Numerical and Experimental Investigation of the Hydrostatic Performance of Fibre Reinforced Tubes

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Abstract: - The expanding requests in subsea industry, for example, oil and gas, prompted a quickly developing requirement for the utilization of cutting edge, elite, lightweight materials, for example, composite materials. E-glass fiber covered pre-preg, fiber wound and twisted tubes were tried to annihilation under hydrostatic outer weight with a specific end goal to ponder their clasping and pounding conduct. Distinctive fiber designs and wind edges were tried at a scope of divider thicknesses featuring the preferred standpoint that circle support offers. The exploratory outcomes were contrasted and hypothetical forecasts acquired from exemplary overlay hypothesis and limited component examination (ABAQUS) in view of the important that the dominating disappointment mode was clasping. SEM examination was additionally performed to explore the subsequent disappointment systems, demonstrating that the disappointment instruments can be more mind boggling with an assortment of watched modes occurring, for example, fiber break, delaminating and fiber-lattice interface disappointment.
Keywords: - Filament winding, Braiding, Buckling analysis, Hydrostatic external pressure, Textile composites.

INTRODUCTION

As the prerequisite for accomplishing higher subsea profundities is expanding so does the interest for the utilization of lightweight, superior composite materials, with an end goal to supplant the generally utilized metallic structures. The move towards investigation and advancement of composite materials for profound water subsea applications in oil and gas industry, can limit the basic weight which can be troublesome and expensive to oblige at high water profundities. Furthermore, the strikingly high properties and quality of composite materials can offer a basic option for the plan of various structures, for example, bore risers. There has been a current enthusiasm for using weaving strategies from the materials business with a specific end goal to deliver elite textures for composite structures. These assembling systems intend to conquer issues identified with covered composites, for example, delaminations and interface confound between the constituent materials through the joining of the tows in the through-thickness course [1]. All the more particularly twisting innovation has been recommended for various business applications, for example, fuel lines, rocket dispatch tubes and air ship auxiliary parts because of the basic preferred standpoint over option weaving methods. Three of its significant rivals are fiber winding, pultrusion and tape lay-up. A few investigations have drawn the consideration on the benefits of meshing as far as basic uprightness, plan adaptability, harm resistance, repair capacity and low assembling cost [2]. Complex shapes can be effectively created while the execution can be controlled through the direction of the interlace, pleat point and other geometrical attributes.

Meshed tubes show a better basic quality due than the way that the interlacements go about as split captures as opposed to overlaid and fiber wound tubes where the breaks keep running along the filaments [3, 4]. A few examinations have concentrated on the smash conduct of overlaid, woven and weaved composite tubes. These examinations explored the parameters that can influence the devastating qualities, for example, fiber and framework materials, fiber example and shell geometry. Also broad work has been done on the numerical examination and examination of the devastating modes. However little work has concentrated on the vitality assimilation and squashing mode investigation of meshed tubes. Among the most striking work; Karbhari et al. featured the benefits of 2D plaited composite tubes for vitality assimilation applications by concentrate distinctive sorts of filaments, quantities of layers and mesh designs [5]. Chiu et al. inferred that plaited composite tubes with 20◦ edge displayed propelled vitality assimilation execution [6]. Chiu et al. contemplated the utilization of crossover 2D interlaced composite tubes fortified with Kevlar and carbon strands and recognized their devastating modes [7].

The ebb and flow look into means to add to the current learning beginning from the more ordinary covered (tape layup) tubes, and after that extending to fiber wound and twisted tubes, all strengthened with E-glass filaments. This was accomplished through the test testing of tests at a scope of divider thickness and fortification edges and through the comprehension of their unpredictable disappointment systems when subjected to hydrostatic outer burdens. This work

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likewise examined the ideal fiber edge that can give higher execution under remotely connected weight. The result was additionally related with the customarily utilized netting investigation as indicated by which the ideal edge is 55◦. To empower the improvement ponder, limited component models were created for every fiber strengthened tube class which were additionally approved with test comes about.

In Segment 2, a concise audit of fiber winding and twisting techniques is exhibited, concentrating on assembling and geometrical parts of composite tubes. In Area 3 insights in regards to the instruments and examination of remotely pressurized composite tubes are talked about alluding to past work. In Segment 4, the definite test set up followed in the present work is shown. Segment 5 shows every one of the outcomes got from trial and numerical work. At long last Segment 6 exhibits some finishing up comments.

I. AUDIT OF FILAMENTWINDING AND INTERLACING FOR THE ASSEMBLING OF COMPOSITE TUBES

2.1 FilamentWinding

Fiber winding is one of the most seasoned assembling techniques for composite assembling. The technique is utilized for non-joined fiber layup. The assembling procedure involves a pivoting and a crossing unit. This basic mechanical handling enables twisting fibers from helical to circle introduction. The flexibility in fiber layup at different edges and the straightforwardness of the system made fiber twisting one of the broadly utilized procedures. The utilization of fiber twisting for composite assembling went from military to business utilizes as a part of aviation to hydrospace enterprises. In spite of the fact that fiber winding can be utilized for creating structures, for example, wind turbines and motor fan cutting edges, it is likewise broadly utilized for assembling of a scope of round and hollow structures. The strategy is widely utilized for assembling composite weight vessels, stockpiling tanks, tubes and furthermore strong poles. Industrially accessible fiber winding machines incorporate a pitch shower for impregnating the fibers previously winding onto a pivoting mandrel. The in-line wetting process takes out the extra procedure of pitch impregnation for a dry fiber preform. The navigating of the fiber conveyance point along the length of the pivoting mandrel delivers a winding example generally known as loop and helical winding. Winding point is one of the major basic outline parameters. Amid winding procedure the numerous layers are stacked over each different as the distance across changes with a specific end goal to keep the coveted winding point generally steady between the layers, the procedure parameters-rotational and navigate speed requires altering. Exploratory outcomes from a past report demonstrates that winding edges 55◦ and □ }75◦ are ideal for biaxial and circle weight stacking individually [8]. Another examination introduced that for unadulterated circumferential stacking twisting edge of □ }75◦ and for hub stacking winding point under □ }55◦ displayed higher worry at crack [9]. It is clear that choosing ideal winding point is required in light of the composite application in thought.

There are other preparing parameters which can impact the execution of a fiber wound composite structure and winding pressure is one of those. The fiber tows are twisted at high strain to accomplish a merged structure. The coveted fiber strain can be accomplished from a tensioning gadget between the fiber conveyance creel and the gum shower. A past report recommends that an expanded winding strain can help to achieve neighborhood fiber volume portion as high as 70 % [10]. Higher winding pressure additionally adds to the mechanical properties for fiber commanded stacking. An enhanced burst weight and circle modulus of composite chambers was seen from the trials in which higher winding strain was utilized [11]. Winding stacking succession was seen to have affected interlaminar shear properties [11]. A scattered stacking of winding example accomplished higher shear disappointment stack contrasted with that of a collected stacking of a similar example inside the stack [11]. A couple of studies were likewise done on multi point fiber twisted composites through the examination of their thickness and stacking succession [12, 13]. Higher twisting point in composite prompts higher circle modulus that can oppose clasping caused by outer weight though bring down winding edge, for example, 20◦, would add to higher pivotal modulus and quality. Consequently multi pivotal fiber twisting displayed to have enhanced pressure and clasping properties [12].

2.2 Interlacing

Interlacing is a contending strategy to fiber twisting for creating round and hollow composites [14]. The guideline of the two methods inalienably delivers round and hollow structures settling on them a decent decision for assembling tubes. The two procedures have the benefit of support progression [9]. The technique in which the fiber tows are laid onto mandrel by plaiting is not quite the same as that of fiber winding. This distinction creates a bidirectional perform (+ve and −ve fiber introduction) in a solitary layer not at all like fiber winding. What's more, mesh structure has fiber interlacement not at all like fiber winding. At long last there are contrasts in abilities of fiber introduction in the two procedures [14]. Contrasted and fiber winding, twisting is another innovation inside the preforming business, consequently explore into interlacing under outside weight conditions has been restricted. There is along these lines necessity for examination concerning relative investigation of composite tube under outside weight created utilizing plaiting and in addition fiber winding and woven texture wrapping.

2.2.1 Plaiting Standard

The most well-known 2D plaiting machines utilized for creating tubular preforms are either spiral or maypole braiders. Both of these machines create tubular twisted preform with two arrangements of counter turning bobbins with filaments. Keeping in mind the end goal to deliver a tubular meshed perform of certain distance across, a strong center mandrel is utilized for over-interlacing. The mandrel is mounted on a direct take up system. In this examination tubular mandrels were overbraided on a 48 transporter maypole twisting machine for creating composite tubes for hydrostatic execution assessment. Amid the bobbin turn, as the bearers are mounted on horn adapts, the counterrotating strands deliver interlacement in helical introduction inside the twist structure. For a meshed structure the fiber introduction concerning the mandrel pivot is known as "plait point". As the composite tube basic properties rely upon fiber introduction, the point can be controlled by changing the rotational speed or straight take up speed for a given distance across of the mandrel. Uniform take up is basic to the plait design; impermanent expanded take up (bastards) or stops will create separate restricted twist augmentation or swarming [15]. Both of these events will cause varieties in mesh edge. Rawal et al. recognize four twist development factors which join to characterize an interlaced structure comprising of; the transporter speed about the plait deck (rakish speed), the take up speed, the mandrel cross-area and the quantity of yarns utilized [16].

2.2.2 Interlace Engineering

Interlace engineering can be clarified with a few parameters that determine the development of the twist. These parameters are plait point, cover factor and crease which will in the long run impact the mechanical properties of an interlaced composite. As clarified in the past segment, interlace point is the greatness of an off-hub position of a fiber situated as a helix inside the plait. Once the fiber introductions are chosen, before the interlacing the edge (α) can be ascertained by utilizing the accompanying condition.

$$\alpha = \tan^{-1}(\Omega r\ v) \quad (1)$$

where ω is the average angular velocity of bobbins (rad/s), R is the radius of cylindrical mandrel (mm) and v is the take up speed (mm/s). Another important parameter is the cover factor which indicates the extent of mandrel surface coverage by the braid. If the surface is not fully covered, even with a multi layer braided perform, the uncovered areas can leave through the thickness resin pocket within the composite. The cover factor (CF) can be calculated using the following equation.

$$CF = 1 - (1 - \frac{W_y N_c}{4\pi R(cos\alpha)})^2 \quad (2)$$

In the above equation, W_y , N_c, R and α indicate the fibre tow width, number of carriers, effective braid radius and braid angle respectively. The crimp of the fibre tow within a braid structure is a measure of undulation due to the interlacement. In this study, all the braided preforms had a regular (2/2) pattern. The percentage of crimp (e) can be calculated considering the fibre interlacement (Fig. 1) which is used later in the study for finite element analysis.

$$e = \frac{L - l}{l} \cdot 100 \quad (3)$$

II. REMOTELY PRESSURIZED COMPOSITE TUBES

The significant expansion of composite tubes to a few applications in seaward building has expanded the interest for remotely pressurized composite tubes over inside pressurized. Funnels and vessels that are liable to weight (interior or outside) are liable to a blend of pivotal and circle worries, in specific instruments whose collaboration is essential to comprehend before plan. The circle and pivotal anxieties applied over the 2D plane of a chamber divider are shown in Eqs. 4 and 5, which show that the circle stretch is twice that of the pivotal worry for a shut end thin walled tube [24].

$$Hoop\ stress:\quad \sigma_H = \frac{P \cdot r}{t}$$

$$Axial\ stress:\quad \sigma_A = \frac{P \cdot r}{2t}$$

where P is the applied pressure, r is the radius of the tube and t is the tube thickness. However the underlying mechanisms for isotropic tubes are very different to the ones for anisotropic tubes. Netting analysis is one of the simplest methods that has been extensively used to identify the optimum reinforcement angle for fibre reinforced composite materials, particularly well suited to pressure vessels and tubes. This is a modelling technique which assumes that all loads are carried by the fibers only and the matrix strength and stiffness is taken to be negligible [25]. It also assumes that no shear loading is present resulting in a system where filaments are loaded with pure tensile or compressive stresses allowing for simplified analysis [26]. Equation 6 can therefore be derived, which describes the optimum reinforcement angle (α) for cylinders and pipes under pressure loads [25]:

$$\alpha = tan^{-1}\sqrt{R} \qquad (6$$

where R is the hoop to axial stress ratio ($\sigma H / \sigma A$). If we consider that the ratio R is equal to 2, then the optimum angle is α=54.73◦ for tubes under pure pressure loads [25]. A number of researchers have investigated the accuracy of netting analysis [26, 27] or used it as a base assumption for further work [25, 28]. Netting analysis provides a basis for the understanding and further analysis of the complex mechanisms that take place during failure when a composite tube reinforced with long fibres is subject to crushing loads. However the nature of these phenomena is expected to be more complicated, and the response depends on interaction between the different mechanisms that control the crushing process such as transverse shearing, lamina bending, and local buckling. These failure modes further depend on the mechanical properties of the constituent materials, the structure of the specimen, the crushing speed and the crushing length [29]. Some studies have previously suggested that although α=55◦ offers the highest resistance to internal pressure, the same principle does not apply for buckling under external pressure [30]. The benefits of the extra reinforcement of the hoop direction were highlighted first by Mistry [31] and later by Messeger et al. [32] who proved composite wound tubes consisting of high angle (80◦ and 90◦) layers provided higher resistance to buckling under external pressure than α=55◦. Several researchers have explored fracture phenomena, design parameters and failure modes of composite tubes under external loading or biaxial loading [33–35]. The fracture mechanisms can be very complex, resulting from a combination of different failure modes. Harte et al. found that the dominant failure mode of composite braided tubes subjected to compressive loads is diamond shaped buckling, which initiates at a peak stress and further propagates at a lower load as seen in Fig. 2a [36]. The work by Davies et al. which focused on the collapse failure mode of a hybrid steel/composite cylinder under hydrostatic pressure demonstrated that an out of plane lateral buckling was observed which was not predicted by the FE model [37]. In addition little work has focused on the understanding of how the fibre angle can influence the failure modes.

III. EXAMPLE ARRANGEMENTS AND TRIAL SET UP

Tubes made of various assembling techniques (overlaid pre-preg, fiber winding and plaiting) were tried in this examination. However the example readiness and testing strategy stayed steady to take into account a similar examination. The means took after for the planning of the examples preceding testing are outlined beneath:

1. The provided tubes were machined to the coveted lengths; 220 mm length each.

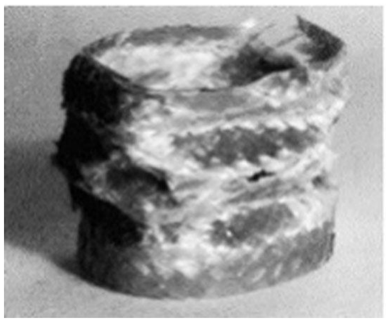
2. Aluminum end tops were machined for push fit associations into the tube closes.

3. The surfaces of the tube tests and the end tops were cleaned by sanding taken after by oil evacuating and CH3)2CO wiping.

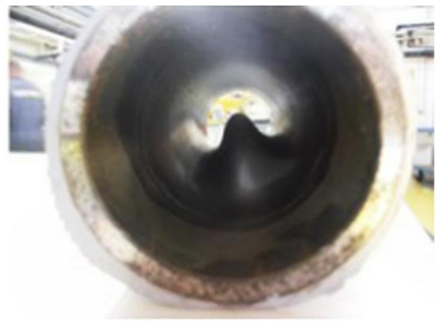
4. Fitting measure of Scotch-Weld (2216 B/A Dim Epoxy Cement) was set up by blending 70 gr of adjusted amine (quickening agent) and 50 gr of altered epoxy (base).

5. The cement was connected on the surface of the end tops, on the internal surface of the tube and over the tube cross area as appeared in Fig. 3a.

6. The end tops were connected at the one end of the tube first. The fortified side was then situated at the base with the goal that any broad glue spillage is avoided.



(a)



(b)

Fig. 2 Difference in axial and lateral buckling **a** Axial buckling of glass/PP composite tube [36] **b** lateral buckling of a steel/composite hybrid cylinder [37]

7. Same procedure was performed for all the tubes. The adhesive was left to cure under two heating lambs overnight while the tubes and end caps were clamped in order to achieve better adhesion as shown in Fig. 3b.
8. The same procedure was followed for the adhesion of the end caps at the other end of the tubes.
9. Once both end caps were fitted and the adhesive was semi-cured, all tubes were left overnight in an oven at 60 ◦C for the adhesive to fully cure, according to the recommendations of the adhesive supplier.

This study focused on the hydrostatic testing of tubes to failure. The tubes were tested in a pressure pot with capacity of 6 litres which can reach testing pressures equal to 1,973 bars. The testing equipment consists of a piston, pressure transducers, a pressure pot and a tube which is used in order to pump in water to the pressure pot. The test specimen is placed inside the pressure pot, water is pumped in and any rapid change in the pressure is translated as failure as water starts coming through the crushed specimen. This change in the pressure is detected by the pressure transducers. The pressure pot operates at a controlled temperature.
The test follows an ASTM D2736-78 standard testing procedure. Approximately three to four tubes per configuration were tested to failure and the average performance is presented in the next section.

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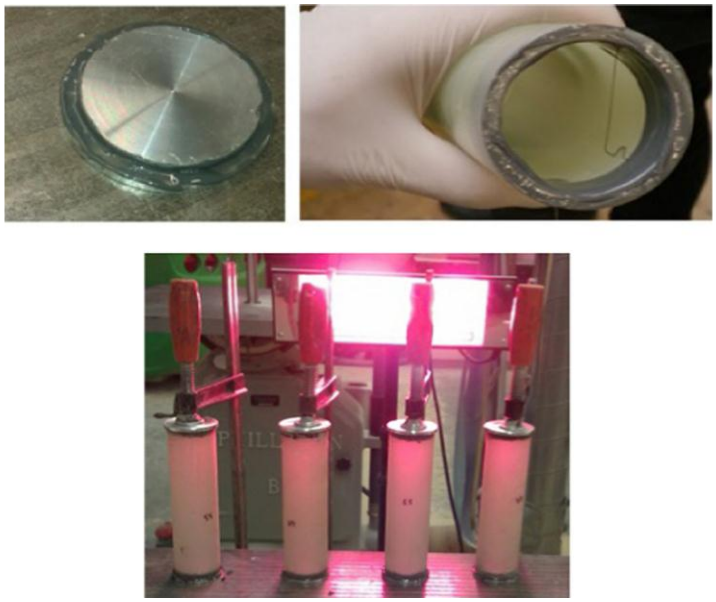

(b) Tubes clamped and under heating lamp for the pre-cure of the adhesive.
Fig. 3 Specimen preparation

IV. RESULTS

5.1 Pre-Preg Tubes

For the manufacturing of the laminated tubes, two types of fabrics were considered. Both types were reinforced with glass fibres; the standard property tubes are made of plain weave while the enhanced property black and clear as standard are made of 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 total fibre volume of 60 % as shown in Fig. 4. Plain weave indicates the most simple textile weave style where the weft alternates over and under the warp. In contrast, in the 4-satin weave, the fill yarn passes over three warp yarns and under one. The difference in the weave style has an imminent impact on the fibre volume fraction along the two main directions.

The thickness of each ply was 0.23 mm for the plain weave and 0.25 for the 4-harness satin weave. The respective mechanical properties are illustrated in Table 1 as provided by the tube supplier. The tubes were wound at 0/90 degrees; the weft direction was aligned with the axial axis of the tube and the warp direction was aligned with the circumferential direction of the tube. The length of all the manufactured tubes was 220 mm length and their internal diameter was 50 mm. Tubes were made at a range of wall thicknesses from 2 mm to 5 mm. (Fig. 4). As shown in Table 1 the axial and hoop tensile and compressive strength of the 4-harness satin weave are directly related to the fibre reinforcement pattern. As a result the axial strengths are more than 4 times lower than the respective hoop strengths. The tubes were cut to size and the specimens were appropriately prepared for testing in the pressure pot under hydrostatic compression as described in Section 4. Figure 5 illustrates representative examples of failed tubes made of plain weave and 4-harness satin weave. As shown, failure initiated at the centre of the tube across its length due to fibre cracking and delamination and further propagated towards the end caps. The primary observation is that the tubes failed due to a combination of inelastic buckling and axisymmetric yield failure. Satin weave exhibited a more brittle failure compared to plain weave which is probably

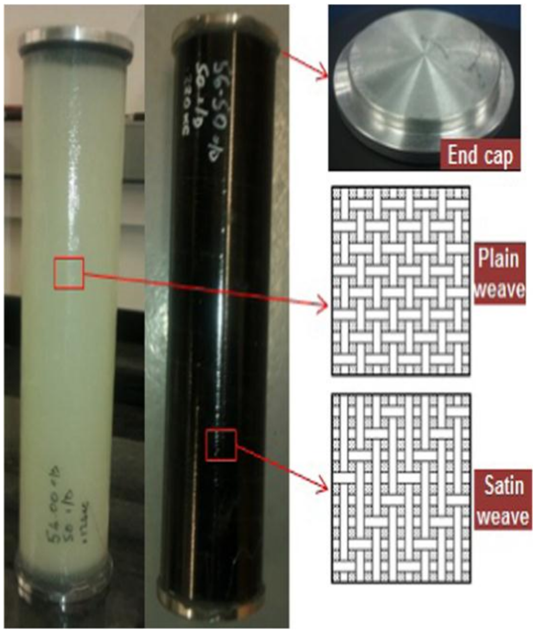

Fig. 4 Illustration of specimens with fitted end caps prior to testing

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

Mechanical properties	Plain weave	4-harness satin weave
Young's modulus (Hoop): E_1(C)	20 GPa	35 MPa
Young's modulus (Axial): E_2(C)	20 GPa	8.9 GPa
Shear strength: G_{12}(C)	3 GPa	1.5 GPa
Poisson's ratio; ν_{12}(C)	0.3	0.32
Tensile strength (Hoop): S_1(T)	250 MPa	657 MPa
Tensile strength (Axial): S_2(T)	250 MPa	99 MPa
Compressive strength (Hoop): S_1(C)	300 MPa	500 MPa
Compressive strength (Axial): S_2(C)	260 MPa	80 MPa

related to the fact that the satin weave consists of more fibres at the hoop direction with less fibre carrying the axial loads.

One tube from each wall thickness made out of plain weave was taken out of the batch before testing for microscopic testing. The microscopic analysis aimed to validate the porosity level through the tube thickness and hence assess the capability of the manufacturing technique. Possible porosity could mask the true failure mode. The microscopic analysis was performed on pieces machined out of the middle section of the tubes along their length, where damage due to external pressure was expected to initiate during testing. The instrument used was a Dinolite Premier2 Digital camera model number AM7013MTL with a magnification equal to 20-70x, and a resolution equal to 1280 x 960. The microscopic analysis of the plain weave tubes showed that at low wall thickness, air pockets of up to 1mm thick are present, and which could potentially act as internal delaminations that could alter the properties of the cured lamina (Fig. 6). As the tube thickness increases, the consolidation during curing is better and the number of air pockets is lower as shown in the same figure.

V. CONCLUSION

This work examined the execution of composite tubes when subjected to outer hydrostatic weights. Initial a writing survey featured the most basic outline and assembling parameters for material composite tubes; fiber wound and interlaced. At that point the work concentrated on the exploratory and numerical investigation of pre-preg overlaid tubes made of plain and silk weave and fiber wound and twisted tubes twisted at a scope of fortification edges. Their relating conduct under outer hydrostatic weight was researched. Limited component (FE) models of the tubes were created keeping in mind the end goal to explore the hypothetical execution of a greater scope of tube thickness and interior widths contrasted with what was tried. The FE examination accepted that clasping is the essential driver of disappointment and consequently centered around the investigation of the weights causing the tube clasping modes. Exemplary cover hypothesis was directed through ESA Comp programming so as to additionally approve the FE models produced particularly for the overlaid tubes. At that point a similar FE displaying approach was taken after for fiber wound tubes produced at a scope of twisting edges keeping in mind the end goal to set up which is the most ideal edge. This part took after a straightforward approach of evaluating the material trucks required for the FE reenactment in light of the Halpin-Tsai conditions for the fiber wound tubes and on an altered model proposed beforehand in writing for the twisted tubes. The FE forecast of the interlaced tubes execution depended on an altered model as per which the successful consistence grid of a crease yarn can be acquired by averaging the changed consistence network of the minuscule yarn fragment through the pleat edge. The FE models were produced and effectively approved against the test outcomes. An advancement ponder was led for the fiber wound tubes which showed that the ideal plots for most extreme protection against outside hydrostatic weights are the ones nearer to the heading of the circle support. At last SEM was directed for the interlaced tubes keeping in mind the end goal to additionally get it the disappointment modes from a tiny perspective. The work reasoned that the disappointment instruments of composite tubes when presented to outer hydrostatic weights are mind boggling and along these lines outline against outside weights needs cautious thought. As SEM pictures of the meshed tubes appeared, the disappointment mode is blended, conceivably influencing the filaments, grid and additionally the interphase. What's more, the FE investigation of non traditional fiber fortified tubes, for example, fiber wound and meshed isn't generally clear. This investigation took after straightforward methodologies which concentrated on the foundation of layer-by-layer lay-up assembled. However to acquire the material properties of a solitary layer when the fiber fortification comprises of interlacements can challenge. This examination exhibited a rearranged displaying approach which was effectively approved against the test outcomes. Moreover it can be contended that in spite of the fact that the distinctive assembling techniques can not be specifically thought about, the fiber wound and plaited tubes can possibly display higher protection from outer hydrostatic weight contrasted with the pre-preg overlaid tubes. At long last, the examination demonstrated that albeit past work recommends that fiber support of 55◦ offers the most elevated protection from inward weight, a similar guideline does not make a difference for outside weight, where the tubes with fiber fortification moving toward the band heading showing higher execution. This lies on the way that the appropriation of hub and transverse burdens amid utilization of inner weight is distinctive to the use of outside weight consequently prompting diverse disappointment systems. Outside weight brings about higher powers being connected on the loop bearing contrasted with hub, while inward weight brings about an alternate load circulation where pivotal and band strands both contribute fundamentally to the tube burst quality.

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