NUMERICAL AND EXPERIMENTAL ANALYSIS OF COMPOSITE TUBES UNDER EXTERNAL HYDROSTATIC PRESSURE

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Abstract
The increasing demands in oil and gas industry led to a rapidly growing need for the use of advanced, high performance, lightweight materials such as composite materials. E-fibre glass laminated pre-preg, filament wound and braided tubes were tested to destruction under hydrostatic external pressure loading in order to study their buckling and crushing behaviour. Different fibre architectures and winding angles were tested in a range of wall thicknesses highlighting the advantage that hoop reinforcement offers. The experimental results were compared with theoretical predictions obtained from classic laminate theory and finite element analysis and indicated that the prominent failure mode was buckling. Non destructive testing was performed in order to investigate the effect of defects on the obtained results which highlighted the effect of poor curing on the crush resistance.

1. Introduction

As the requirement for achieving higher subsea depths is increasing so does the demand for the use of lightweight, high performance materials, such as composite materials, in an effort to replace the traditionally employed metallic structures. The move towards exploration and development of composite materials for deep-water subsea applications in oil and gas industry, can minimise the structural weight which can be difficult and costly to accommodate at high water depths. In addition, the remarkably high properties and strength of composite materials can offer a structural alternative for the design of a number of structures such as drill risers.

There has been a recent interest in textiles industry for the use of different weaving techniques in order to produce high performance fabrics for composite structures. These manufacturing techniques aim to overcome problems related to laminated composites, such as delaminations and interface mismatch between the constituent materials through the inter-lacing of the tows in the through-thickness direction [1]. More specifically braiding technology has been suggested for a number of commercial applications such as fuel lines, rocket launch tubes and aircraft structural parts due to the structural advantage over alternative weaving techniques. Three of its major competitors are filament winding, pultrusion and tape lay-up. Several studies have drawn the attention on the advantages of braiding in terms of structural integrity, design flexibility, damage tolerance, repair ability and low manufacturing cost [2]. Complex shapes can be easily

Mechanical properties	Plain weave	4-harness satin weave
$E_1(C)$	20 GPa	35 MPa
$E_2(C)$	20 GPa	8.9 GPa
$G_{12}(C)$	3 GPa	1.5 GPa
$v_{12}(C)$	0.3	0.32
$S_1(T)$	250 MPa	657 MPa
$S_2(T)$	250 MPa	99 MPa
$S_1(C)$	300 MPa	500 MPa
$S_2(C)$	260 MPa	80 MPa
$S_{12}(C)$	55 MPa	10 MPa

Table 1. Material properties for plain weave and 4-harness satin weave E-glass fabric impregnated with epoxy resin.

produced while the performance can be controlled through the regulation of the braid and crimp angle and other geometrical characteristics. Braided tubes exhibit a superior structural strength due to the fact that the interlacements act as crack arrests in contrast to laminated and filament wound tubes where the cracks run along the fibres [3], [4].

Several studies have focused on the crush behaviour of laminated, woven and knitted composite tubes. These studies have focused on the parameters that can affect the crushing characteristics such as fibre and matrix materials, fibre pattern and shell geometry. In addition extensive work has been carried out on the numerical analysis and investigation of the crushing modes. However little work has focused on the energy absorption and crushing mode analysis of braided tubes. Among the most notable work; Karbhari et al. highlighted the advantages of 2D braided composite tubes for energy absorption applications by looking at different types of fibres, numbers of layers and braid patterns [5]. Chiu et al. concluded that braided composite tubes with 20^{o} angle exhibited advanced energy absorption performance [6]. Chiu et al. studied the use of hybrid 2D braided composite tubes and identified the crushing modes while using Kevlar and carbon fibres [7]. The current work aims to build up on the existing knowledge and show a progressive shift from the traditionally used laminated tubes to filament wound and braided tubes through the understanding of the complex failure mechanisms of tubes subjected to hydrostatic external loads and the optimisation of the fibre arrangement.

2. Experimental set up

For the manufacturing of the laminated tubes, two types of fabrics were considered, namely plain weave and 4-harness satin weave. Both plain weave (style 7637) and 4-harness satin weave were reinforced with E-glass fibres, impregnated with epoxy resin, with a fibre volume of 60%.

The thickness of each ply was 0.23 mm for the plain weave and 0.25 for the 4-harness satin weave. The respective properties are illustrated in Table 1. The tubes were wound at 0/90 degrees while the weft direction was alighted with the axial axis of the tube and the warp direction was aligned with the circumferential direction of the tube. Tubes of 220 mm length and 50 mm internal diameter were employed in a variety of wall thicknesses (2 to 5 mm).

A number of filament wound tubes were manufactured at a range of wall thicknesses (2 to 4 mm) reinforced with John Manvilles 1200 tex 906 glass fibres. The resin system that was used was a urethane methacrylate Scott Blader CP1250LV resin. Preliminary numerical analysis showed that the optimum angle is the one closer to the hoop reinforcement. Therefore the tubes followed different wind angles, including low, high as well as hybrid angles, in an effort to investigate the effect of the angle on the performance under hydrostatic pressures, namely 45°, 55°, 65°, 87°, 87°/70°/87°. The tubes were 220 mm long for comparative reasons.

A 48-carrier conventional maypole braiding machine was used for the manufacturing of the braided tubes. The preforms were produced with E-glass fibres on a 600 mm epoxy resin mandrel. Two angles were produced, namely 45° with 10 layers and 55° with 8 layers of a thickness approximately equal to 2mm. Epoxy resin was then injected under vacuum in order to achieve a uniform resin impregnation. The tubes were finally cut at length, equal to 220mm. All tubes were sealed with aluminium end caps which were glued with a Scotch-Weld, epoxy adhesive prior to testing.

The tubes were tested in a pressure vessel with capacity of 6 litres which can reach testing pressures equal to 1,973 bars. The testing equipment consists of a tensometer controlled by a piston, pressure transducers which can reach up to 20.000 psi., a pressure pot with an operating pressure up to 1380 bars and a tube which is used in order to pump in water to the pressure pot. The tested specimen was placed inside the pressure pot, water was pumped in through the tube which was connected to the hydraulic machine, and any rapid change in the pressure was translated as failure. This change in the pressure was detected by the pressure transducers. The test followed an ASTM D2736-78 standard testing procedure. Approximately three to four tubes per configuration were tested to failure.

3. Results and discussion

3.1. Numerical and experimental analysis of laminated tubes

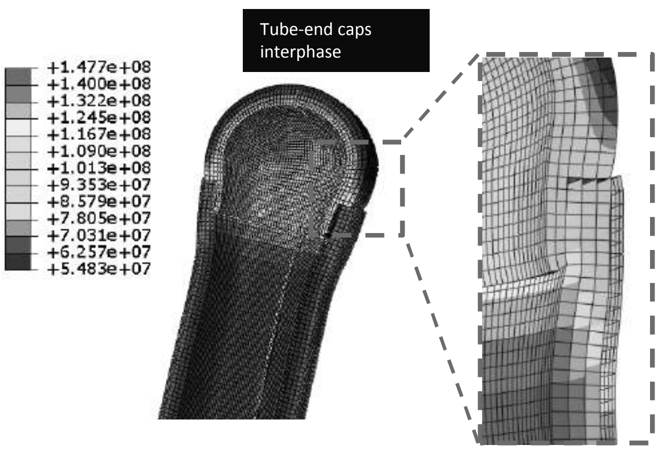


Figure 1. Von Misses stresses of a plain weave laminated tube sealed with hemispherical end caps.

The numerical analysis was performed with ABAQUS Version 6.12. Continuum shell (SC8R) were used in order to model the 50 mm diameter tube, while the lamina angles of the composite lay-up was consistent with that of the experimental set-up, $[90]_n$ where n represents the number of layers/wall thickness. The model followed the experimental configuration where direction-1 of the fabrics was aligned with the hoop direction in order to enhance the strength of the tubes under hoop failure. A mesh convergence analysis identified the optimum element size which was approximately 0.01 mm. The end caps were modelled with solid elements (C3D8R). The interphase between end caps and tube was approximated through the consideration of perfect tied contact. Uniform external pressure was applied on the whole model, while for the buckling analysis, one end cap of the model was fixed. A tube with hemispherical end caps for better illustration was modelled (Figure 1) whose results indicate that stress concentration occurs at the bore of the tubes while the end caps do not dictate significant physics of the problem solution since the tube-end caps interphase is not a critical region. Failure initiates far from the end caps.

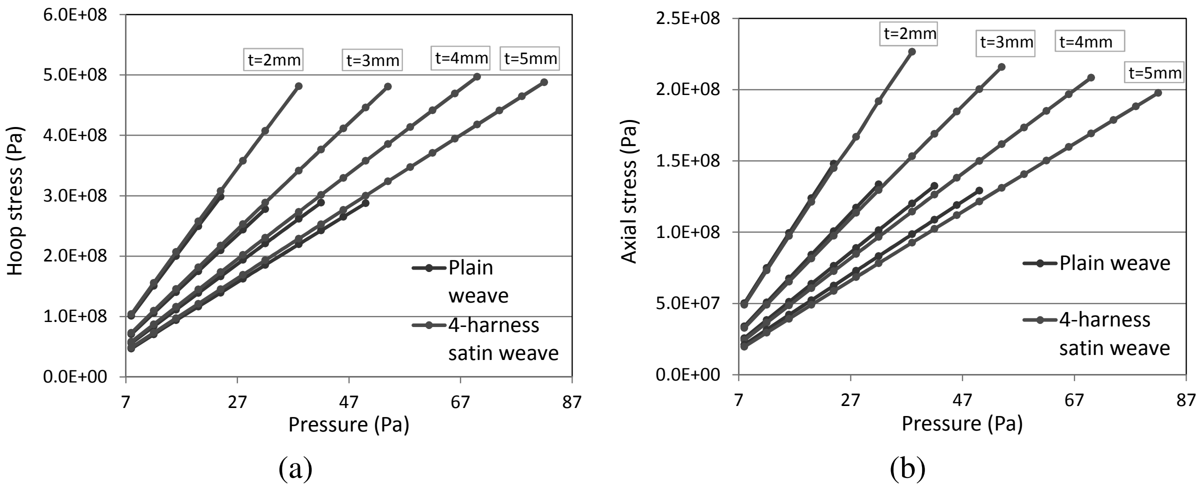
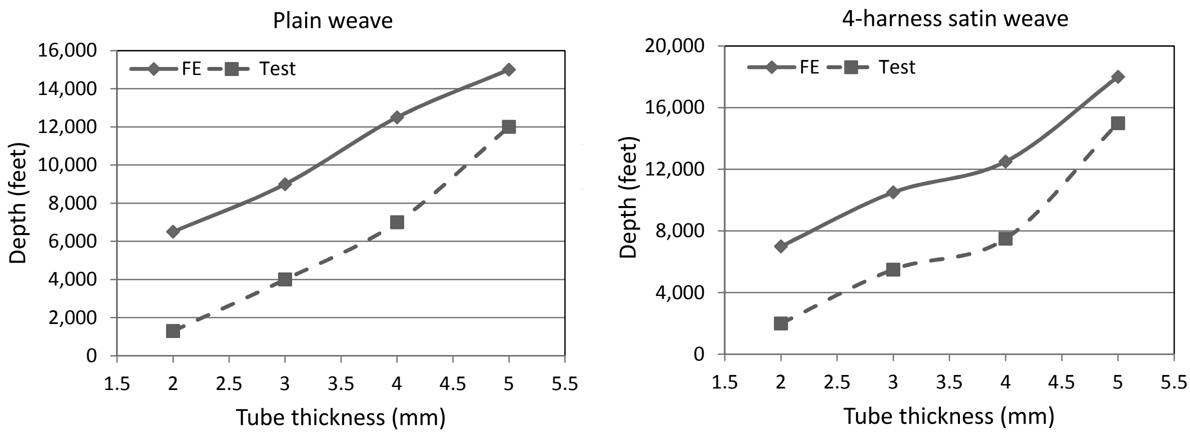


Figure 2. Compressive (a) hoop and (b) axial stresses at different applied pressures (corresponding to a water depth range equal to 3,000-30,000 feet) for tubes made of plain weave and 4-harness satin weave.

Figure 2 illustrates the numerical results of the developed hoop and axial stresses on the laminated tubes made of the plain and 4-harness satin weave until the pressure at which they failed. The failure point was estimated through the maximum stress criterion according to which longitudinal failure under compression occurs when $\sigma_{11}>S_1(C)$ and transverse failure under compression occurs when $\sigma_{22}>S_2(C)$. As observed from the properties of the two materials in Table 1, $S_1(C)$ is 500MPa significantly higher than the respective strength of the plain weave (only 300MPa). Since this represents the hoop reinforcement when the tubes were laminated, is it reasonable that the satin weave fails at much higher external pressures as shown in Figure 2. This is justified by the fact that the hoop stresses are two times higher than the axial stresses.

The experimental results showed the considerable advantage of the satin weave over the plain weave due to the extra reinforcement of the hoop direction (Figure 3). It can be observed that a superior performance can be achieved over the range of different wall thicknesses. The water depth increases considerably with the increase of the wall thickness with only a slight increase in the tube weight. However a significant disagreement between the numerical and test results especially at low wall thicknesses, resulted in a subsequent interest in the non destructive testing of the tubes to monitor their consolidation level assessment. A microscopic analysis of the plain weave tubes showed that at low wall thicknesses significant air pockets of up to 1mm thick can act as internal delaminations and can significantly alter the properties of the cured lamina (Figure 4). The instrument used was a Dinolite Premier2 Digital camera model number



(a) (b)

Figure 3. Comparison between the test and numerical results for the depth at which the tubes crushed for the (a) plain and (b) satin weave laminated tubes.

AM7013MTL with a magnification equal to 20-70x, and a resolution equal to 1280 x 960. The FE model considered perfect structure without any internal defects or delaminations. As the thickness increases, a better agreement is achieved.

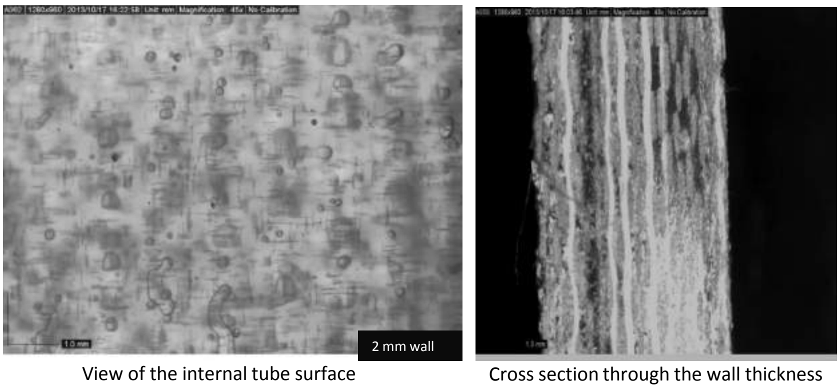
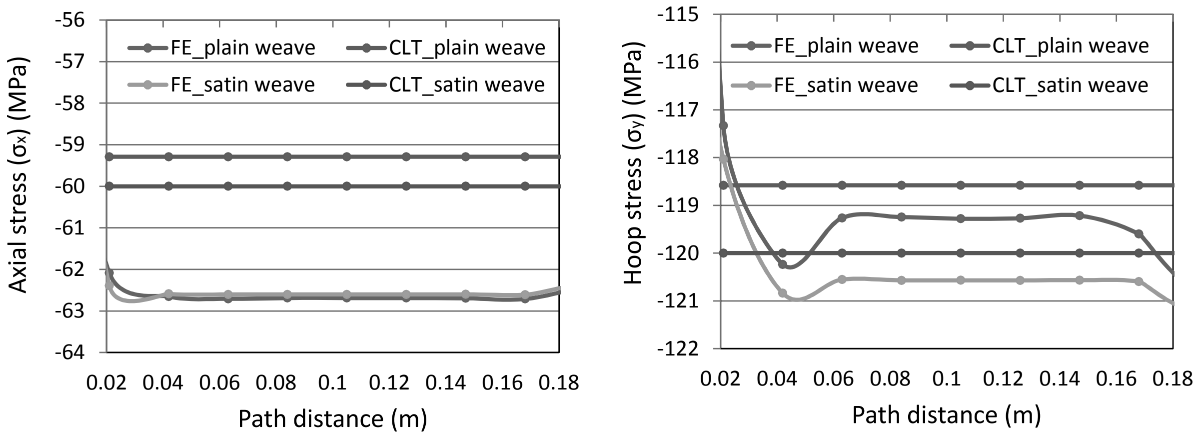


Figure 4. Microscopic analysis of laminated tubes (plain weave) at 2mm wall thickness.

Another method of validating the FE model was pursued through the implementation of a classical laminate theory based analysis. ESA Comp. Version 4.4.1. was used in order to calculate the resulting axial and hoop stresses of the two types of laminated tubes (plain and satin weave) under a representative pressure of 12MPa. This analysis estimated the resulting stresses at a representative unit cell at the centre of the tube along the length. Comparison with the corresponding numerical results showed a very good agreement. It is evident that as the path moves towards the ends of the tube (tube-end cap interphase), the stresses obtained from the FE analysis vary due to the end effect.

Composite tubes reinforced with continuous fibres can exhibit failure due to local buckling. This crushing mode consists of the formation of local buckles. Brittle fibre-reinforced composite materials usually do not exhibit post-crushing integrity due to the lack of plastic stress-strain response and they fail in a catastrophic mode with interlaminar cracks being formed at the buckles [8]. A buckling analysis was carried out with ABAQUS based on the aforementioned model.



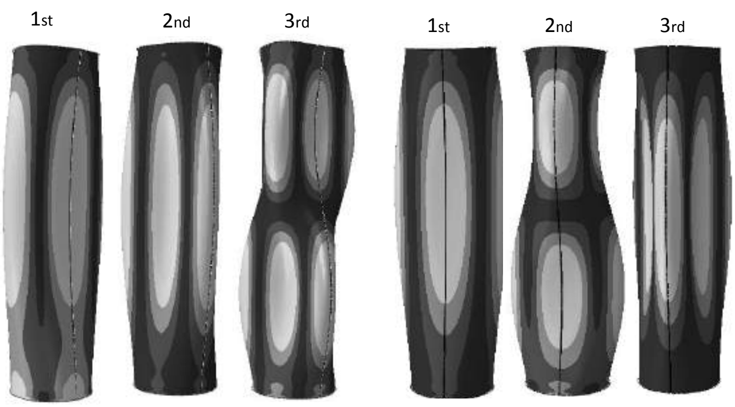
(a) (b)

Figure 5. (a) Axial and (b) hoop stresses at a pressure of 12 MPa obtained from a classical laminate theory (CLT) analysis compared with numerical results for plain and satin weave over a path that corresponds to the middle layer of the laminate along the tube length.

The first three buckling modes are illustrated in Figure 6. Each material exhibits different symmetric and anti-symmetric buckling shapes. Figure 7 illustrates a comparison between the numerical (after buckling analysis) and experimental depths at failure. A considerable agreement is achieved which indicates that most probably the tubes failed due to buckling. Further non destructive analysis needs to verify this assumption.

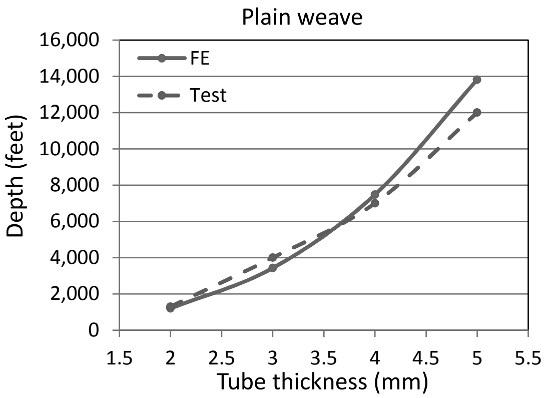
3.2. Crush behaviour of filament wound and braided tubes

The current work is looking at the advantage of hoop reinforcement while gradually moving from the laminated tubes to more advanced textile-based composites. Figure 8(a) shows that as the wind angle approaches the hoop then the advantage over the achieved depth under hydrostatic loads is clear. Highest performance is achieved with the hybrid $87^o/70^o/87^o$ and 87^o angle. However as observed from the failure modes in Figure 9 as the angle moves towards the hoop a more brittle (without any post buckling integrity) behaviour is observed which needs further investigation since it might not be suitable for certain applications. The same failure

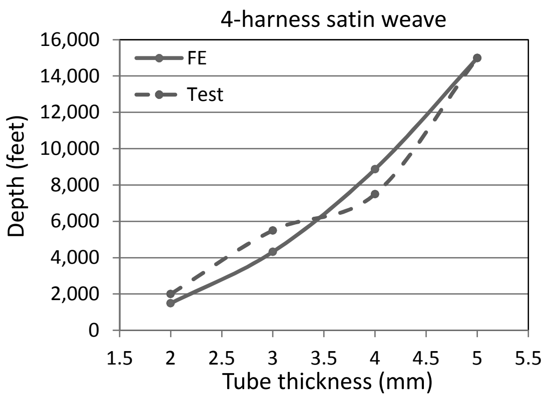


(a) (b)

Figure 6. First three buckling mode shapes of a 2 mm wall thickness laminated tube made of (a) plain weave and (b) 4-harness satin weave (deformation scale factor=1e-02).



(a)



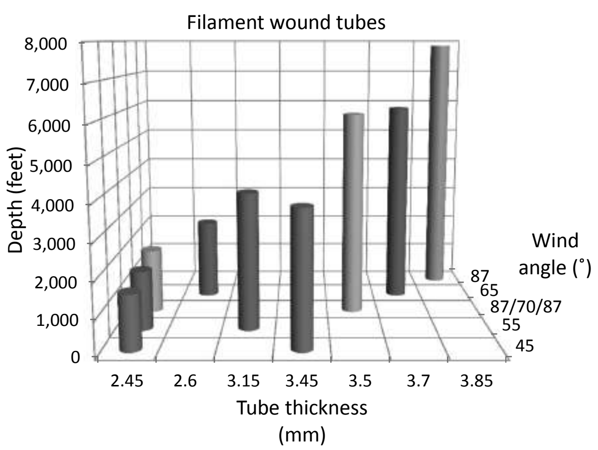
(b)

Figure 7. Comparison between the test and numerical buckling analysis results for the depth at which the tubes crushed for the (a) plain and (b) satin weave laminated tubes.

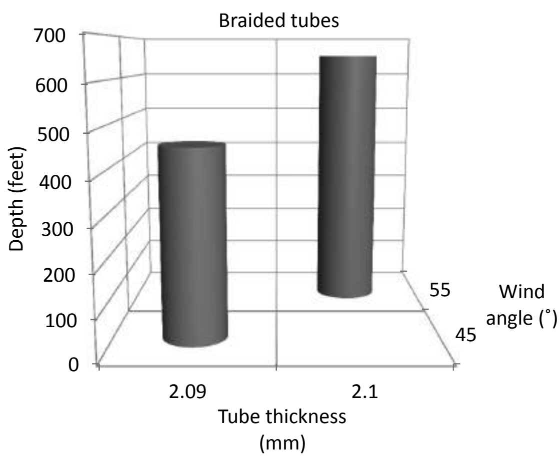
phenomenon can be observed if the plain weave and satin weave laminated tubes are compared; satin weave exhibits more brittle failure than plain weave. The braided tubes exhibited superior performance than the respective plain weave laminated tubes but relatively lower than the filament wound and the satin weave tubes. This is an ongoing research that will look at further optimising the braid angle so that it is comparable to that obtained with filament winding.

4. Concluding remarks

The current work demonstrated a preliminary study on the behaviour of E-glass fibre reinforced laminated, filament wound and braided tubes under hydrostatic compressive loads. A range of different fibre arrangements for each manufacturing technique were investigated with a supplementary finite element analysis and classical laminate theory. Results indicated the superior performance of the textile-based composite tubes, especially of those whose reinforcement approaches the hoop. Further work will focus on advanced finite element work for the optimisation of the microsctructure of braided and filament wound hybrid fabrics and their experimental



(a)



(b)

Figure 8. Comparison between the hydrostastic compressive testing results of (a) filament wound tubes and (b) braided tubes.

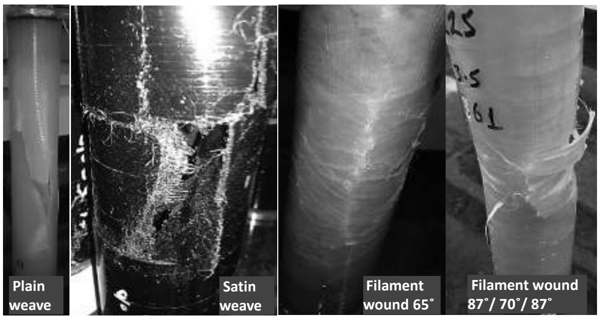


Figure 9. Illustration of specimens with fitted end caps after testing.

verification through testing and non destructive evaluation.

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