

Numerical Comparison between Single Layer Woven Flexible Pipe and Reinforced Thermoplastic Pipe

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Paper History

Received: 25-September-2016

Received in revised form: 30-October-2016

Accepted: 7-November-2016

ABSTRACT

The weight of a conventional flexible pipe poses a major challenge for installations when reaching significant water depths which makes composite material an ideal alternative for steel in the armor layers. In light of this matter, a woven configuration was developed for the armor layer utilizing glass epoxy, namely the woven flexible pipe. However, the performance of the woven flexible pipe in deep water conditions are unknown, thus the need of 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 show higher stress experienced by the woven flexible pipe compared to the reinforced thermoplastic pipe. It is hoped that the results of this research will contribute to future studies of flexible pipelines.

KEY WORDS: *Woven flexible pipe; Composite material; Numerical analysis*

1.0 SUBTITLE

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. Furthermore, the ability of each layer to move over each other

improves the overall flexibility of the pipe.

However, as the amount of hydrocarbons 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 as there is a significant amount of hydrostatic pressure thus requiring thicker layers. In addition to that, beyond 2000 meters of water depth, the weight of a conventional flexible pipe becomes critical not only for the pipe laying equipment and vessel, but also for the production floaters [1]. The reason is caused primarily by the weight of the armor layers which are formed by helically wound metal strips to withstand internal and external pressure. Nevertheless, despite providing excellent strength, the usage of steel could also potentially lead to failure due to corrosion. The armor layer, located in the annulus area, is never in contact with seawater as it is protected by a thermoplastic layer, the external sheath. Internally, the pipe is covered by an internal sheath to contain the flow of hydrocarbons. However, corrosive gas such as carbon dioxide (CO₂) and hydrogen sulfide (H₂S) can still permeate through the internal sheath into the annulus area. 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.

In light of this matter, extensive research has been made in replacing the steel armor layer with composite materials which proves to be lighter and has more resistance towards corrosion, thus, a new non-metallic flexible pipe was developed which employs glass epoxy tapes and a woven configuration, combining the armor layers into a single layer. However, given the high pressure conditions of deep water 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, a numerical comparison was performed for the woven flexible pipe with a typical bonded flexible pipe called the thermoplastic reinforced pipe to compare their strength under internal pressure where only one layer of the woven flexible pipe

is considered. The objective is to study the performance of the woven flexible pipe using varying thickness.

2.0 LITERATURE REVIEW

2.1 Flexible Pipeline

A typical unbonded flexible pipe consists of several layers where each layer serves a specific function. The key layers as well as its function are shown in Figure 1 and Table 1.

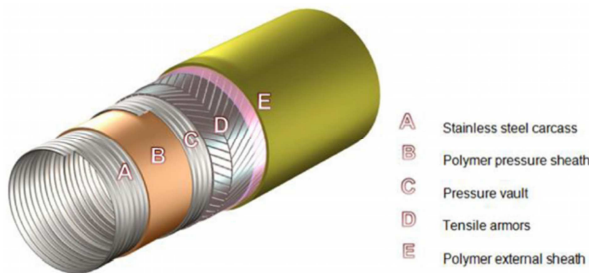


Figure 1: Typical flexible pipe construction with main layers [2].

Table 1: Key layers and functions of unbonded flexible pipe

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

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 continuously sustainable temperature of 130°C and above [2]. Other layers are also applied when needed such as anti-wear tape between the layers, and aramid fibers which is wrapped around the armor layers to prevent birdcaging. The challenge however lies in the weight of the pipe where the self-weight of the pipe becomes the limiting issue [3]. This is mediated through the use of buoyancy modules to compensate to some extent the submerged weight of the offloading line [4] and utilizing different laying methods.

Although it helps to lessen the load of the pipe, unfortunately deploying buoyancy modules also increases the overall installation costs [5]. Furthermore, as exploration moves to deepwater, the collapse loads becomes simply too high thus pushing the designs using current material technologies to their limits. In view of the weight issues, different methods are sought for weight reduction such as replacing with lighter materials.

2.2 Composite Material

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, [6] simplifies 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 [7].

In terms of reinforcement, carbon fiber and glass fiber are usually chosen due to their strength. There are also cases where aramid fiber is used. Table 2 shows the generalization of their mechanical property as well as cost and toxicity in fire [6], while Table 3 shows a comparison of fiber strength provided by [8]. 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 fibers [9].

Table 2: Mechanical properties of thermosetting resins

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

Table 3: Mechanical properties of reinforcement fibers

Fiber	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



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 behavior	Very good	Good	Adequate
Fatigue behavior	Excellent	Good	Adequate
Bulk density	Good	Excellent	Adequate
Alkaline resistance	Very good	Good	Inadequate
Price	Adequate	Adequate	Very good

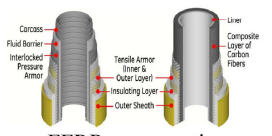
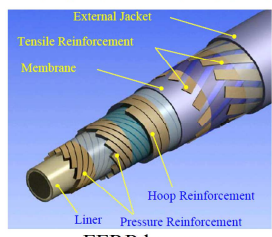
Based on the material properties shown, the matrix and reinforcement fiber chosen are epoxy and glass fiber respectively for the development of the woven flexible pipe. Although carbon fiber is superior, it is believed that glass fiber also possesses comparable strength. Due to the fact that composite materials have excellent strength to weight ratio as well as high corrosion resistance, it has been implemented in several flexible pipeline designs which are called composite pipelines.

2.1 Composite Pipeline

The significant weight of the steel armor poses a challenge in the installation of pipeline which has prompted the development of several designs employing composite materials. A few designs of composite pipelines are detailed in Table 5.

Table 5: Composite pipeline designs

Pipe design	Description
<p>Carbon Fiber Composite Armor [1]</p>  <p>Configuration of CFA.</p>	<ul style="list-style-type: none"> The steel armor layers are replaced with Carbon Fiber Armor 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%.
<p>Flexible pipe using carbon fiber armor [4]</p>  <p>20 inch CFA flexible pipe.</p>	<ul style="list-style-type: none"> A 20-inch flexible pipe where the steel armor layers are replaced with composite armors using carbon fiber (CFA). Weight comparison between the CFA pipe and the conventional 20-inch flexible pipe shows a reduction of 30 – 34%.

<p>Flexible fiber reinforced pipe using carbon fiber [10]</p>  <p>FFRP cross section.</p>	<ul style="list-style-type: none"> The carcass and the hoop layer are combined into a single composite layer of carbon fibers. Weight comparison with a conventional flexible pipe shows a 30 – 35% weight reduction.
<p>Unbonded flexible pipe employing glass epoxy [11]</p>  <p>FFRP layers</p>	<ul style="list-style-type: none"> The steel armor 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.

From Table 5, it can be deduced that the weight reduction gained from employing composite armors are roughly around 30 to 50 %. This reduction allows several advantages in pipeline installation. [12] 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.

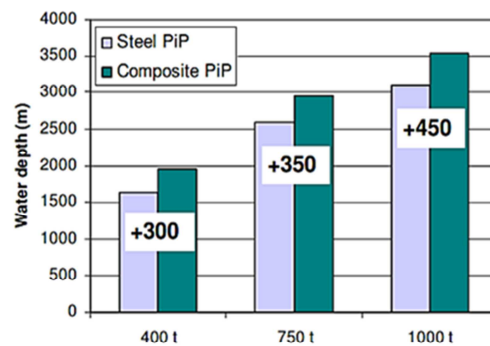


Figure 2: Pipe laying capacity [12]

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 behavior and the availability of trusted inspection methods [13]. The use of composites is further discouraged through the absence of a standard qualification process for composite pipelines. This matter however was studied by [14] which provided an extensive qualification process as well as a roadmap.

With reference to the weight issues as well as the advantages of composite materials, a new design of flexible pipeline was developed which adopts a woven configuration. Details of the design can be found in section 3.

3.0 METHODOLOGY

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 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 as shown in Figure 3.

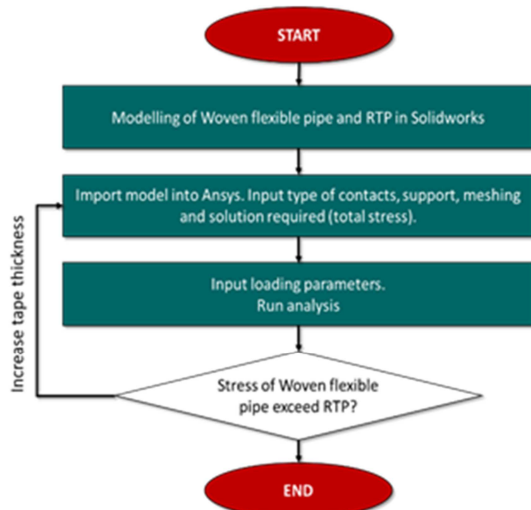


Figure 3: Flow of analysis

This RTP was selected owing to the fact that an existing stress analysis was conducted by [15] 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.

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	

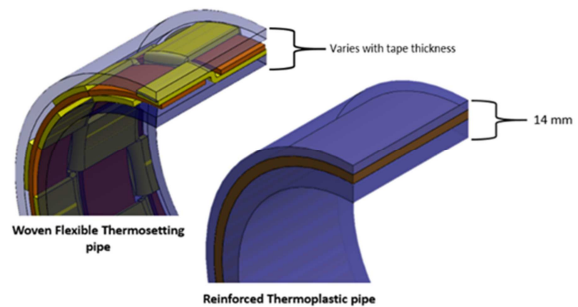


Figure 4: Wall thickness of woven flexible pipe and RTP

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3.1 Woven Flexible Pipe Configuration

The new composite flexible pipe is developed using composite material, namely glass epoxy, which adopts a woven configuration to combine the armor 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 resists the internal and external pressure loadings while the near-axial thermosetting tapes resists the axial loads. If required, additional woven layers may be added to provide more strength for the pipe.

However, given the conditions of the deep water 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 analyzed. The woven flexible pipe considered for analysis comprises three major elements namely the hoop armor, the tensile armor 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	

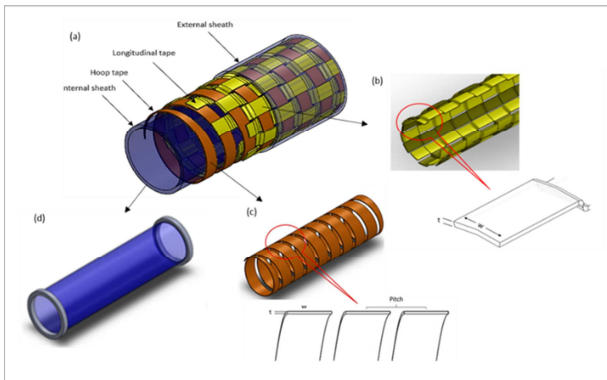


Figure 5: (a) Single layer woven flexible pipe (b) Longitudinal tape (c) Hoop tape (d) Polymer sheath

3.2 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 fibers sandwiched between two polymer layers. The design of the RTP is depicted in Figure 6.

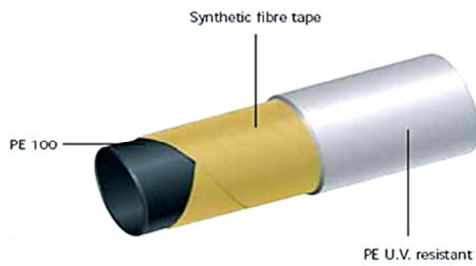


Figure 6: Reinforced Thermoplastic Pipe [15]

Similar to the typical flexible pipe, the inner and outer polymer layer act as a barrier to prevent seawater from reaching to the fiber layer. The synthetic fibre tape, which in this case is the aramid fiber, 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 [15] using the same RTP to verify the results obtained. The mechanical properties and design parameters are shown in Table 8.

Table 8: Properties of Soluforce RTP

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 Fiber	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

3.3 Soluforce Reinforced Thermoplastic Pipe

The loadings applied to both models are identical to the ones used by [15] to verify the results. An internal pressure of 6 MPa is applied to the internal sheath of the models.

4.0 RESULTS AND DISCUSSION

Based on the parameters mentioned, the following results, shown in Table 9, are obtained.

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.

From the results, it can be seen that both models did not exceed their materials' capacity. However, clearly the RTP performs better than the woven flexible pipe as it experiences less stress. This result could be due to the difference in the material used, specifically for the reinforcement layer. Another explanation would be the amount of contacts present in the woven flexible pipe. The nature of the woven configuration results in a large amount of contact areas, especially between the tensile tapes and hoop tapes. As pressure is applied, friction could be produced in these areas although this is yet to be conclusive.

Based on the stress distribution on the tensile and hoop armor, it can be deduced that the behavior of the woven pipe, shown in Figure 7, is within expectations. The blue color designates the area with low stress while lighter colors that are approaching red are areas with higher stress. It can be seen that the hoop armor experiences more stress than the tensile armor. This is because the internal pressure is mostly resisted by the hoop armor. On the other hand, the area of the hoop tape covered by the tensile armor experiences less stress as shown in Figure 8.

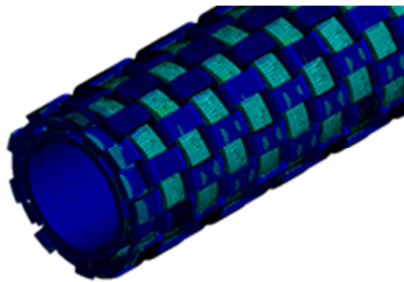


Figure 7: Stress distribution on woven flexible pipe

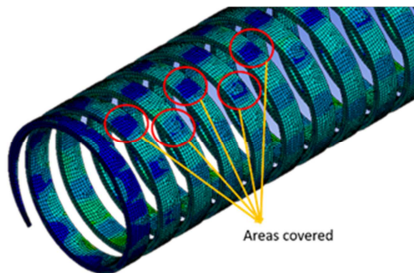


Figure 8: Stress distribution on hoop tape

The condition is resulted from the woven configuration where the tensile armor also contributes in resisting the internal pressure. In addition to that, the woven flexible pipe shows improvement as the thickness of the tapes increases which is expected. The performance can be seen graphically shown in Figure 9. The trend of the graph suggests that an increasing the tape thickness could further strengthen the woven flexible pipe. As mentioned earlier, the analysis covers only one layer of the woven flexible pipe. Thus, as part of future study, a different approach would be to increase the number of layers to strengthen the pipe as shown in Figure 10. This method is not uncommon as it is usually employed for the conventional flexible pipes when more strength is required.

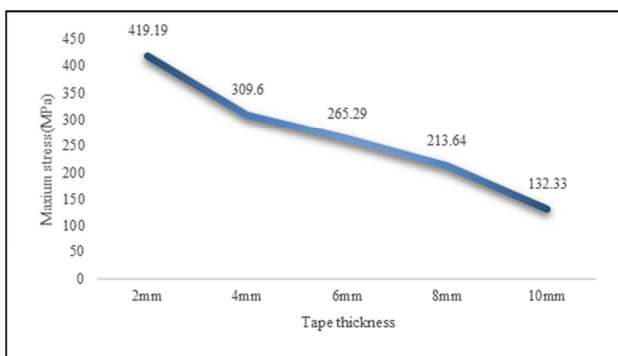


Figure 9: Graph of stress vs tape thickness

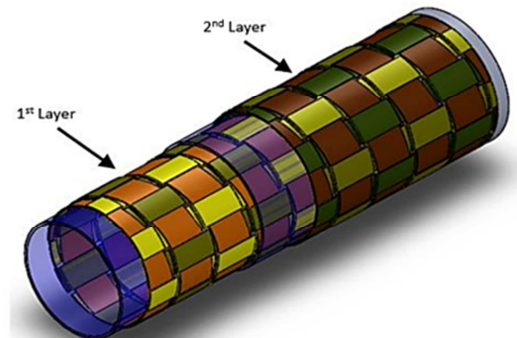


Figure 10: Multilayer woven flexible pipe

5.0 CONCLUSION

Currently the commercial flexible pipe, the thermoplastic reinforced pipe (RTP) performs better than the woven flexible pipe with a margin of 49 %. The results also suggest that friction could be part of the issue as well as the difference in material used, specifically the material used for the reinforcement layer. In order to increase the strength of the woven flexible pipe, the thickness of the tape could be increased, as depicted in figure 9, or additional layers can be added. Regardless, the results are yet to be conclusive as further analysis is required. Future studies will include the optimization of tape thickness and the number of layers of the woven flexible pipe.

ACKNOWLEDGEMENTS

This research was supported by the Technology Innovation Program (Grant No.: 10053121) funded by the Ministry of Trade, Industry & Energy (MI, Korea) and Energy Efficiency & Resource of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (Grant No.: 2014301002-1870). The authors would also like to thank for the great support of POSTECH, POSCO, and Daewoo E&C, Republic of Korea.

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