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Quasi-Static Indentation of Reinforced Thermoplastic Pipe (RTP)

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Abstract: Reinforced Thermoplastic Pipe (RTP) is a type of flexible composite pipe that extensively being used in Oil & Gas Industry, it possesses a huge potential as a replacement of commercial carbon steel pipe, especially in high corrosive environment. However, the commercial design of RTP does not consider the effect of lateral load from external interference. In the quasi-static indentation test conducted, the maximum local deformation recorded is 62.5 mm at lateral load of 16.1 kN. However, the effect of elastic rebound reduced 92% of the maximum deformation to produce a permanent dent of 5 mm, it can be hypothesized that a dent in RTP might not represent the actual degradation of RTP. This paper discussed the procedure, response and degradation of RTP when subjected to lateral compressive load in a Quasi-static environment.

Keywords: RTP, Quasi-Static, indentation, dent, thermoplastic, aramid fiber, polyethylene

1. Introduction

Reinforced Thermoplastic Pipe (RTP) was introduced by Tubes d'Aquitaine in France in early 1990's (Career, 2008), the main intention is to develop a highly sustainable pipe in for a corrosive environment, especially in the onshore of middle east field (Olabisi, Fallatah, Somali, & Badghaish, 2003). Now, the application is rapidly moving into offshore application and deep water. It is reported that, in 2008 more than fifteen million feet of RTP has been installed in North America (Conley, Weller, & Slingerland, 2008). It has been used for offshore oil gathering process, water injection pipe and gas transfer line from a depth range of 30 m to 900 m and a pressure rating up to 27 MPa with temperature up to 65 °C (Bai, Xu, Cheng, Wang, & Ruan, 2013). RTP is a type of flexible composite pipe, it is a result of evolving Polyethylene Pipe (PE) and in most cases made up of nonmetallic material. It consists of three major layers known as inner liner, reinforcement layer and outer cover as shown in Fig. 1. The inner liner and outer cover are extruded from Polyethylene (PE100 and PE80), while the reinforcement layer is constructed from high strength fiber such as carbon fiber, glass fiber or aramid fiber(commercially known as Kevlar)(Conley et al., 2008). This high strength fiber is helically wrapped around the liner of RTP at angle of approximately ± 54° (Bai et al., 2013; Conley et al., 2008; Kruijer, Warnet, & Akkerman, 2005) and embedded in thermoplastic matrix, the winding angle is designed in such a way that it will provide a high tensile stiffness and strength in the pipe. However, the reinforcement will not enhance the capability of RTP in resisting external pressure such as hydrostatic pressure (Bai, Tang, Xu, Cao, & Wang, 2015).

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Pipeline is an important asset in the oil and gas industry. It possesses an explosive character,that make it crucial to have a proper structural integrity assessment. In pipeline failure cases, most of it is due to external interference or known as third party intrusion. The problem occurs for both, onshore and offshore applications. A report from European Gas Pipeline Incident Data Group (EGIG) in 2015 (EGIS, 2013) shows that 35% of gas pipeline failure in Europe from 2004 to 2013 is caused by external interference, it represents the highest percentage of pipeline failure in the chart, details as shown in Fig. 2. The external interference in onshore pipelines is usually from contact with excavator, graders, ditchers, plows or any other machineries. While in offshore application, the external interference usually come from ship anchor, ship kneel, or impact from trawling board in fishing activities (Rezaee, Sharifi, Rashed, & Niknejad, 2018), the details on types of external hazard for offshore pipelines can be referred from Table 1 (Det Norske Veritas, 2010a). The damages caused by the external interference can be in form of dents, gouge or a scratch, the recommended methods to assess the burst strength of defected pipeline can be refer to (A. Cosham, Hopkins, & Macdonald, 2007).

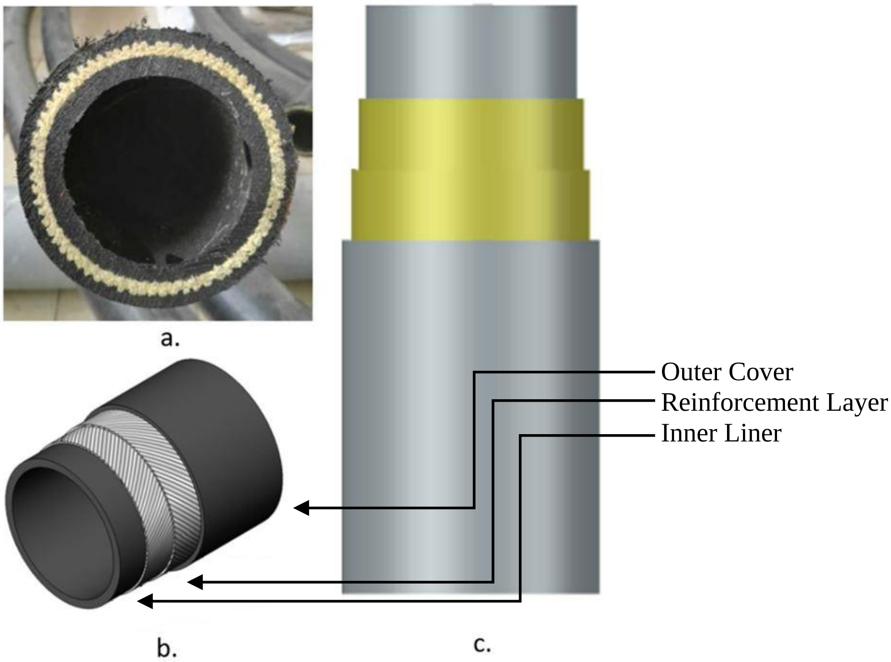


Fig. 1 - RTP configuration (a) cross-section of RTP; (b) isometric view of RTP; (c) side view of RTP.

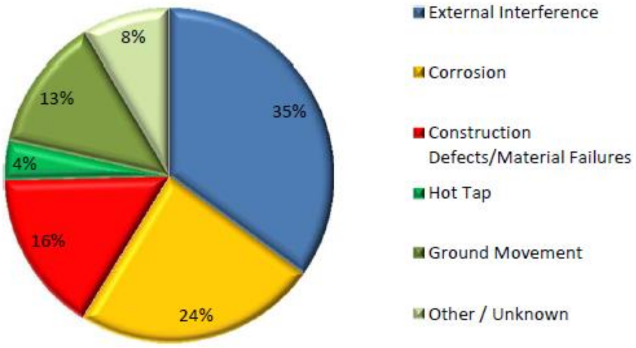


Fig. 2 - Pipeline Failure Incident (2004-2013) (EGIS, 2013).

Table 1 - Summary of hazards for pipelines based on activity conducted (VERITAS, OCT 2010)

Activity	Hazard
Pipeline Installation	Dropped and dragged anchor/anchor chain from pipe lay vessel Vessel collision during laying leading to dropped object, etc Damage during trenching, gravel dumping, installation of protection cover, etc. Damage during crossing construction.
Installation of risers	Dropped objects Dropped Anchor Chain
Anchor handling (Rig and lay vessel operations)	Dropped anchor, breakage of anchor chain, etc. Dragged anchor Dragged anchor chain
Subsea operations (simultaneous operations)	ROV impact Manoeuvring failure during equipment installation/removal
Trawling activities	Trawl board impact, pull-over or hooking
Tanker, supply vessel and commercial ship traffic	Collision (either powered or drifting) Emergency anchoring Sunken ship (e.g. after collision with platform or other ships)

A dent in pipeline as shown in Fig. 3 is defined as a permanent plastic deformation of the circular cross section of a pipe. It is a gross distortion of the pipe cross-section as a result when pipeline is in contact with foreign object (Rezaee et al., 2018; Allouti, Schmitt, Pluvinage, Gilgert, & Hariri, 2012). With regards of any factors that contribute to the dent defect, the severity of the dent is measured based on the dent depth (H) (applicable to steel-based pipeline), it is defined as the maximum reduction of the pipe diameter compared to its actual diameter. In a typical pipeline dent, H represents dent depth, D represents pipeline actual diameter and t represents pipeline wall thickness (Allouti et al., 2012; Macdonald, Cosham, Alexander, & Hopkins, 2007; Yu, Zhao, Li, & Yu, 2016).

It is speculated that, the dent of RTP might not produce a typical indentation as a steel pipe specimen. RTP is a non-homogeneous pipe with thermoplastic as its major components, and the reinforcement layer is having an anisotropic property. A dent in RTP will not fully represent the structural degradation of RTP under indentation load.

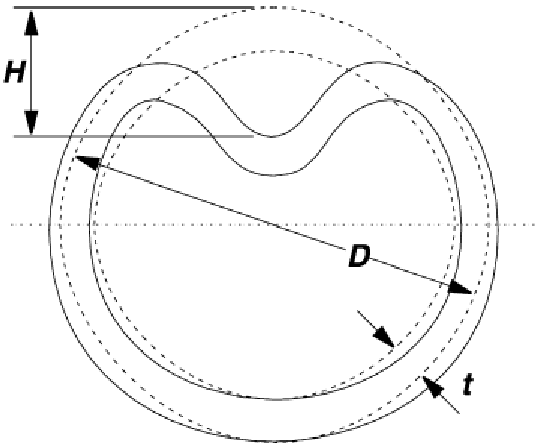


Fig. 3 -Typical dent after quasi-static indentation for steel pipe specimens (Andrew Cosham & Hopkins, 2004)

2. Quasi-static Indentation

Quasi-static indentation is a generic name for the process to create a dent on specimens, it involves with process of applying a constant lateral load on specimens in quasi-static environment. Quasi-static indentation is usually used to model a Low Velocity Impact (LVI) testing in a static load condition, although there are lots of arguments in this modelling method, but quasi-static indentation test always provide more detail information as compared to LVI test. The quasi-static indentation has been used years ago on various types of specimens (i.e. steel pipes, composite plate) to study the structural response and structural degradation of the specimens under lateral load, a standard on quasi-static

Indentation of fiber reinforced polymer composite has been published by ASTM to guide the process of indentation on fiber reinforced polymer matrix composite (ASTM, 2017).

Under steel pipes specimens, several researches have been conducted by few groups of researchers(Allouti et al., 2012; Brooker, 2004; Firouzsalari & Showkati, 2013; Gresnigt, Karamanos, & Andreadakis, 2006; Han, Tan, Zhang, & Zhang, 2018; Karamanos & Andreadakis, 2006; Macdonald et al., 2007; Rezaee et al., 2018; Yu et al., 2016; Zeinoddini, Parke, & Harding, 2002) around the globe. Rezaee et al. (2018) conducted an experimental and numerical analyses, to investigate the influence of indenter geometries, internal pressure, pipeline geometries on the mechanical behavior of the pipeline (Rezaee et al., 2018). Brooker (2004) conduct a numerical study to investigate the impact of types of supports used in quasi-static indentation, he compared the numerical results with published papers previously and derived an equation to predict the permanent dent depth for a given indentation load. Besides, Karamanos & Andreadakis (2006) conduct a numerical research to investigate the effect of internally pressurized pipe specimens under lateral load, they suggested that the presence of internal pressure is significantly affecting the specimens denting resistance, this statement were also supported by Rezaee et al. (2018), and there are numerous amount of other research focusing on this particular testing method.

3. Indenter Profile

In the quasi-static indentation, an indenter is used in transferring the lateral load to the specimens. It is usually made up from hardened solid steel. The profile of indenter is one of the important aspects in quasi-static indentation. There are several researchers who compared the indenter profiles and its significance on the dent formed. In a research conducted by Rezaee et al. (2018), they used a cylindrical indenter with a conical nose as shown in Fig. 4. The cone apex angle (α), conical nose diameter (Ød_1), and diameter of the cylindrical part (Ød_2) were varied. The significance of each indenter parameter was determined in the test. Rezaee et al. (2018) concluded that, the α-angle will determine the penetrance of the indenter, as the angle decreased the penetrance will be increase and vice versa. On the other hand, increasing the conical nose diameter, will generally reduce the dent depth. Considered the same amount of lateral load is applied. Razaee et al. (2018) in the same article provided information on the indenter profile that being used in the previous study. The information is tabulated based on the years of study, in Table 2. The most typical type of indenter profile used is a wedge-shaped indenter, followed by hemispherical indenter.

Karamanos et al. (2006) used a wedge-shaped indenter to dent pressurized tubes specimens under lateral load. They conduct indentation works using a round and pointed wedge indenters as shown in Fig. 5. Firouzsalari & Showkati (2013) also used a wedge shaped indenter to investigate the free-spanned behavior pipeline behavior with regards to axial forces and local load on specimens. The similar shaped indenter were also used by Zeinoddini et al. (2002) when they tested the lateral impact of wedge-shaped indenter on axially pre-loaded steel tubes (Fig. 5).

In a recommended practice published by Det Norske Veritas (2010b), the preferable profile of indenter is in the form of rectangular plate of 300 mm height, 50 mm width, and with a round (25 mm) or sharp tip (10 mm) (Det Norske Veritas (2010b)). The indenter profiles are reflecting the shape of the trawl equipment that usually having a roundel frontal shape (Det Norske Veritas, 2010b), Fig. 6 illustrate the recommended indenter profile.

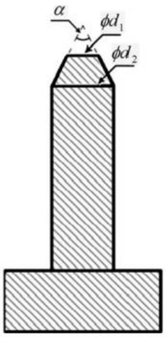
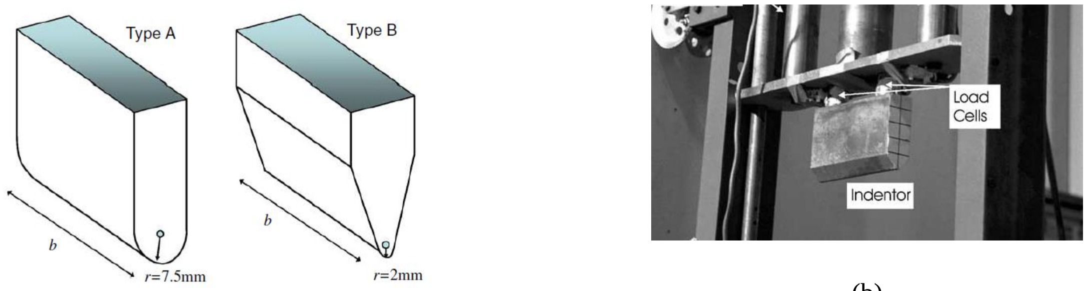


Fig. 4 - Cross Sectional View of Cylindrical Indenter with Conical Nose as used by Rezaee et al. (Rezaee et al., 2018)

Table 2 - Summary of indenter profile adapted and modified from Rezaee et al. (2018).

Year	Researcher	Indenter Profile
2018	Razaee et al.	Cylindrical with Cone Nose
2015	Ghaednia et al.	Rectangular
2014	Allouti et al.	Hemispherical
2013	Zeinoddini et al.	Wedge
2013	Niknejad and Javan	
2013	Firouzsalari and Showkati	
2010	Jones and Birch	
2006	Karamanos and Andreadakis	
2005	Hyde et al.	Hemispherical
2005	Iflefel et al.	
2004	Ruggieri and Ferrari	Tube shaped indenter
2004	Brooker	Knife edge
1976	Thomas et al.	Wedge



(a)

(b)

Fig. 5 - a. Type-A and Type-B wedge-shaped indenter used by Karamanos et al. (Karamanos & Andreadakis, 2006), b. Wedge shaped indenter used by Zeinoddini et al. (Zeinoddini et al., 2002)

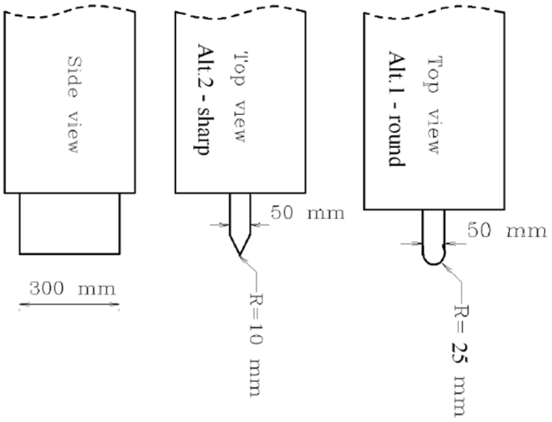


Fig. 6 -The indenter profile as suggested in DNV Recommended Practice (Det Norske Veritas, 2010b)

4. Quasi-static Load vs Dynamic Load

Quasi-static indentation is a process of applying a lateral load on the specimens slow enough such that an inertial effect can be ignored. This type of indention work is conducted by using a Universal Testing Machine (UTM). In contradictory to that, a dynamic load indentation or known as LVI is usually conducted to simulate the impact from a dropped object. The load is usually applied by dropping the indenter with some additional weight and the drop height might be added to increase the impact load. Razaee et al. (2018) conducted the indentation with quasi-static lateral load of 10 mm/min and simulate the same test numerically by using ABAQUS software. The load is varied to 0.001, 0.01 and 0.1 m/s. Gresnigt et al. (2006) also conducted a quasi-static indentation for investigating the lateral loading of internally pressurized steel pipes. The research was conducted experimentally and numerically. Zeinoddini et al. (2002) used a dynamic load in the indentation of axially pre-loaded steel tubes subjected to lateral impacts research. To vary the impact, the height and weight of indenter were varied. An impact tower of height 4.5 m was used to vary the impact height.

On the other hand, some other literature compared the result from both tests (Quasi-static and LVI) on several type of specimens (Bienias, 2013; Curtis, Hinton, Li, Reid, & Soden, 2000; Gning, Tarfaoui, Collombet, Riou, & Davies, 2005; Li et al., 2012). Curtis et al. (2000) compared both indentation methods on a filament-wound composite tubes. The quasi-static indentation was carried out by using an Instron 1195 UTM. The lateral load was applied at velocity of 10 mm/min, while in the LVI test, a Rosand IFW5 instrumented impact test machine were used. A similar indenter was used for both indentation methods. In the test conducted, both methods produced a similar physical appearance of dent. From the specimens burst test conducted, the burst pressure of both previously quasi-static indented and impacted specimens have a similar pattern of burst pressure (Curtis et al., 2000). Li et al. (2012) compared the quasi-static indentation and LVI of a foam core sandwich composites. They conclude that damage behavior of both tests from cross-sectional view show a similarity.

In addition, some other researchers prefer to use an actual object that usually cause damage towards pipe. Kawsar et al. (2015) for example studied the impact of dropped object on pipe by using probability and numerical analyses methods. Rectangular and spherical shapes of object were simulated. Numerical tests were conducted to simulate the impact energy produced and absorbed by the pipe. Yu et al. also used the same approach, but the test was conducted both experimentally and numerically. In the test, a ship anchor was dropped on pipe as shown in Fig. 7 and the pipe deformation was studied by using a three-dimensional numerical method, known as the local Galerkin discretization method for shell structures (Yu et al., 2016).

Fig. 7 Ship Anchor used by Yu et al. (2016) (Yu et al., 2016)

5. Experiment

5.1 Specimens

The specimens used in this research is a 110 mm (4 inch) RTP with wall thickness of 17.5 mm, each specimen having a length of approximately 1000 mm. It is designed to resist pressure 7.5 MPa with operating temperature up to 65 °C. The recommended operating condition is at 5 MPa with temperature of 50.8°-62°, the design life is for 15 years. The cover and liner of specimens is extruded from HDPE (PE 100). The reinforcement layer is made up of twisted impregnated polyaramid fiber embedded in a thermoplastic matrix (PE80). The fiber is helically wrapped at angle of ± 55.47^{o}. Details on pipe specimen is tabulated in Table 3, while Table 4 provides the reinforcement details.

Table 3 - RTP specimen specification.

Description	Unit	Value
Pipe ID	mm	75
Pipe OD	mm	110
Pipe WT	mm	17.5

Description	Unit	Value
Design Pressure	MPa	7.5
Design Temperature	℃	65
Hydrotest Pressure	MPa	11.3
Operating Pressure	MPa	5.0
Operating Temperature	℃	62 - 50.8
Design Life	years	15
MBR	m	1.34
Pipe Unit Weight in Air	kg/m	4.825
Pipe Submerged Weight (Flooded with Seawater)	kg/m	-0.338

Table 4 - Polyaramid fiber properties.

Material Properties	Value
Density	1.44 g/cm3
Specific Strength	>20 cN/dtex
Ultimate Breaking Strength	>5200 N
Elongation	>3.3%
Winding Angle	55.47º

5.2 Set-up and Procedure

i. Installation of Indenter: The indenter is fabricated prior to quasi-static indentation test. It is designed to fit the UTM cylinder piston by using six sets of 20 mm bolts and nuts. Fig. 8 shown the UTM used in the test.

ii. Installation of specimens: It is important to ensure that the specimen tested, safely secured its position during the test. For this, a pipe holder is fabricated. It is designed to allow any deformation of the specimen and at the same time keep the specimen in place during the test. The pipe holder is clammed to an I-Beam by using 2 pieces of G-Clamp.

iii. Applying lateral load: To create a quasi-static loading condition, the lateral load speed is set at rate of 10mm/min. It is the common speed used in most of quasi-static indentation work (Gresnigt et al., 2006; Rezaee et al., 2018). The indenter is slowly adjusted until it touches the surface of the specimen. Once everything is set, the load will be applied with the speed determined. The displacement and applied load will be recorded by using a data logger. Fig. 9 illustrates the process conducted.

iv. The recorded data is plotted into a load-displacement curve. The curve is analyzed to investigate the resistance of RTP towards lateral loads.

v. The dent elastic rebound is measured after the unloading phase. Fig. 10 showings the elastic rebound of RTP after load has been removed.

Fig. 8 - UTM Machine.

Fig. 9 - Process of applying quasi-static lateral load on RTP specimen.

Fig. 10 - Elastic Rebound of RTP after process of unloading.

5.3 Indenter Profile

The selection of indenter profile in a quasi-static indentation test is one of the crucial factors to be considered. In this test, the indenter used is a cylindrical with cone nose shaped indenter, adapted from (Rezaee et al., 2018). The indenter was specially fabricated by using a hardened mild steel to fit UTM machine (Zwick Roell Amsler HA50

UTM). The indenter profile was chosen to imitate the dent defect that typically caused by sharp object such as ship anchor and trawl impact. Besides that, the indenter profile is chosen with the main interest on the dent depth based on applied lateral load, considering the symmetrical geometries. This profile seemed to be an ideal choice $Ø_1$ is set at 50 mm, approximately 45% from specimens' outer diameter (110 mm) and cylindrical part diameter, $Ø_2$ is set at 10 mm and α is set at 135° considering that it will not penetrate the PE100 thermoplastic liner.

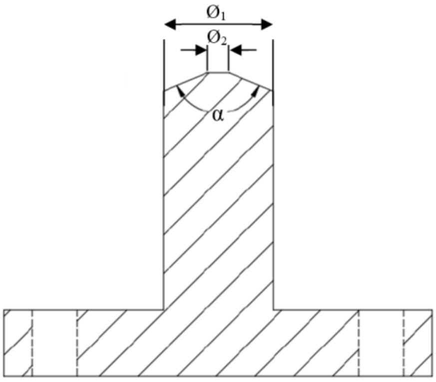


Fig. 11 - Cylindrical with conical nose indenter, $Ø_1$ = 50mm, $Ø_2$ = 10mm, α = 135°

6. Result and Discussion

From the quasi-static indentation test conducted, a load-displacement curve has been plotted as shown in Fig. 12. The slope of load-displacement curve represents the specimen bending stiffness. The maximum dent depth recorded is 62.5 mm with maximum lateral load recorded 16.1 kN. The result can be divided into two-phases as in Fig. 13. Phase I shows a slightly fluctuated curve, with a gradient of approximately 0.4 kN/mm. RTP is constructed in three layers, the reinforcement layer is fused to the thermoplastic liner and covered using a thermoplastic. Thus, the fluctuation is a result from delamination between layers and internal delamination in reinforcement layer. However, the delamination process is not visually visible. In Phase II, the curve shows a more proportional result compared to Phase I, no more fluctuation in the curve. Thus, shows delamination phase has ended and the curve gradient has dropped to 0.17 kN/mm. The drop in the gradient represent the reduced stiffness of the specimen to resist lateral load from indenter.

The RTP is an alternative to carbon steel pipe. Thus, it is a good idea to compare the load-defection curve of a carbon steel pipe specimens with an RTP specimens. In

Fig. 14 both specimens are having an outer diameter of 110 mm and using a similar indenter profile. In general, carbon steel is a stiffer material compared to thermoplastic. The resistance towards deformation is much higher for carbon steel pipe. For example, to indent a 50 mm dent, 39 kN of load is required for a carbon steel pipe, while only 14 kN of load is required for RTP.

The maximum dent for 4" carbon steel pipe is 75 mm at load of 47 kN, while the maximum dent for a 4" RTP is 62.5 mm at load of 16.1 kN. The difference in the maximum dent depth is due to difference in thickness between each specimen.

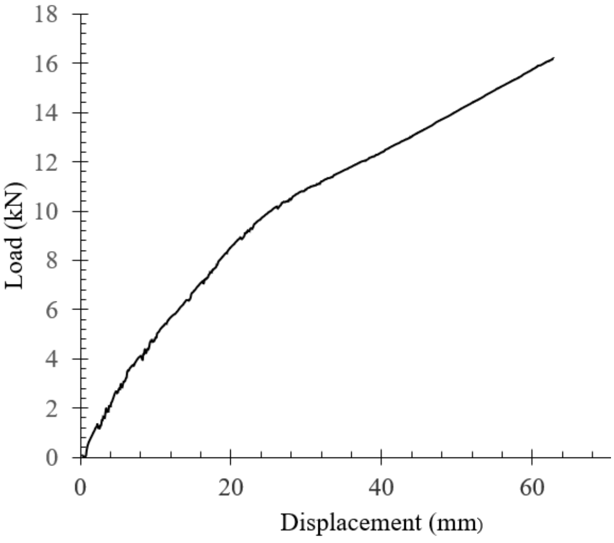


Fig. 12 Load - Displacement Curve.

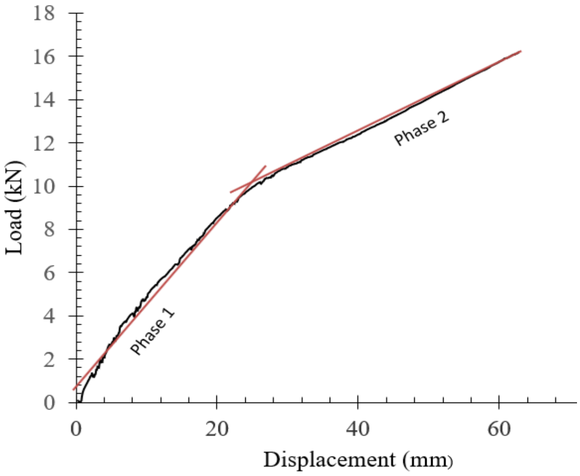


Fig. 13 Load - Displacement Curve, with a linear line representing Phase 1 and Phase II.

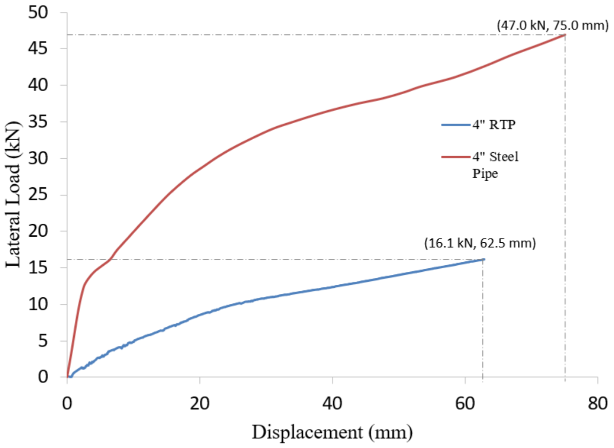


Fig. 14 A comparison of Load-Displacement Curve for RTP and for carbon steel pipe (for carbon steel pipe, the curve is adapted from (Rezaee et al., 2018).

In the indentation work carried out, the maximum dent recorded is 62.5 mm at load of 16.1 kN. However, the effect of elastic rebound is observed after the indentation work. Elastic rebound is defined as the rebound of the dent formed during the process of unloading the indenter. It is observed that, RTP specimen tested has an elastic rebound of 92%. The maximum dent recorded is at 62.5 mm, while the permanent dent recorded is only at 5.0 mm. The high elastic rebound effect is expected due to high elastic properties of PE as the major component in RTP. Although the elastic rebound factor is more observable in a plastic based pipe (96% for RTP) a steel pipe also exhibits a similar rebound effect, it has been mentioned by Han et al. (2018), in their study. The indentation work carried out for a steel pipe with outer diameter of 508mm, and a wall thickness of 8 mm, the maximum dent depth recorded during loading is 160 mm, and the permanent dent after unloading is recorded at 110 mm, it shows an elastic rebound of 31.25 % from maximum dent recorded. Fig. 13 illustrate the process of elastic rebound.

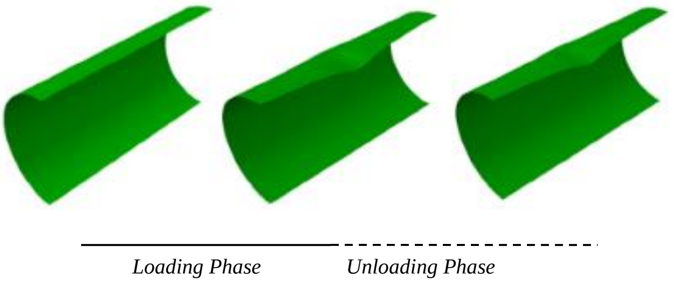


Fig. 15 - Elastic Rebound during loading and unloading of specimens (adapted from (Han et al., 2018)).

7. Conclusions

Quasi-static indentation is one of the common methods to indent pipe specimen. In this paper, the resistance of RTP towards a lateral load under lateral load was investigated and compared with a steel-based pipe specimen with a similar outer diameter. It led to the following conclusions:

i. The load-displacement curve of RTP subjected to transverse load can be divided into two phases; In phase 1, delamination between layers occur. Thus, resulting a fluctuate curve. While in phase 2, a more linear curve is observed due to ending process of delamination.

ii. RTP specimens has a lower resistance towards lateral load compared to steel-based pipe. With a similar lateral load, a higher deformation is recorded for RTP. However, due to high rebound effect in RTP, the final permanent deformation is low in RTP.

Acknowledgement

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