fibre chosen are epoxy and glass fibres, respectively for the development of the woven flexible pipe. Although carbon fibre is superior in strength, it is believed that glass fibre also possesses a comparable strength. Since composite materials have excellent strength to weight ratio and high corrosion resistance, they are implemented in several flexible pipeline designs, which are called composite pipelines.

Table 2. Mechanical properties of thermosetting resins [17].

Resin	Mechanical integrity	Toxicity in fire	Cost
Polyester	*****	*	***
Vinyl ester	*******	*	******
Epoxy	*********	*	*********
Phenolic	*****	****	****
Mod Acrylic	****	******	****

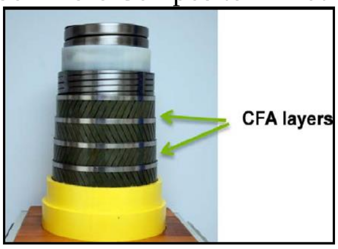
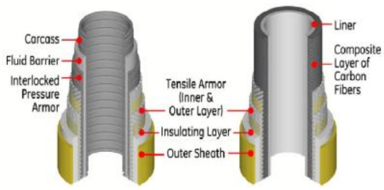
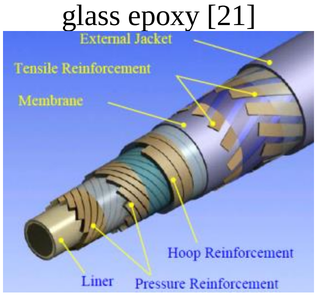
Table 3. Mechanical properties of reinforcement fibres [19].

Fibre	E glass	Aramid	Carbon
Specific Gravity	2.54	1.44	1.56
Ultimate Tensile Strength (MPa)	1550	1379	1600
Young’s Modulus (GPa)	72.4	62.05	125

Table 4. Qualitative comparison between reinforced polymers [20].

Criterion	Carbon	Aramid	E-Glass
Tensile strength	Very good	Very good	Very good
Compressive strength	Very good	Inadequate	Good
Modulus of elasticity	Very good	Good	Adequate
Long term behaviour	Very good	Good	Adequate
Fatigue behaviour	Excellent	Good	Adequate
Bulk density	Good	Excellent	Adequate
Alkaline resistance	Very good	Good	Inadequate
Price	Adequate	Adequate	Very good

Table 5. Composite pipeline designs.

Pipe design	Description
Carbon Fibre Composite Armour [3]  	• The steel armour layers are replaced with Carbon Fibre Armour layers (CFA) for weight reduction. • The weight of an 11 inch CFA pipe was compared at a 2500-meter water depth. • Weight comparison shows a reduction of 50 – 55%.
Flexible pipe using carbon fibre armour [6] 	• A 20-inch flexible pipe where the steel armour layers are replaced with composite armours using carbon fibre (CFA). • Weight comparison between the CFA pipe and the conventional 20-inch flexible pipe shows a reduction of 30 – 34%.
Flexible fibre reinforced pipe using carbon fibre [4]  	• The carcass and the hoop layer are combined into a single composite layer of carbon fibres. Weight comparison with a conventional flexible pipe shows a 30 – 35% weight reduction.
Unbonded flexible pipe employing glass epoxy [21]  	• The steel armour layers are replaced with glass epoxy composite • Each layer of reinforcement is made of multi-start stacks of specially made pre-cured unidirectional composite tapes. • Weight comparison with a conventional flexible pipe was mentioned to be roughly 50% reduction.

The significant weight of the steel armour for deepwater installations and the threat of corrosion have prompted the development of several designs employing composite materials. A few designs of composite pipelines are detailed in Table 5. From Table 5, it can be deduced that the weight reduction gained from employing composite armours are roughly around 30 to 50 %. This reduction allows several advantages in pipeline installation. Arbey et al. [22] stated that the usage of lighter material for pipelines, specifically composite material, enables an increase of the maximum achievable water depth. This was calculated for different laying capacities, ranging from 400 tons to 1000 tons, as shown in Figure 2. However, care should be taken as too much reduction in weight could also cause complications, such as the stability of the pipe on the seabed. In such situation, additional weight, such as concrete covers are required. It is worth noting that, despite the advantages outlined, the issue in using composites are clearly identified in two areas which are the long term behaviour and the availability of trusted inspection methods [23]. The use of composites is further discouraged through the absence of a standard qualification process for composite pipelines. This matter however was studied by Kalman, Yu, & Durr [24] which provided an extensive qualification process as well as a roadmap. Regarding the weight issues as well as the advantages of composite materials, a new design of flexible pipeline which adopts a woven configuration is developed. Details of the design can be found in the next section.

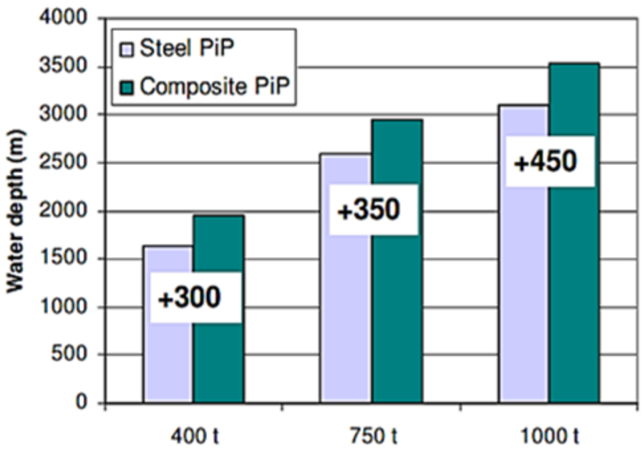


Figure 2. Pipe laying capacity [22].

METHODS AND MATERIALS

In this paper, a comparison stress analysis between the woven flexible pipe and a commercial flexible pipe, a reinforced thermoplastic pipe (RTP), is carried out by using ANSYS to study the performance of the woven flexible pipe. The flow of work involves the modelling of both pipes and the input of analysis parameters is shown in Figure 3. This RTP was selected owing to the fact that an existing stress analysis was conducted by [25] using the same model by Soluforce. Therefore, the loadings used for the numerical analysis will be identical to that of the existing study for verification purposes. The inner diameter will also be identical to the existing study as shown in Table 6 and Figure 4. The design details for the woven flexible pipe and RTP are explained later.

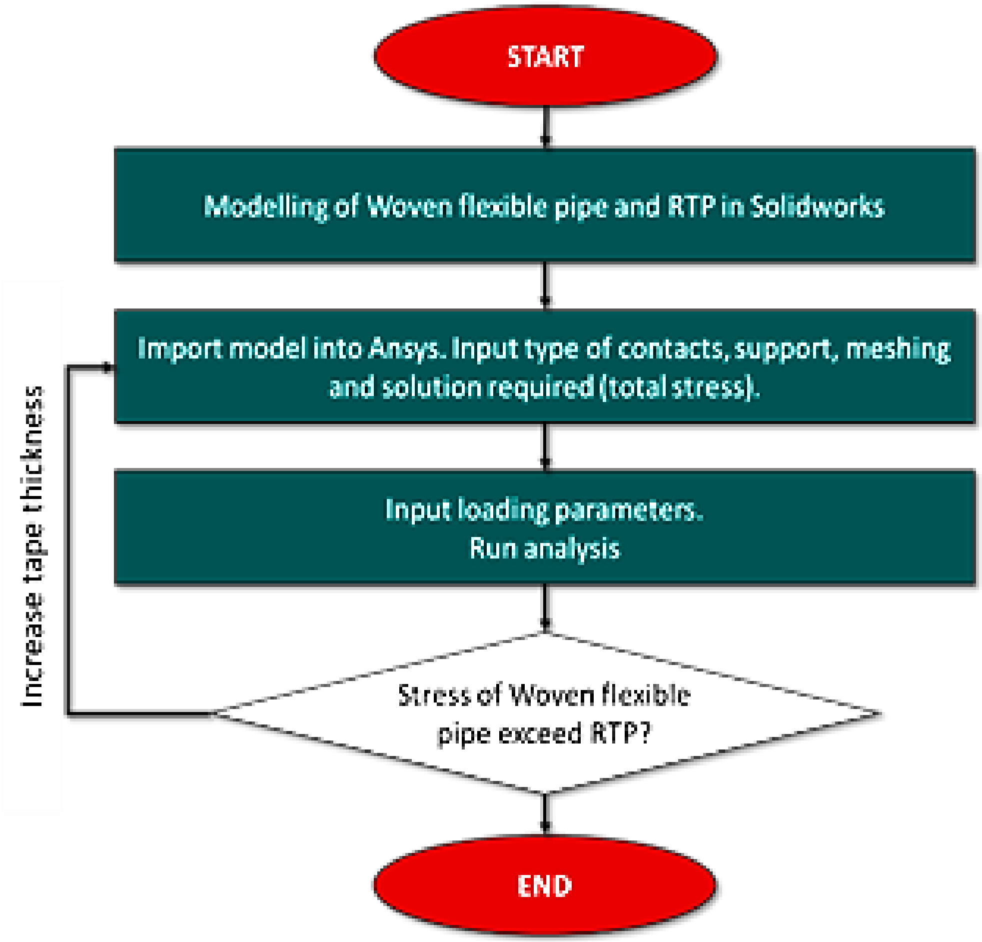


Figure 3. Flow of analysis.

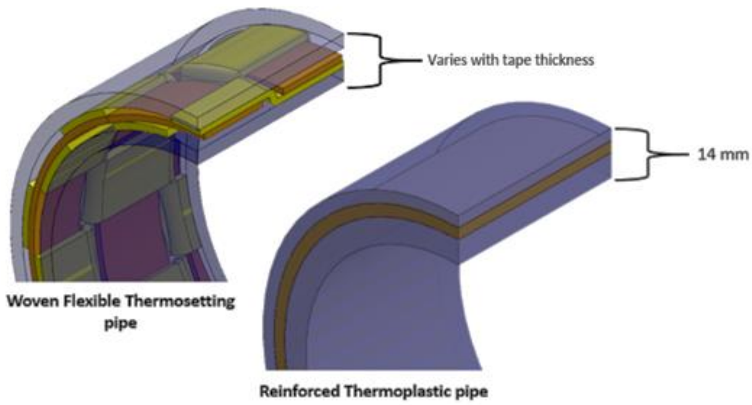


Figure 4. Wall thickness of woven flexible pipe and RTP.

Table 6. Thickness and diameter of pipes.

Pipe	Thickness	Internal Diameter
Woven flexible pipe	14 mm	100 mm (4 inch)
RTP	Varies with tape thickness	

Woven Flexible Pipe Configuration

The new composite flexible pipe is developed by using composite material, namely glass epoxy, which adopts a woven configuration to combine the armour layers into a single layer. The woven layer consists of unidirectional glass epoxy tape stacks which are in the axial direction and hoop direction. The near-hoop thermosetting tapes resist the internal and external pressure loadings while the near-axial thermosetting tapes resist the axial loads. If required, additional woven layers may be added to provide more strength for the pipe. However, given the conditions of the deepwater environment, the woven configuration of thermosetting tapes is yet to be tested under high pressure externally and internally. Thus, the need of a numerical analysis and experimental test for verification purposes. In this paper, only one layer of the woven flexible pipe will be analysed. The woven flexible pipe considered for analysis comprises three major elements, namely the hoop armour, the tensile armour and the polymer sheaths. Details of the design parameters are shown in Table 7 and Figure 5.

Table 7. Design parameters of the woven flexible pipe.

Layers	Width (mm)	Thickness (mm)	Material
Longitudinal tape	20	2 – 10	Glass epoxy
Hoop tape	20	2 – 10	
Internal sheath	100 (ID)	7	Polyethylene
External sheath	-	3.5	

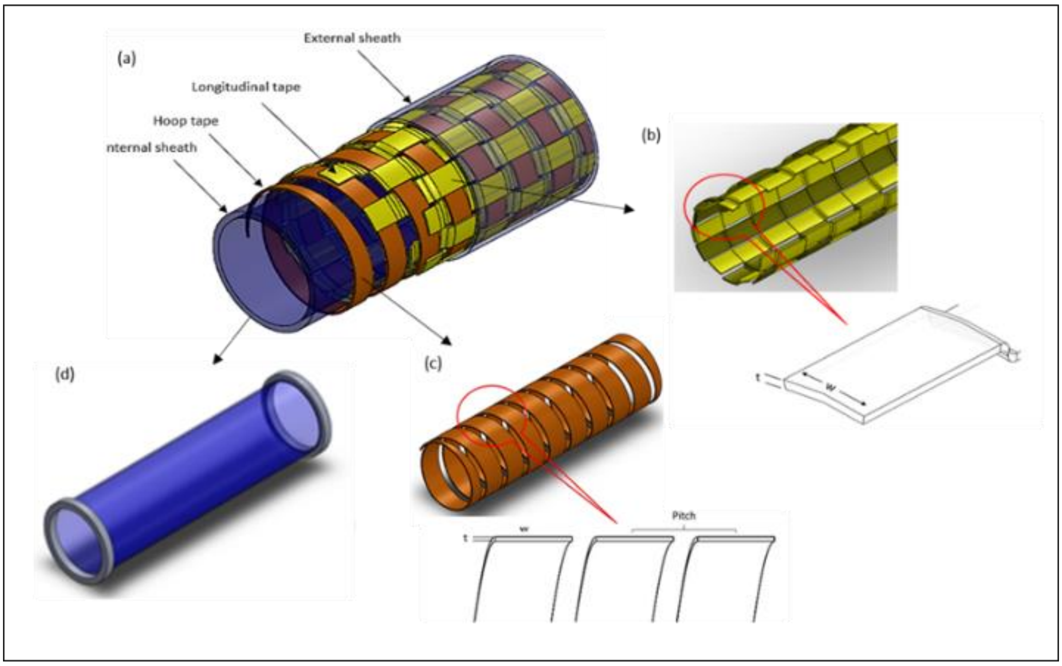


Figure 5: (a) Single layer woven flexible pipe (b) Longitudinal tape (c) Hoop tape (d) Polymer sheath

Soluforce Reinforced Thermoplastic Pipe

The RTP considered for comparison is a product by Soluforce, specifically the Soluforce M480 HPG. It is a three-layer bonded pipe consisting of a layer of aramid fibres sandwiched between two polymer layers. The design of the RTP is depicted in Figure 6.

Similar to the typical flexible pipe, the inner and outer polymer layers act as a barrier to prevent seawater from reaching to the fibre layer. The synthetic fibre tape, which in this case is the aramid fibre, functions as a reinforcement layer for the RTP. The mechanical properties and design parameters used are referred to a stress-strain analysis carried out by Reutov [25] by using the same RTP to verify the results obtained. The mechanical properties and design parameters are shown in Table 8. The loadings applied to both models are identical to the ones used by Reutov [25], which is an internal pressure of 6 MPa, to verify the results. Normally, a comparison in performance is made by comparing the burst strength of pipes with reference to the ultimate tensile stress. However, since the ultimate tensile strength of the material used in the RTP was not given, it is difficult to predict the burst pressure of the RTP other than the maximum operating pressure provided by Soluforce. Therefore, the comparison was made with reference to the stress experience.

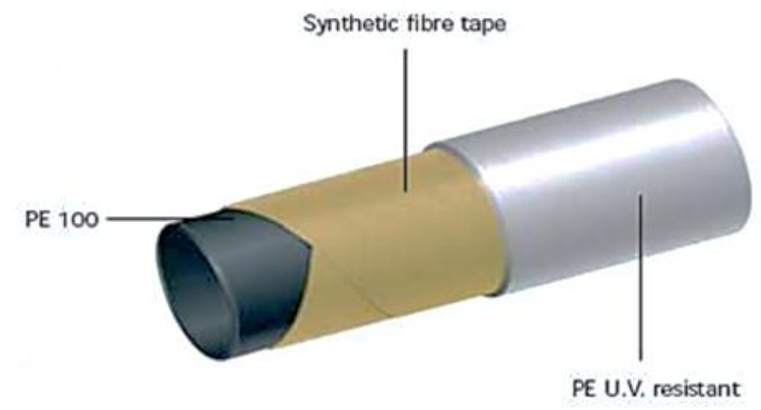


Figure 6. Reinforced Thermoplastic Pipe [25].

Table 8. Properties of Soluforce RTP [25].

Pipe name	Soluforce M480 HPG		
Inner diameter, mm		100	
Outer diameter, mm		128	
Layer	Inner	Middle	Outer
Layer thickness, mm	7	3.5	3.5
Layer material	PE 100	Aramid Fibre	PE 100
Young's modulus MPa	1300	10000	1300
Poisson Ratio	0.43	0.3	0.43
Density g/m^3	954	1440	954
Thermal Conductivity coefficient, W/(m.K)	0.38	0.04	0.38
Specific thermal capacity, J/(kg.K)	1900	1420	1900
Linear expansion coefficient, K^{-1}	1.3(10)$^{-4}$	4(10)$^{-6}$	1.3(10)$^{-4}$

RESULTS AND DISCUSSION

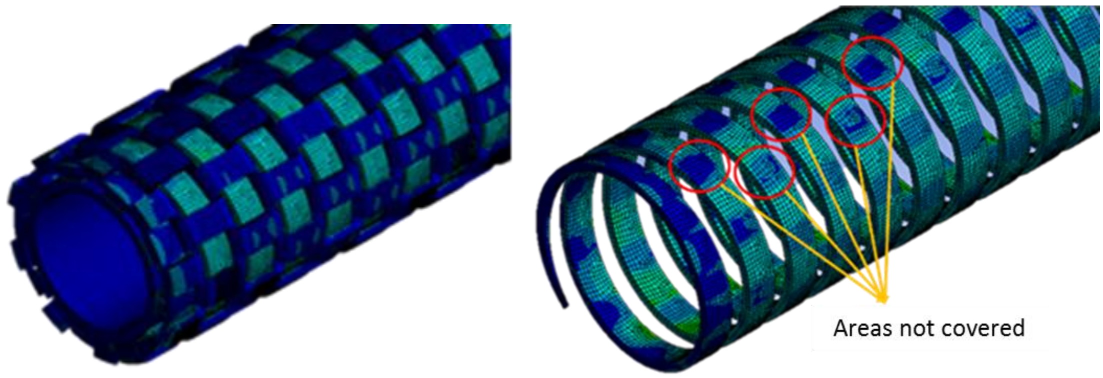
Based on the parameters mentioned, the following results, as shown in Table 9, are obtained. From the results, at 6 MPa, the woven flexible pipe is able to withstand the load when the tape thickness is more than 6 mm. This is determined based on the ultimate tensile strength of glass epoxy obtained from tensile tests, which is at 266 MPa. However, under the same pressure loading, the RTP experiences stress at approximately half of the RTP by using tape thickness of 10 mm. Although the ultimate material strength of the RTP is not mentioned, it is stated by SoluForce that the Soluforce RTP is able to withstand pressure of up to 113 bar. Therefore, it is assumed that at 6 MPa, the RTP is experiencing 53% of the maximum stress.

Table 9. Stress analysis result.

Tape thickness (mm)	2	4	6	8	10	RTP
Maximum stress (MPa)	419.2	309.6	265.3	213.6	132.3	65.09

* Note that the table is the result of the analysis of one layer as shown in figure 5.

In addition to that, it can be seen based on the stress experienced by the model, the RTP performs better under the same pressure loading. The lower stress is attributed to the material properties of the composite aramid fibre and HDPE where the elastic modulus is lower compared to glass epoxy, thus allowing more deformation at lower stresses. Furthermore, although the interlocking mechanism of the woven configuration is expected to improve the overall strength of the pipe, the simulation suggests that the numerous contacts between the hoop and tensile tapes have caused a higher stress between the contact surfaces. This can be seen in Figure 7 where higher stress occurs between the contact surfaces compared to the free surface. The reason for this behaviour is due to the friction between these surfaces where higher normal loads result in higher friction and wearing. This was demonstrated in a study by [26], where the relation of friction and normal loads are shown in Figure 9.



(a) woven flexible pipe (b) hoop tape

Figure 7. Stress distribution on woven flexible pipe and hoop tape.

The optimisation of the thickness of the tapes for the woven flexible pipe depends on the required operating pressure. The optimisation of tape thickness is defined as the lowest thickness of tape required to withstand the operating pressure, which in this case is 6 MPa. Therefore, based on the loading applied, the tape thickness is optimised at a thickness of 6 mm as the ultimate tensile strength of the material is at 266 MPa. However, the validity of the results is still in question due to the absence of experimental data and other numerical analysis which have similar configuration and application as the woven flexible pipe to validate with (Figure 9). Therefore, at best, the result provided in this paper can be considered as an estimation of the performance of the woven flexible pipe for future experimental tests.

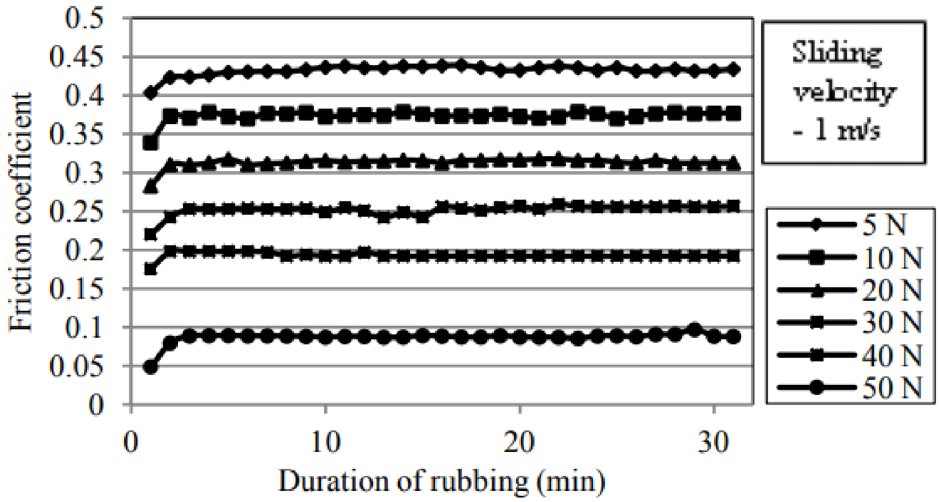


Figure 8. Stress distribution on hoop tape [27].

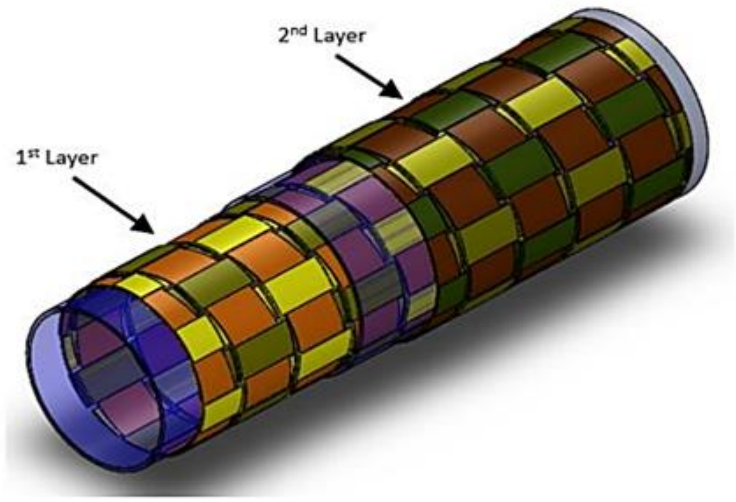


Figure 9. Multilayer woven flexible pipe.

CONCLUSIONS

A comparison has been made between the performance of the woven flexible pipe and the RTP in terms of the stress experienced from the same internal pressure loading. In terms of stress experienced, the woven flexible pipe experiences 50.8% higher stress than the RTP. However, in terms of burst strength, the RTP is able to withstand pressure up to 113 bar. On the other hand, the woven flexible pipe can withstand a pressure of 6 MPa by using thermosetting tapes of 6 mm thick. Therefore, at 6 MPa, the thickness of the thermosetting tapes is optimised at 6 mm thickness. The numerical results however still require validation from experimental tests and thus can only serve as an estimation on the performance of the woven flexible pipe. The success of this research would deem the design of the pipe to be suitable as a corrosion resistant pipe for deepwater applications.

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