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Flexure analysis of spoolable reinforced thermoplastic pipes for offshore oil and gas applications

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Abstract

This article is concerned with the numerical modelling and analysis of the mechanical behaviour of composite pipes used for offshore oil and gas applications. Specifically, the bending of the reinforced thermoplastic pipes during the reeling process of reel-lay installation is modelled using non-linear finite-element procedures. In particular, the possible buckling of the reeled composite pipes has been investigated. Composite pipes reinforced with one angle-ply and two angle-ply layers are considered and the effects of different diameter-to-thickness ratios and different angle-ply combinations on the mechanical behaviour of these pipes have been studied.

Keywords

Buckling, finite-element method, reinforced thermoplastic pipe, reel-lay installation, spoolability

Introduction

In the oil and gas industry, the use of pipes made of composite materials is gaining momentum because of the attractive properties offered by these materials compared with conventional steel pipes. Currently there are several composite pipe solutions available in the market for low to very high pressure applications such as oil and gas gathering lines, water injection and water disposal lines and composite coiled tubing.[1–6] Efforts have been made to use composite pipes in drilling and production riser and choke and kill line applications offshore. The reinforced thermoplastic pipe (RTP) with a relatively simple wall structure is one of the most attractive solutions on offer.[3,7–9] The structure of a typical wall of an RTP is shown in Figure 1, which normally consists of the following three layers: (a) internal thermoplastic liner; (b) helically wound layers of fibre-reinforced thermoplastic and (c) outer thermoplastic cover.

The initial material and manufacturing costs of the RTP or composite pipes, in general, are somewhat greater than those of conventional carbon steel pipes but it has been shown that in many cases the reduced installation cost as well as the higher corrosion resistance resulting in reduced maintenance and improved durability make the composite pipes economically feasible over their service life.[1] RTPs can be constructed as 'bonded' or 'non-bonded' structures. In bonded construction, the reinforcement tape is fused to the liner and cover whereas in non-bonded construction, relative movement is allowed between different layers. Although, the pressure capacities could be similar for both constructions under pressure loading, RTPs with bonded construction offer greater resistance to liner collapse on depressurisation or cover blow-off due to diffused gases.[2] The analysis of bonded construction of the RTPs has been considered in this study.

Currently, the RTPs are typically available in the diameter range of 50–150 mm (2–6 in.), pressure capacities up to 35 MPa and maximum working temperatures up to 65°C. For liner and matrix of reinforced

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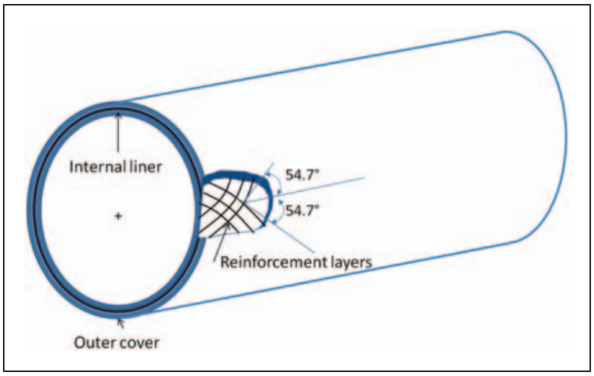

Figure 1. A typical RTP.
RTP: reinforced thermoplastic pipe.

layers, various grades of polyethylene (PE) (PE80, PE100, etc.)[3] are being used for product temperatures up to 65°C. Also, RTPs can be manufactured with other thermoplastic materials to suit particular operational requirements (loadings, temperature, product type, etc.). If required, RTPs can be designed for higher operating temperatures by using appropriate thermoplastic materials like polyamides (PA), PA11 or PA12 (up to about 80°C), polyvinylidene fluoride (PVDF) (up to about 125°C) or polyether ether ketone (PEEK) (up to about 140°C). PEEK, though expensive, offers better thermal properties, chemical resistance, permeation and explosive decompression capabilities compared with other polymers such as PE, PA or PVDF.

In general, the installation of offshore pipelines is one of the most challenging and costly offshore operations. Among different installation methods, reel-lay installation is, probably, the most efficient installation technique. The RTPs are supplied in long continuous forms spooled on reels, allowing cost-effective and fast installation. In this method, the installation is achieved by continuously unwinding the pipe from the reel and laying it on the seabed. The reel-lay method provides significant cost and schedule advantages compared with other conventional methods of laying rigid pipe, e.g. S-Lay and J-Lay techniques, where the rigid segments of pipes are welded together on-board of the installation vessel. Existing reel-lay vessels can lay pipes at speeds up to 90 km/day compared with laying speeds of 3–4 km/day of the conventional S- and J-lay vessels.[10] In addition, the RTPs offer significant advantages over rigid composite or metallic pipes due to their flexibility, corrosion resistance and high pressure capacity. Also, the materials of inner liner and outer covers have relatively low friction coefficient, which would provide both better internal flow characteristics and ease of trenching.

The reel-lay installation method has also been employed for conventional steel pipes and it has been reported that due to winding and unwinding off the reel, these pipes may undergo excessive deformations into the plastic range, resulting in some cases in ovalization of the cross-section. Analysis of the metal pipes undergoing plastic deformation upon spooling onto a reel has been adequately reported in the literature.[11–13] However, there have been very few studies found in the literature exploring the mechanical behaviour of spoolable composite pipes when subjected to excessive bending deformations. Rodriguez and Ochoa[1] studied the flexural behaviour of glass/epoxy and carbon/epoxy non-spoolable pipes using four-point bending tests and numerical simulations. The tubes considered in their study were of relatively small diameter and thick pipes having an internal diameter (D_i) of 55 mm with an outside diameter-to-thickness ratio (D_o/t) that was less than 22. Progressive damage analysis has been used to study their mechanical behaviour. Xia et al.[14] performed the stress analysis for filament-wound fibre-reinforced carbon fiber/epoxy and glass/epoxy pipes under pure bending using analytical method based on the classical laminated-plate theory. Similar studies have been undertaken by Natsuki et al.,[15] who conducted experiments in conjunction with analytical study in order to predict the bending strength of filament-wound composite pipes. It should be noted that no consideration has been given in the aforementioned research to the possible buckling of the pipes that could occur during the spooling process of flexible pipes.

In addition to spoolability, composite pipes should withstand substantial internal pressure. The netting analysis[16] is often employed in the design and analysis of the filament-wound pipes subjected to this loading. This approach is based on the utilisation of monotropic model of composite ply, which ignores the strength and stiffness of the matrix and assumes that the ply takes the load only in the fibre direction.

According to this, the helical single angle-ply layer of the cylindrical filament-wound pipe/pressure vessel should be reinforced with the angles $\pm 54.7^\circ$ to withstand the internal pressure, i.e. when hoop to axial stress ratio is 2:1.[17] This angle of fibre reinforcement orientation is commonly accepted in composite pipe designs.[7,16] However, in practical applications, this ratio of hoop to axial load may not be maintained and would result in the reduced axial and pressure capacity of the RTP reinforced with the single angle-ply layer. For instance, during installation of RTPs in deeper water, high axial loads may be exerted on these pipes, which need to be accounted for when designing the pipelines for offshore applications. This can be improved if a two angle-ply reinforcement layer system, $[(\pm\phi_1)_m/(\pm\phi_2)_n]$, where ϕ_1 and ϕ_2 are the fibre orientations and 'm' and 'n' are the number of helical angle-ply layers, is implemented. This type of reinforcement will significantly enhance the axial and pressure capacity of the RTP due to the balanced nature of the reinforcement structure.

The objective of the current study is to investigate the mechanical behaviour of the RTPs when these pipes are being spooled onto the reel and subjected to substantial bending deformation. In particular, the stresses developed in the pipe wall and deformation of the cross-section consequently leading to buckling of long RTPs when subjected to excessive bending have been analysed. RTPs with the single angle-ply and two-angle reinforcement structures and having different diameter-to-thickness ratios and lengths have been considered. These analyses have been supplemented with the strength analysis of the pipes subjected to the bending deformation. Finite-element modelling and non-linear analysis of the RTPs under consideration has been accomplished using ABAQUS.

Numerical model

The RTP being reeled onto a spool experiences large deformations. The geometrically non-linear modelling approach should be developed and employed to adequately simulate the mechanical behaviour of the pipe under these conditions. In this study, the problem is solved using general static solution procedure of ABAQUS/Standard including NLGEOM option.

This procedure accounts for the geometric non-linearity of the model during the solution step. A direct equation solver method has been employed and Newton's method is used as a numerical technique to solve the non-linear equations. The simulation of the bending loading of the pipe under consideration has been performed by application of the rotational displacement to one end of the pipe, whereas the other end was considered to be fully clamped. The applied rotational displacement is ramped linearly over the solution step using automatic incrementation with a maximum number of increments of 1000, an initial increment size of 0.1 and a minimum increment of 1×10^{-20}.

It is expected that due to the excessive deformations experienced by the RTP during the spooling, especially when the cross-section is allowed to be deformed (in the non-linear large deformation analysis), the solution could be unstable and difficult to converge. In order to facilitate the convergence of computational process, the automatic stabilization option in ABAQUS/Standard is employed. In this method, a damping factor, 'c', is specified to trigger the stabilization of the non-linear quasi-static procedure. Viscous forces utilizing the damping factor are added to the global non-linear equilibrium equations.[18]

As mentioned above, in order to model the scenario of RTPs being spooled on a reel for storage and installation, a rotational displacement, 'θ' is applied at one end of the pipe while the other end is kept fixed. The bending deformation is induced using a reference point located at the axis of the pipe, by applying a rotational displacement. In order to link the degrees of freedom of the nodes of the cross-section to the reference point, the kinematic coupling option available in ABAQUS has been utilised. For an applied rotational displacement, the resultant moment is calculated at the reference point in order to obtain the moment-rotation curves for each RTP. During each solution step, the stresses and deformations in all the layers are recorded for post-processing of the results. The two-dimensional eight-noded quadrilateral shell element S8R, with six degrees of freedom per node, is employed. S8R is based on the first-order transverse shear deformation shell theory.[18] The latter enables the analysis of relatively thick pipes. The finite-element model has been composed of 20 elements around the circumferential direction and 40 elements along the tube axis. Shell middle surface has been adopted as a reference when defining the composite layup.

Numerical analysis

In this study, the RTP composed of inner thermoplastic liner (PEEK), reinforcement layers of carbon fibre-reinforced PEEK (AS-4 PEEK) and outer thermoplastic cover (PEEK) is considered as an example. For the helical filament-wound reinforcement layers of one angle-ply RTPs, the angle of orientation of the reinforcement of 54.7° has been employed. In addition, to assess the effect of different number of plies and fibre orientations on the mechanical behaviour, various combinations of two angle-ply reinforcement layers are analysed. The following lay-ups have been considered: [±25/±50], [±25/±75], [±50/±25] [±50/±75] and [±75/±25] and [±75/±50].

The material properties used in the analysis are shown in Table 1, where, E_{11} and E_{22} are the elastic moduli in the fibre and transverse direction, respectively, ν_{12} is the Poisson's ratio and G_{12} is the shear modulus of the ply material.

The thickness of the angle-ply layers used in all models is 1.2 mm consisting of a layup of $[\pm 54.7]_4$. The thickness of the inner liner and outer cover are kept constant at 3 mm. Three different internal diameter pipes $D_i = 100$, 200 and 300 mm, with lengths of $L = 1000$ and 2000 mm are analysed in this study. For different diameter RTPs, the wall structure is kept the same. The non-linear stress and buckling analyses are performed in order to calculate the minimum bend radius based on the strength and buckling constraints.

The stress allowables used in the modelling are shown in Table 2, where $S_{11,\mathrm{tension}}$ and $S_{11,\mathrm{comp}}$ are the allowable tensile stress and compressive stress in the fibre direction, respectively, $S_{22,\mathrm{tension}}$ and $S_{22,\mathrm{comp}}$ are the allowable tensile stress and compressive stress in the transverse direction, respectively, and S_{12} is the allowable shear stress in the lamina. Two stress-based failure theories are considered in the stress analysis of the RTP: maximum stress theory

$$\sigma_{11} \geq S_{11},\ \sigma_{22} \geq S_{22},\ \sigma_{12} \geq S_{12}$$

and Tsai–Hill theory

$$\left(\frac{\sigma_{11}^2}{S_{11}^2} - \frac{\sigma_{11}\sigma_{22}}{S_{11}^2} + \frac{\sigma_{22}^2}{S_{22}^2} + \frac{\sigma_{12}^2}{S_{12}^2}\right) \geq 1$$

Table 1. Lamina and liner properties.[19]

Property	AS4-PEEK	PEEK
E_{11} (GPa)	131.0	3.6
E_{22} (GPa)	8.7	–
ν_{12}	0.28	0.4
G_{12} (GPa)	5.0	–

PEEK: polyether ether ketone.

Table 2. Lamina and liner stress allowables.[20]

	AS4-PEEK	PEEK
$S_{11,\mathrm{tension}}$ (MPa)	2060	110
$S_{11,\mathrm{comp}}$ (MPa)	−1080	−100
$S_{22,\mathrm{tension}}$ (MPa)	78	–
$S_{22,\mathrm{comp}}$ (MPa)	−196	–
S_{12} (MPa)	157	65

PEEK: polyether ether ketone.

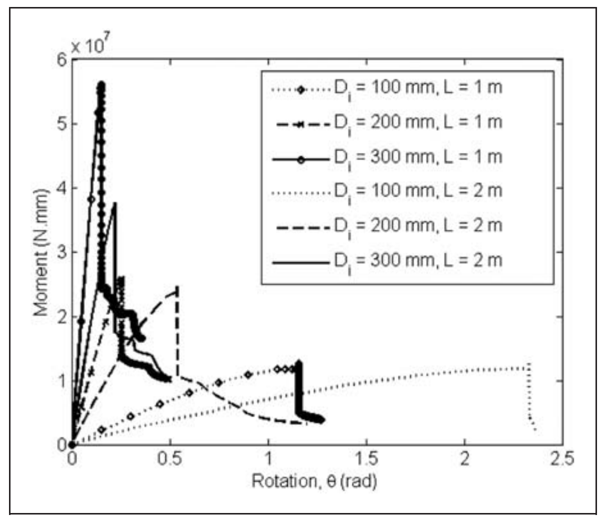

Figure 3. Moment-rotation responses for different diameter RTPs.
RTP: reinforced thermoplastic pipe.

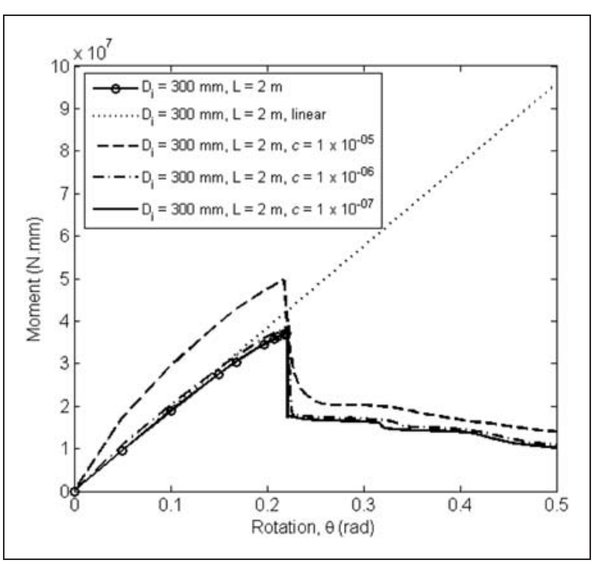

Figure 2. Moment-rotation response for different RTPs with $D_i = 300$ mm, $L = 2000$ mm.
RTP: reinforced thermoplastic pipe.

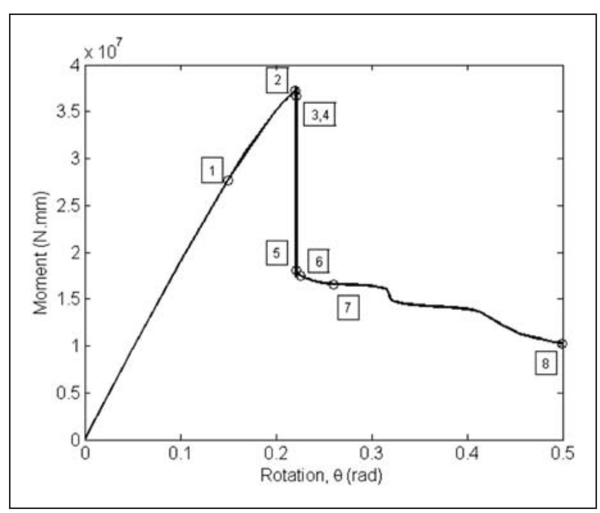

Figure 4. Moment-rotation response for an RTP with $D_i = 300$ mm, $L = 2000$ mm; markers and numbers denote the rotations for which the deformed shapes are plotted in Figure 5.
RTP: reinforced thermoplastic pipe.

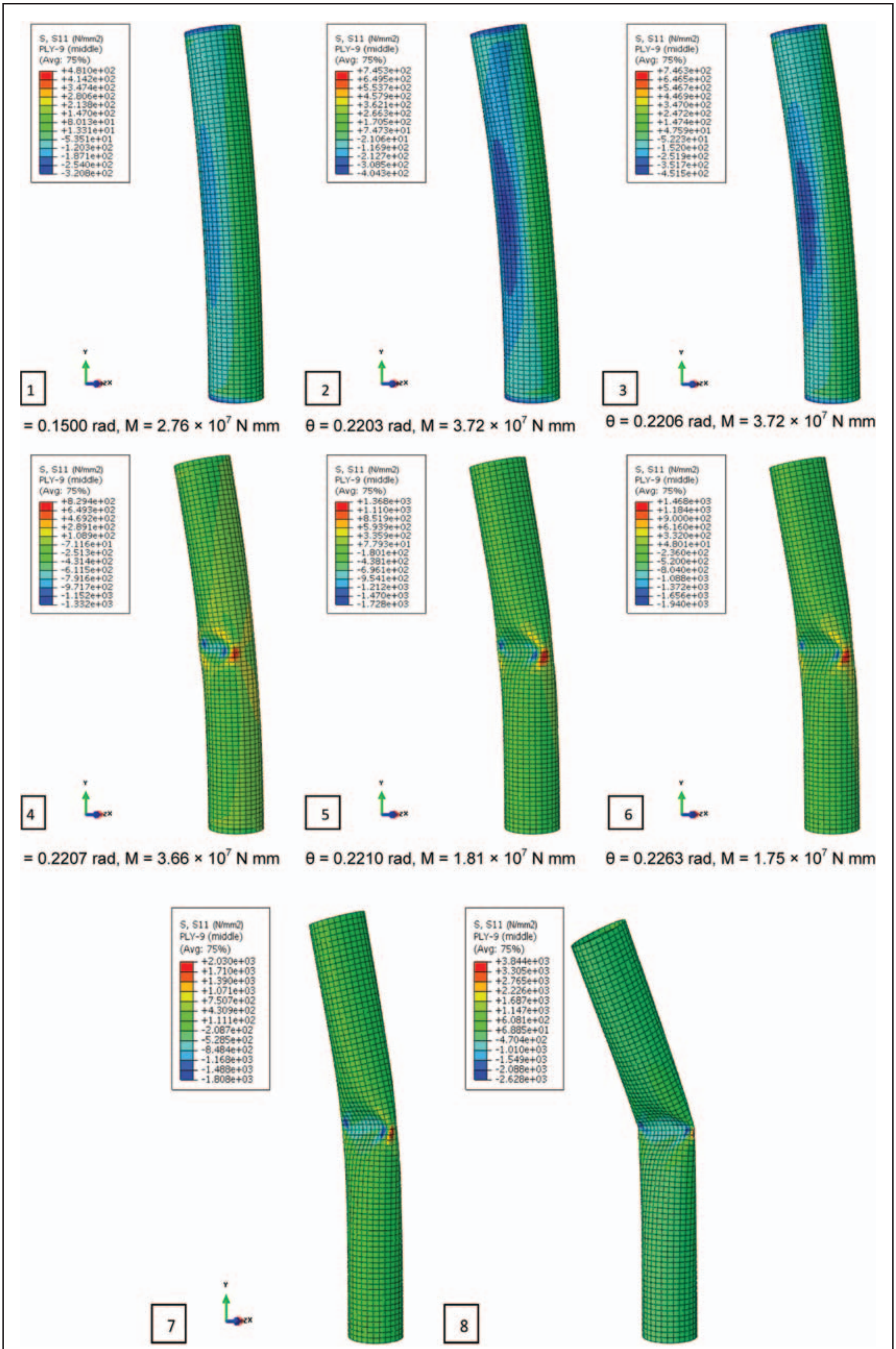

Figure 5. Stress contour (along fibre direction) and deformed shape (scale factor = 1.0) showing buckling of an RTP of large D_o/t ($D_i = 300$ mm, $L = 2000$ mm) under moment load corresponding to the markers plotted in Figure 4.

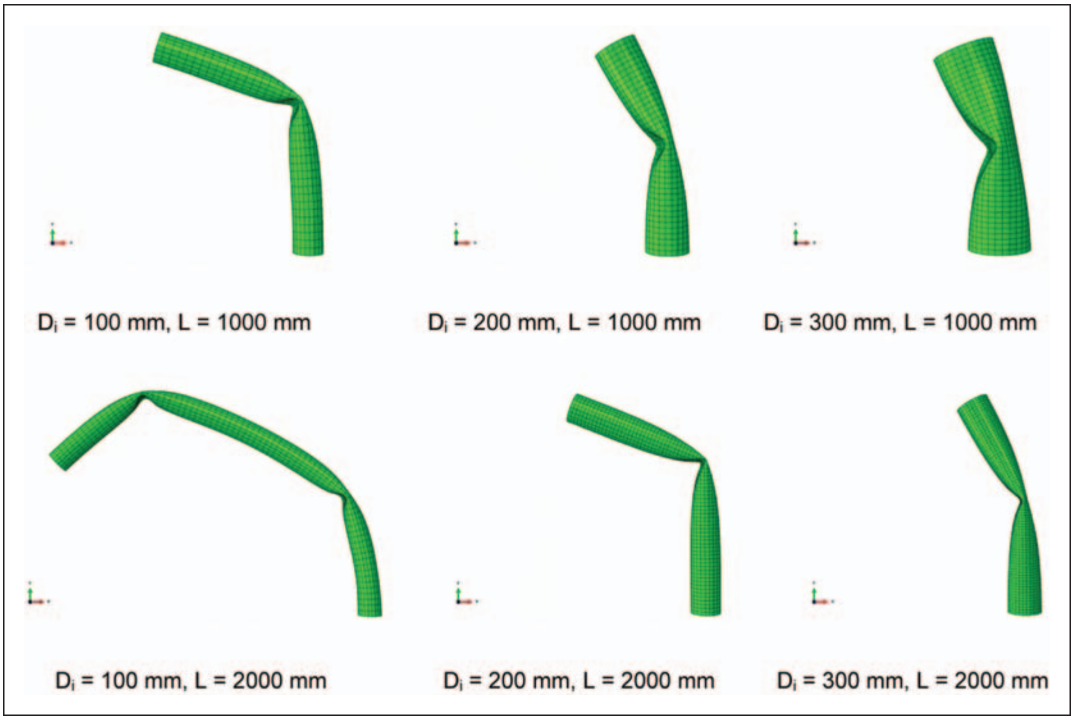

Figure 6. Deformed shapes of different RTPs under moment load.
RTP: reinforced thermoplastic pipe.

Table 3. Values of failure criteria functions at different bend radius, $D_i = 100$ mm, $L = 1000$ mm.

Rotation (θ)	Bend radius, L/θ (m)	Tsai–Hill criterion (Ply2)	Tsai–Hill criterion (Ply9)	Maximum stress criterion (Ply2)	Maximum stress criterion (Ply9)	Maximum stress criterion (liner)	Maximum stress criterion (cover)
0.05	20	0.19	0.19	0.16	0.16	0.10	0.10
0.1	10	0.40	0.38	0.32	0.32	0.20	0.21
0.175	5.71	0.70	0.67	0.58	0.58	0.36	0.36
0.2875	3.47	1.17	1.11	0.96	0.98	0.57	0.60
0.4	2.5	1.63	1.55	1.34	1.39	0.79	0.86
0.5	2	2.04	1.93	1.68	1.75	0.98	1.08

Table 4. Summary of bend radius calculations for different diameter RTPs.

D_i (mm)	L (mm)	Bend radius (m) (Tsai–Hill criterion)	Bend radius (m) (maximum stress criterion)	Failure
100	1000	4.5	3.5	Matrix in tension
200	1000	9	8	Matrix in tension
300	1000	13.5	12.5	Matrix in tension

RTP: reinforced thermoplastic pipe.

where σ_{11} and σ_{22} are the stresses in fibre and transverse directions and σ_{12} is the shear stress.

As discussed earlier for the geometrically non-linear problems, the stabilization procedure is required for the convergence of the solution. For this, three different values of damping factors were employed. For the validation of the current solution method, the moment-rotation responses of the RTP obtained with linear and non-linear large deformation analyses are compared in Figure 2. Though all the non-linear solutions obtained by using stabilization provide converged solutions, it can be seen that for a damping factor of $c = 1 \times 10^{-7}$, both the linear and non-linear solutions match closely in the pre-buckling region of moment-rotation curve, whereas larger values of the damping factor cause overly stiff response of the pipe. Therefore, $c = 1 \times 10^{-7}$ has been used for all the simulations presented in this study.

Results and discussion

Effect of different diameter-to-thickness ratio

The mechanical behaviour of all RTPs simulated is shown by the moment-rotation curves given in Figure 3. All of the pipes analysed in this study show similar post-buckling behaviour. After reaching a critical rotation, the load-carrying capability of the pipe suddenly drops. For clarity, the moment-rotation curve of the large diameter RTP ($D_i = 300$ mm, $L = 2000$ mm) is plotted in Figure 4. The corresponding buckling mode and deformed shapes are presented in Figure 5. The mechanical responses observed are similar to the one that was first reported by Brazier[21] for homogeneous, isotropic, linearly elastic thin tubular members of circular cross-sections under bending. Brazier[21] showed that the progressive ovalization of the cross-section under moment load causes non-linearity. As the curvature is increased, the moment of inertia of the section reduces, which results in buckling failure.

The buckling mode shapes for all the RTPs simulated in this study are plotted in Figure 6. All configurations show a single kink appearing midway along the length of the pipe, except for the RTP with $D_i = 100$ mm and $L = 2000$ mm, where two kinks have developed, which may be attributed to the largest length-over-diameter ratio. However, the mechanism of developing these buckled shapes in all the pipes is very similar, i.e. starting with the ovalization of the cross-section and followed by the kinking occurred due to buckling failure.

It should be noted that during the spooling of an RTP, depending on the D_o/t ratio, the failure may occur due to buckling of the pipe wall, which must be considered for safe design of larger diameter RTPs. As indicated earlier, in addition to the investigation of failure due to buckling of RTPs, stress analysis at different stages of rotational displacement is also performed in the current numerical analysis.

The values of the failure criteria functions calculated at different stages of the loading for an RTP with $D_i = 100$ mm, $L = 1000$ mm are listed in Table 3.

Table 5. Rotation at different failure occurrences.

D_i (mm)	L (mm)	θ_{MF}	θ_c	θ_{FF}
100	2000	0.60	2.32	1.84
200	2000	0.26	0.53	0.53
300	2000	0.17	0.22	0.22

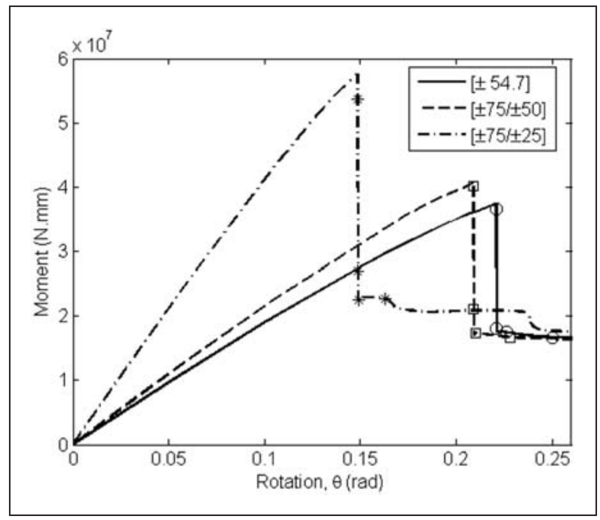

Figure 7. Moment-rotation response for an RTP with $D_i = 300$ mm, $L = 2000$ mm. Markers denote the points for which the deformed shapes are plotted in Figure 4.
RTP: reinforced thermoplastic pipe.

It can be seen that for a bend radius of 3.47 m, the Tsai–Hill criterion predicts the failure in the reinforcement layers. However, according to the maximum stress criterion, the pipe is just safe enough to be bent to this radius. It should also be noted that the bending load is mainly carried by the reinforcement layers as the stress levels in the inner liner and outer cover are well below their failure limits at this instant.

The results of the minimum bend radius calculation for three different pipe diameters are listed in Table 4. The difference in the bend radii calculated based on the maximum stress and Tsai–Hill theories can be attributed to the fact that the latter takes into account the interaction among the normal and shear stresses acting in the unidirectional plies. The minimum bend radius that can be achieved for a 100 mm internal diameter RTP is 3.5 m, without inducing damage in the pipe.

For the material properties used, the dominant mode of failure observed is the tensile failure of the reinforcement matrix. However, it is also observed that as the diameter of the pipe is increased from 100 to 300 mm at a constant thickness, the start of the buckling failure approaches the start point of the reinforcement matrix

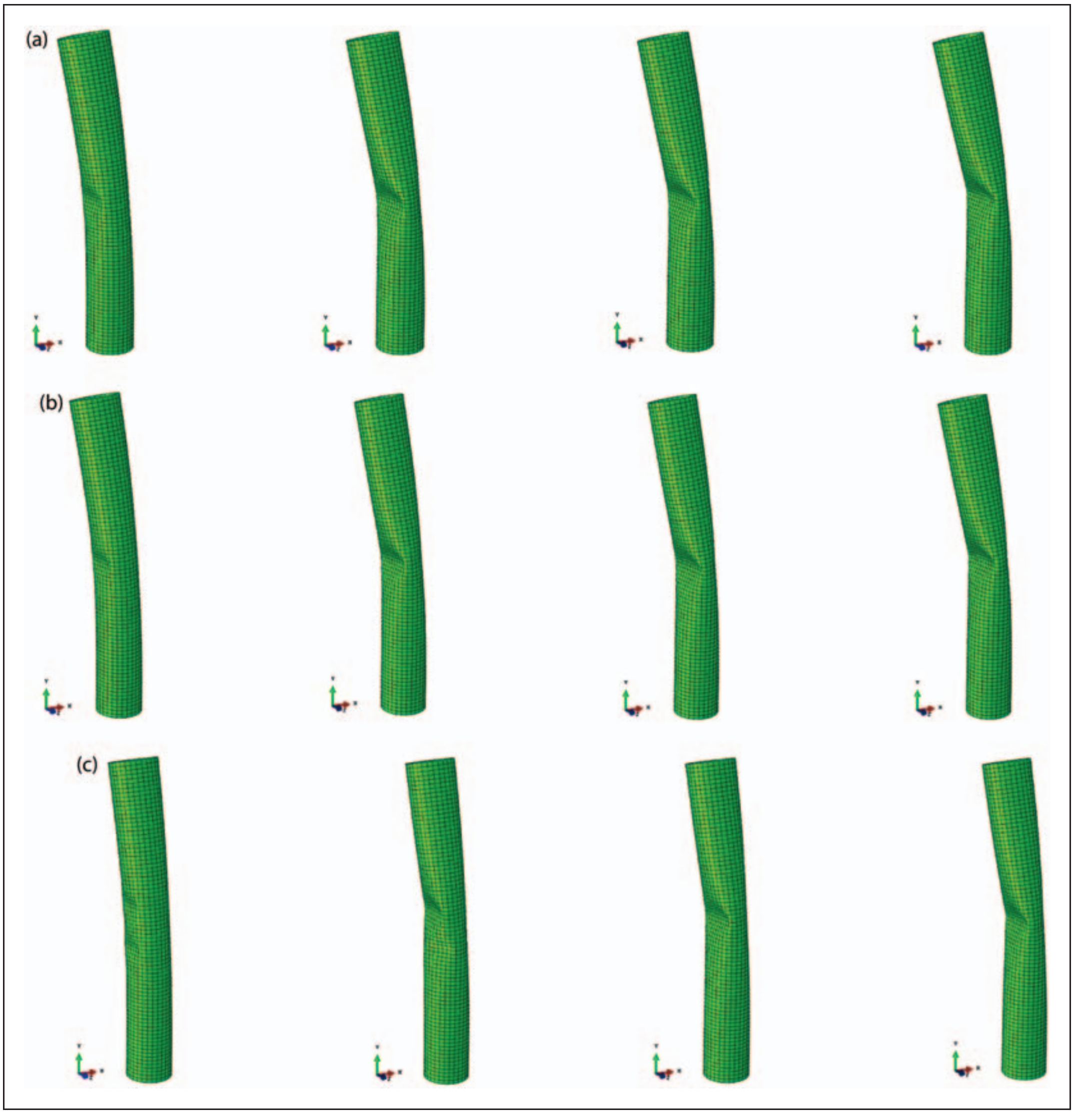

Figure 8. Buckling of an RTP of large D_o/t ($D_i = 300$ mm, $L = 2000$ mm) due to excessive rotational displacement corresponding to the markers plotted in Figure 7.
RTP: reinforced thermoplastic pipe.

failure. This is shown in Table 5, where θ_{MF}, θ_c and θ_{FF} are the rotational displacements at the instant when failure occurs in reinforcement matrix, at the start of buckling and when the fibre failure occurs, respectively. For larger diameter RTPs, the buckling of the pipe becomes a more significant factor. Table 5 also shows that for the RTP with $D_i = 100$ mm (lowest D_o/t investigated), the buckling of the pipe wall is the least dominant mode of failure.

Effect of different reinforcements orientations

The buckling behaviour of the RTPs simulated is shown by the moment-rotation curves given in Figure 7. For clarity, only three curves are plotted in Figure 7, with corresponding buckling mode and deformed shapes presented in Figure 8. The stacking sequence of the two-angled reinforcement layers had very little influence on the mechanical behaviour of the RTPs. The two-angled RTP with [±75/±50] shows buckling failure mechanism that is similar to that of one angle-ply reinforcement layer case, i.e. the progressive ovalization of the cross-section under increasing moment load causes non-linearity and ultimately buckling failure.[21]

For the case with either [±75/±25] or [±50/±25] (response for the latter not shown here) when more fibres are distributed in the axial direction, the RTP's response to the applied rotation is much stiffer than that of an angle-ply case. The initial buckled mode shape is also different in this case. After the initial ovalization of the cross-section, two kinks appear in this case, which upon increasing the rotation show a diamond-shaped buckle in the pipe wall. As the curvature is further increased, the final buckled mode shape is similar to one angle-ply reinforcement layer cases, i.e. a single kink at midway along the length of the pipe.

For the orientation angles considered in this study, the use of two angle-ply reinforcement layers did not show immediate benefit in terms of reducing the spool radius of an RTP. However, it may be useful to enhance the axial load capability of an RTP as more fibres are placed in the axial direction. Also, the spoolability can be controlled by manipulating the number of the angle-ply layers in the laminate.

Conclusion

The non-linear mechanical behaviour of RTPs with different diameter-to-thickness ratios and different angles of orientation of the reinforcement layer subjected to bending has been successfully modelled. Failure due to buckling as well as due to strength is considered in the non-linear analysis. It has been shown that for the pipe geometry investigated, a 100 mm internal diameter RTP can be spooled on a 3.5 m spool radius without inducing any damage to the pipe wall. The ability of the pipe to be bent on smaller spool radii is limited by the strength of the matrix used in the reinforcement layer as well as the buckling of the pipe wall. It has been shown, that the buckling failure of the RTPs under excessive rotational deformation is caused by the flattening of the cross-section, which results in a kink in the pipe wall. It is found that the buckling of the pipe wall becomes a critical mode of failure only for larger outside diameter-to-thickness ratio RTPs (i.e. $\geq$40) for the pipes analysed in this study.

For different angle of orientation of the reinforcement layers, in general, the pipes with two angle-ply reinforcement layers offer a stiffer response compared with one-angled plies in the reinforcement layers. However, this can be controlled by the appropriate selection of the number of layers in the laminate. For the parameters analysed in this study, it is concluded that the axial capacity of an RTP can be increased at the expense of a larger spool radius when additional reinforcement fibres are placed close to the axial direction.

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Conflict of interest statement

None declared

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