Journal of Pressure Vessel Technology
June 2016, Volume 138, Issue 6, Pages 060907 (8 pages)
http://dx.doi.org/10.1115/1.4033942
http://archimer.ifremer.fr/doc/00343/45409/

Composite cylinders for deep sea applications, an overview

Davies Peter [1, *], Choqueuse Dominique [1], Bigourdan Benoit [1], Chauchot Pierre [1]

[1] IFREMER ,Marine Structures Laboratory, Centre Bretagne, F29280 Plouzané, France

* Corresponding author : Peter Davies, email address : peter.davies@ifremer.fr

dominique.choqueuse@sfr.fr ; Benoit.Bigourdan@ifremer.fr ; pierre.chauchot@orange.fr

---

Abstract :

In order to develop the knowledge base necessary to design deep sea pressure vessels it is essential to understand the full chain from design and manufacturing through NDT and characterization to long term behavior under hydrostatic pressure. This paper describes results from European and national research programs focusing on the use of composites for underwater applications over the last 20 years. Initial tests on small glass/epoxy cylinders were followed by large demonstration projects on carbon/epoxy cylinders with implosion pressures of up to 600 bar, corresponding to 6000 meter depth. Numerical modeling has enabled end closures design to be optimized for test performance. Thin and thick wall cylinders have been tested under quasi-static, and long term loading. Both thermosetting and thermoplastic matrix composites have been tested to failure, and the influence of defects and impact damage on implosion pressure has been studied. These deep sea exploitation and exploration studies were performed for oceanographic, military and offshore applications, and extensive data are available. The aim of this paper is to indicate existing results, particularly from European projects, in order to avoid costly repetition.

INTRODUCTION

Composite materials offer great potential for underwater applications. This potential has been recognized for many years [1], and external hydrostatic pressure tests on small cylinders were reported 50 years ago by Hom and Couch [2]. Smith and colleagues in the UK [3], and Stachiw and colleagues in the USA [4] then described various studies on glass and carbon reinforced cylinders. Bigourdan et al [5] also reported results from implosion tests performed at Ifremer in the late 1980’s. These were followed by extensive testing in France (Figure 1), both in special pressure chambers and at sea, and the development of specific modeling capabilities. The first applications were for electronic housings for oceanographic exploration, then interest moved to underwater vehicles such as AUVs (Autonomous Underwater Vehicles). Today the use of composites is being studied for the offshore industry, as deeper exploitation (down to 4000 meters depth in the near future) demands lighter structures which have given a new impetus to the use of composite materials.

In order to avoid a long list of all the programs which have been carried out on the topic of the use of composite for underwater applications, this paper focuses on some of the key problems which have been addressed during these studies. This is not strictly a chronological list, but shows the progress which has been made towards development of large, complex underwater structures, and provides a view of the current state of the art on deep sea composite pressure vessels.

MATERIAL PROPERTIES

For many applications, filament winding of cylinders is the preferred manufacturing process. Special efforts have therefore been focused on the determination of the mechanical properties of filament wound materials. The loading conditions and the expected failure mode of the structure (buckling for thin wall tubes, biaxaial compression material failure for thick walls) make the determination of the compression behavior the priority, and the first step is to characterize the elastic behavior of the material. These values are needed for modeling and design and can be used to give a first indication of buckling behavior. Both the curvature and thickness of these cylindrical structures make the use of standard tests difficult, and so an inter-comparison of results from different types of test has been performed.

Table 1 presents examples of results from tests on a glass/epoxy cylinder (25 mm thick, wound at ± 55° to the cylinder long axis), using different experimental methods. These include ultrasonic wave speed measurements, modal vibration analysis of rings, and model predictions:

- Ultrasonic wave speed analysis: this involves measurement of the speed of ultrasonic waves of different polarization (compression and shear) directly on thick coupons of material taken from the structure, then using an inverse method to access the 9 anisotropic elastic parameters of the material. This method has been developed in some detail by Hosten and colleagues, and is detailed in [6].

- Vibration analysis [7]: this consists of measuring the modal frequencies of a ring taken from the structure (in plane, out of plane, and extension mode-shapes), then using an optimization method to determine five independent elastic moduli of the material.

The values from these two methods were compared with results from micro-mechanics models based on the homogenization method [5]. The results in Table 1 underline the difficulty in establishing reliable material properties, even the elastic constants, needed to simulate the behavior of thick composite cylinders.

When compression strengths are required the situation is even more complex. An international standard for compression testing now exists [8], but it includes various test options for simple specimen geometries of unidirectional composite. Several authors have discussed the difficulties associated with compression testing, e.g. [9-11], but the additional constraints in ensuring fiber and specimen alignment for specimens produced by filament winding, a process which tends to produce asymmetry through the specimen thickness, are considerable. An alternative, but rather expensive, approach is to test instrumented cylinders directly under external pressure and use results to back out compression behavior. This can provide reliable elastic constants, but the quality of strength data is then strongly dependent on test conditions and particularly end closures, as will be shown below. Unfortunately there is also little agreement on failure criteria in the compression-compression quadrant of the hoop/axial stress diagram as illustrated by the Worldwide Failure Exercise [12]. In the latter the same input data were supplied to different groups which used their failure criteria to estimate failure under a range of combined stress loading cases. Predictions were compared with experimental data for a ±55° glass/epoxy cylinders. For the external pressure case all the predictions underestimated failure, in some cases by 50% [13].

Another aspect of the development of reliable failure predictions, which was unknown when these programs started, is the influence of hydrostatic pressure on material properties. Studies of this type require special test fixtures, enabling direct mechanical property measurements to be made while specimens are subjected to pressures up to at least 600 bars. Various authors have examined this problem over the last 30 years [14,15], in particular at Rutgers University [16,17], within the ONR (Office of Naval Research) Solid Mechanics program among others, and Hoppel et al provided a review of published data [18]. The general conclusion has been that at the pressures of interest in-plane composite strengths may drop due to a loss in matrix toughness. More recently there have been additional studies on the influence of pressure on both interlaminar fracture properties and adhesive behavior [19,20]. These are both polymer dominated and are sensitive to pressure.

NDT CONTROL

Manufacturing of thick composite materials, in particular with carbon fiber reinforcement, has to be strictly controlled in order to verify that internal defects due to thermo-chemical reactions and internal stresses are not present. A NDT method based on the ultrasonic technique has been developed, which uses a 2 MHz focused sensor. Many filament wound carbon and glass reinforced epoxy cylinders up to 60 mm wall thickness have been inspected over the last 30 years at Ifremer, and defects such as delaminations can be clearly identified (Figure 2). The principle of the method is to immerse the cylinder in water on a turn-table and to follow the amplitude level of the signal reflected by a perfect reflector (metallic plate) placed inside the tube. This method has been calibrated in several European projects with structures having artificial internal defects, and attenuation levels up to 30 dB have been related to delaminations.

END CLOSURES

Once the cylinder has been manufactured, end closures are required in order to test it. This is also an operational requirement in the design of instrumentation containers (generally cylindrical tubes) in order to withstand deep sea hydrostatic pressure.

Different solutions can be used such as:

- flat plates with direct contact with the tube ends,
- flat inner-stepped closures with direct contact on the inner periphery of the tube,
- metallic domes with watertight rings bonded to the tube ends,
- composite domes.

Blake and Starbuck described a method to design end closures to limit bending and shear discontinuities [21]. They recommended a linear taper rather than a constant radius, as it provides constant stresses at increasing pressure. To illustrate the importance of end closure design, two flat plate solutions were modeled numerically [22] then tested. The FE mesh configuration is shown in Figure 3. Significant gains in collapse pressure, up to 25 %, have been obtained simply by changing the end closure geometry (Table 2), and these can be reasonably well predicted.

For bigger structures hemispheric domes have been designed and tested in several projects. Buckling of metallic domes has been extensively studied since early work by Galletly and colleagues [23], who have also studied composite domes [24]. A set of composite domes (epoxy resin, carbon fiber), manufactured by RTM (resin transfer molding) has been tested recently [25], (Figure 4), and these provide a significant improvement in the design and manufacturing of closures for such structures.

MANUFACTURING AND TESTING OF LARGE CYLINDRICAL STRUCTURES

The scale of deep sea structures for offshore applications is significantly larger than many of the oceanographic applications and a significant effort has been directed towards ensuring that large structures can be designed, manufactured and tested. One of the results of this effort has been the manufacture of several 1.25 meter long, carbon/epoxy cylinders of thickness up to 40 mm thick and 500 mm inner diameter. These were produced by wet filament winding, within European projects, and subsequently fully instrumented with up to 120 strain gauges before testing to failure in the Ifremer pressure vessels, (Figure 5). The 40mm thick-walled cylinder shown imploded by mode 2 buckling (hoop buckling with 2 nodes) at 610 bars pressure [26]. Figure 6 shows an example of the hoop strain recordings from gauges at mid-length during this implosion test, which clearly indicate the change in geometry as buckling occurs. Recent developments in fast image correlation and special pressure vessels with view-glasses are allowing much more detailed analyses of the mechanisms leading to failure [27-29]. The pressure pulse generated by the implosion of composite cylinders can be detrimental to neighboring structures. The energy released from this implosion pulse can be modified beneficially by using coatings like polyurea [30]. Underwater composite cylinders can also be subjected to shock loadings and their response to such extreme events is barely understood. A recent paper discussed the collapse of carbon composite cylinders to underwater shock loadings [31].

Larger scale test facilities equipped with data recording during pressure tests are very rare in Europe, so demonstration projects on structures larger than 1 meter diameter and 2 meters long may be easier to perform directly at sea.

LONG TERM BEHAVIOR

In order to verify the long term integrity of composite cylinders a number of creep and cyclic loading tests have been performed. The first tests were performed in pressure vessels but later cylinders were instrumented with data loggers and placed at sea, at depths down to 2500 meters for up to one year, Figure 7 [22]. The data recovered, such as that shown in Figure 7 for 140 days at sea, enable shorter term qualification tests in pressure vessels to be validated.

A second aspect of long term behavior is the response of the material to the marine environment. Results from a number of studies of the wet aging of composite tubes have suggested that when the matrix has been correctly chosen and provided the manufacturing procedure is correct the effect of wet aging on the properties of thick composite cylinders is a secondary effect [32,33]. Questions have also been asked about the influence of hydrostatic pressure on water diffusion and aging. Several recent studies have clearly shown that while voids may be filled more quickly with water at high pressures the aging process is not significantly affected [34].

DEFECT TOLERANCE AND INTERNAL STRESSES

There are several types of defect which can appear in composite cylinders. The first is geometrical imperfections which are created during fabrication. The influence of these on buckling behavior has been extensively studied [35,36]. Messager has shown that stacking sequence can be optimized with respect to buckling [37], while Hernandez et al. have examined the influence of winding pattern geometry [38]. A second type of defect is delaminations. An example of delaminations revealed by NDT techniques is shown in Figure 2. Such defects can significantly affect cylinder integrity and extensive studies have been performed to characterize their propagation under different types of loading [39,40]. A third type of defect is damage introduced during service. Impact damage is particularly critical and may result in multiple delaminations such as those shown in Figure 8. Several studies performed in this area in recent years have evaluated impact damage mechanisms in tubes [41,42] and then quantified the influence of that damage on implosion resistance, e.g. [43]. Figure 9 shows one example of the correlation between impact damage, quantified by ultrasonic inspection, and residual implosion strength.

Finally, another form of defect, linked to fabrication, is internal residual stresses. These are more difficult to quantify but recent work using strain gauged specimens and liberating internal stresses by machining has shown that they may be significant and should not be ignored [44].

STUDIES OF LARGE CYLINDRICAL OFFSHORE STRUCTURES

Over the last 10 years, several studies have been performed to examine the potential of large scale filament wound structures for offshore application. One example will be described briefly here, which concerns subsea oil separation systems, Figure 10. These are large reservoirs placed on the sea floor, in which oil is separated from gas, sand and water. The SEPCOMP project (subsea oil SEParation with COMPosite materials) led by Doris Engineering focused on four points:

- the hull of the horizontal gravity separator (30 m^3) made of a sandwich cylinder (skins: carbon filament winding, core: foam) and two hemispheric end closures (RTM, carbon fibres);
- the composite pipes of the module;
- the support frame of the module made of composite beams;

- the protection cover of the installation made of sandwich plates.

Two different water depths were considered (1500 and 3000m). The expected benefits of composites compared to steel for this application are:

- lower costs of deployment, mainly due to the reduction of the module weight;
- lower costs of maintenance, mainly due to the reduction of corrosion problems;
- new design possibilities in the water depths envisaged;
- standardization of a number of structural parts.

Figure 11 shows FE models of the separator tank. Figure 12 shows the overall cost savings for 1500 m depth for the composite design compared to a metallic structure [45]. Manufacturing and installation costs are 30% lower for the composite separator. The calculations also showed that a composite separator designed for a 3000 meter immersion using the same options as those presented above has the weight of a metallic tank designed for 1500 meter water depth. These are very promising applications for composites, which become more attractive as water depth increases.

NEW MATERIALS

The examples described above have been based on “traditional” glass/epoxy and carbon/epoxy materials, but there is considerable current interest in thermoplastic matrix composites for large marine structures. Thermoplastics offer advantages such as avoiding pot-lifetime problems (local melting and compaction is used to form the material) so that large structures can be manufactured with fewer constraints, improved damage tolerance and the possibility of repair by local heating. High performance matrix polymers such as PEEK (poly-ether-ether-ketone) also show excellent high temperature properties, which may be critical in subsea structures where oil temperature can exceed 100°C. These materials have been addressed in a several recent studies [46-48] and are the subject of ongoing developments. One aspect which caused early problems was fiber waviness, which resulted in low compression strengths [49-51]. This has been studied in some detail and results from tests on small tubes indicate that implosion pressures similar to those of carbon/epoxy can be achieved [48]. Other lower cost matrix polymers such as polyamides may also be of interest in carbon fiber reinforced composites provided the influence of moisture can be accounted for [52].

HYBRID STEEL-COMPOSITE STRUCTURES

In order to promote the use of composite materials for deep offshore applications, one intermediate approach is to introduce them in hybrid structures in combination with more familiar steel parts. In a recent development project composite tubes have been manufactured and tested to examine the behavior of such structures under hydrostatic pressure [53]. The objective was to use a composite material layer to increase the safety factor of a metallic tube, in order to reach a satisfactory safety limit and to significantly reduce the weight of the overall structure. However, the interest of such structures under hydrostatic compression was not clearly demonstrated in the project, and an unexpected failure mode has been observed (Figure 13). Post-collapse

FE modeling has predicted the buckling mode of the structure but at this time the collapse pressure cannot be predicted accurately (Figure 14).

In parallel with this study, the use of Fiber Bragg Grating sensors to monitor deep underwater structures has been investigated [54]. The possibility to use embedded sensors has been verified, and a modified interface has been developed. However, taking into account the severe loss of signal due to pressure increase, without any additional precautions the use of embedded sensors has to be limited to a pressure lower than 300 bar (3000 meters). More work is needed on *in-situ* instrumentation for deep sea applications.

FURTHER STUDIES

In spite of the extensive research which has been performed on composite cylinders for deep sea applications over the last 50 years, there are some points which still need to be addressed. These include the optimization of material selection for high temperature applications (e.g deep offshore oil and gas components), the design of cut-outs and inserts, and the modeling and manufacture of large thick sandwich structures. The potential of thermoplastic matrix composites has not been exploited yet but should provide cost-effective solutions in the near future.

CONCLUSIONS

This paper gives a brief overview of some of the subjects which have been addressed in projects performed in Europe with a large number of collaborating organizations over the last 30 years. The development of composite containers for oceanographic applications down to 6000 meters depth has enabled considerable experience to be gained. Tools and technology have been developed which are now being applied to the use of composite materials for deep sea offshore oil & gas applications. Awareness of the existence of these results and the more detailed descriptions provided in the references, may help with other developments and avoid costly repetition.

ACKNOWLEDGMENT

The authors acknowledge the contributions of CNIM (Fr), DCN (Fr), DERA now QinetiQ (UK), DNV (N), Marinetech South (GB), NTUA (Gr), TNO (NL) within European Union funded projects, of Bureau Veritas, CNIM, Doris, IFPEN, PROSERNAT and Total in the SEPCOMP project, and the University of Toulouse and IDIL for the hybrid cylinder and Bragg grating work, both within French CEP&M collaborative projects. The expert advice and support of many colleagues at IFREMER in Brest is also gratefully acknowledged.

FUNDING

The work described here was funded by internal research budgets at IFREMER, within various European Union projects (BRITE-DEVILS, MAST-AUV, MAST- Composite Housings), and within projects for the offshore oil and gas industry financed by the French Ministry of Industry.

REFERENCES

[1] Garvey, R. E., Composite hull for full ocean depth. Marine Technol. Soc. J., 24(2) (1989) 49.

[2] Hom, K. & Couch, W. P., "Investigation of Filament Reinforced Plastics for Deep Submergence Application". David Taylor Model Basin, Report 1824, Nov. 1966.

[3] Smith CS, "Design of Submersible Pressure Hulls in Composite Materials", Marine Structures 4 (1991) 141-182

[4] Stachiw, JD, Frame, B, "Graphite-fibre-reinforced plastic pressure hull mod 2 for the advanced unmanned search system vehicle". NOSC San Diego, Technical Report 1245, 1988

[5] Bigourdan B., Chauchot P, Hassim A, Léné F, 1991, "Homogenization for the design of cylindrical containers made of composite materials" in Mechanics and mechanisms of damage in composites and multi-materials, ed Baptiste D, Mechanical Engineering publications, ,London, 203-212.

[6] Hosten, B., 2001. Ultrasonic through-transmission method for measuring the complex stiffness moduli of composite materials. Handbook of elastic properties of solids, liquids and gases, Volume 1, Academic Press, San Diego, 67-86

[7] Guillaumin F, Guillermin O, Prevosto M, 1989, "Elastic constants identification of an orthotropic thick ring using experimental modal frequencies", Proceedings of the fifth SAS world conference on structural engineering, FEM & CAD, (STRUCENG), Los Angeles, IITT International, August.

[8] ISO 14126, 1999 “Fibre reinforced plastics - Determination of in-plane compression properties”.

[9] Daniels JA, Sandhu RS, 1993, “Evaluation of Compression specimens and test fixtures for evaluating unidirectional composite laminates”, ASTM STP 1206, 103-123

[10] Haberle J, Matthews FL, 1994, “An improved technique for compression testing of unidirectional fibre-reinforced plastics; development and results”, Composites, vol. 25, no. 5, 1994.

[11] Fleck N, 1997, “Compressive failure of fibre composites”, Advances in Applied Mechanics Vol 33, 43-116

[12] Hinton M. J., Kaddour A. S. and Soden P. D., 2004,”Failure Criteria In Fibre Reinforced Polymer Composites: The World-Wide Failure Exercise”, published by Elsevier Science Ltd, Oxford, UK.

[13] Soden PD, Kaddour AS, Hinton MJ, 2004, “Recommendations for designers and researchers resulting from the world-wide failure exercise”, Composites Science and Technology 64, 589–604.

[14] Weaver CW, Williams JG, 1975, “Deformation of a carbon-epoxy composite under hydrostatic pressure”, J. Mat. Sci., 10, 1323-33.

[15] Sigley RH, Wronski AS, Parry TV, 1992, “Axial compressive failure of glass-fibre polyester composites under superposed hydrostatic pressure: influence of fibre bundle size”, Composites Science and Technology 43 (1992) 171-183

[16] Pae KD, Rhee KY, 1995, “Effects of hydrostatic pressure on the compressive behavior of thick laminated 45 and 90° unidirectional graphite-fiber/epoxy matrix composites”, Composites Science and Technology, 53, 281-287

[17] Pae KD, 1996, “Influence of hydrostatic pressure on the mechanical behavior and properties of unidirectional, laminated, graphite fiber/epoxy-matrix thick composites”, Composites Part B 27, 599-611

[18] Hoppel CPR, Bogetti TA, Gillespie JW Jr., 1995, “Literature Review-Effects of Hydrostatic Pressure on the Mechanical Behavior of Composite Materials”, J. Thermoplastic Comp., 8(4), 375-409

[19] Davies P, Cartié DDR, Peleau M, Partridge IK, 2006 “The influence of hydrostatic pressure on the interlaminar fracture toughness of carbon/epoxy composites”, Composites Part B: Engineering Volume 37, Issues 4-5 , June-July, 292-300

[20] Cognard JY, Créac’hcadec R, Maurice J, Davies P, Peleau M, da Silva LFM, 2010, “Analysis of the Influence of Hydrostatic Stress on the Behaviour of an Adhesive in a Bonded Assembly, Journal of Adhesion Science and Technology 24, 1977–1994

[21] Blake HW, Starbuck JM, 1994, “A shear deflection theory for analysis of end plugs for external pressure tests of composite cylinders”, ASTM STP 1185, 113-136.

[22] Davies P, Le Flour D, 2001, “Long term behavior of fiber reinforced structures for deep sea applications”, Paper 21, Proc. Oilfield Engineering with Polymers, London, 255-268.

[23] Galletly GD, Aylward RW,1973, “Buckling under external pressure of cylinders with either torispherical or hemispherical end closures”, International Journal of Pressure Vessels and Piping, Vol. 1, No. 2, April 139-154,

[24] Blachut J, Galletly GD, Gibson AG, 1990, “CFRP domes subjected to external pressure” Marine Structures, 3 (2) 149-173.

[25] Papazoglou V, Livingstone F, Chauchot P, Jennequin G, Kilpatrick I, Meddes R, Stevenson P, 2004, “Lightweight composite pressure housings for mid-water and benthic applications”, Proc. ECCM11, Rhodes, Greece, June.

[26] Davies P, Choqueuse D, Riou L, Warnier P, Jegou P, Rolin JF, Bigourdan B, Chauchot P, 1996, “Composite Materials for 6000 meters depth”, Proc. JNC10 (French Composite materials conference), Paris, 525-536.

[27] Gupta S, Parameswaran V, Sutton MA, Shukla A, 2014 “Study of dynamic underwater implosion mechanics using digital image correlation. Proc. R. Soc. A 470.

[28] Pinto M, Gupta S, Shukla A, 2015, “Study of implosion of carbon/epoxy composite hollow cylinders using 3-D Digital Image Correlation” Composite Structures, Volume 119, 272-286

[29] M. Pinto, S. Gupta, A Shukla, 2015, “Hydrostatic Implosion of GFRP Composite Tubes Studied by Digital Image Correlation”, Journal of Pressure Vessel Technology, 137(5), 051302

[30] Pinto M, Shukla A, 2016,"Mitigation of Pressure Pulses from Implosion of Hollow Composite Cylinders" Journal of Composite Materials, doi: 10.1177/0021998315624254r.

[31] Pinto M, Shukla A, 2015,"Shock-Initiated Buckling of Carbon/Epoxy Composite Tubes at Sub-Critical Pressures", Experimental Mechanics, Vol 56, 4, 583-594

[32] Davies P, Choqueuse D, Mazeas F, 1998, “Composites Underwater”, Proc. Durability of Composite Systems conference (DURACOSYS), Virginia Tech, Balkema Press.

[33] Choqueuse D, Davies P, 2008, “Ageing of composites in underwater applications”, Chapter 18 in Ageing of Composites, edited by Martin R, Woodhead Publishers ISBN 978-1-84569-352-7, 467-498.

[34] Humeau C, Davies P, Jacquemin F, 2016, Moisture diffusion under hydrostatic pressure in composites, Materials & Design, 96, 90-98.

[35] Michelis P, 1999, “Design and Validation of Imperfection-tolerant Laminated Shell structures (DEVILS)”, Synthesis report of European project BRE2-CT94-0962.

[36] Messager T, 2001, “Buckling of imperfect laminated cylinders under hydrostatic pressure”, Comp. Structures, 53, 3, 301-307.

[37] Messager T, Pyrz M, Chauchot P, 2000. “Optimized laminations for submarine composite hulls”, European review of Finite Elements. vol.9 n°1, 199-251.

[38] Hernandez-Moreno H, Douchin B, Collombet F, Choqueuse D, Davies P, 2008, “Influence of winding pattern on the mechanical behaviour of filament wound

composite cylinders under external pressure", Composites Science and Technology, Vol 68/3-4 ,1015-1024

[39] Ozdil F, Carlsson LA, Davies P, 1999, "Characterization of delamination toughness of angle ply glass/epoxy cylinders", Proc. ICCM12, Paris.

[40] Davies P, Carlsson LA, 2009, "Delamination of Composite cylinders, in "Major Accomplishments in Composite Materials and Sandwich Structures – An Anthology of ONR Sponsored Research," editors E.E. Gdoutos, Y. Rajapakse, I. Daniel, Springer publication.

[41] Alderson K. L., Evans K. E., 1992, "Failure mechanisms during the transverse loading of filament-wound pipes under static and low velocity impact conditions", Composites, Vol. 23, N°3, pp 167-173.

[42] Curtis J., Hinton M. J., Li S., Reid S. R., Soden P. D., 2000, " Damage, deformation and residual burst strength of filament-wound composite tubes subjected to impact or quasi-static indentation", Composites: Part B, Vol. 31, pp 419-433.

[43] Gning PB, Tarfaoui M, Collombet F, Davies P, 2005, "Damage development in thick composite tubes under impact loading and influence on implosion pressure: experimental observations", Composites Part B, 36, 4, 306-18.

[44] Casari P, Jacquemin F, Davies P, 2006, "Characterization of residual stresses in wound composite tubes", Composites Part A, 37, 337-34.

[45] Bigourdan B, Chauchot P, Astruge J.C, Micheaux D, 2004, "Composite materials for subsea oil separation", Proc. DOT (Deep Offshore Technology) conference, Marseille.

[46] Gruber MB, Lamontia MA, Smoot MA, Peros V, 1995, “Buckling Performance of Hydrostatic Compression-Loaded 7-Inch Diameter Thermoplastic Composite Monocoque Cylinders”, J. Thermoplastic Compos. Mats., vol. 8, no. 1, pp. 94–108.

[47] Lamontia MA, Gruber MB, Smoot MA, Sloan J, Gillespie JW, 1995, Performance of a Filament Wound Graphite/Thermoplastic Composite Ring-Stiffened Pressure Hull Model, J. Thermoplastic Compos. Mats vol. 8, 1, 15-36.

[48] Davies P, Riou L, Mazeas F, Warnier P,. 2005, “Thermoplastic cylinders for underwater applications”, J Thermoplastic Composite Mats, 18 (5) 417-443.

[49] Adams DO, Hyer MW, 1994, “Effects of layer waviness on the compression response of laminates”, ASTM STP 1185, 65-77.

[50] Brown TL, Hyer MW, 1994, “Effects of layer waviness on the stresses and failure in hydrostatically loaded cylinders”, ASTM STP 1185, 78-94.

[51] Bogetti TA, Gillespie JW, Lamontia MA, 1994, “The Influence of Ply Waviness with Nonlinear Shear on the Stiffness and Strength Reduction of Composite Laminates” Journal of Thermoplastic Composite Mats, vol. 7, 2, 76-90.

[52] Arhant M, Davies P, Burtin C, Briançon C, 2015, Thermoplastic Matrix composites for underwater applications, Proc. 20th International Conference on Composite Materials (ICCM20), Copenhagen.

[53] Choqueuse D, Bigourdan B, Deuff A, 2009, “Hydrostatic compression behaviour of steel-composite hybrid tubes”, Proc. ICCM17, Edinburgh.

[54] Hernandez-Moreno H, Douchin B, Collombet F, Choqueuse D, Davies P, 2009, “Entire Life Time Monitoring of Filament Wound Composite Cylinders Using Bragg Grating Sensors: III. In-Service External Pressure Loading”, Applied Composite Materials, 16 (3) 135 – 147.

Figure Captions List

Fig. 1	Examples of composite cylinders before and after test.
Fig. 2	Ultrasonic C-scan inspection map of thick (50mm) 175mm inner diameter carbon/epoxy filament wound cylinder. Vertical dimension is cylinder length (300mm). Delaminations in blue.
Fig. 3	FE models of cylinder end closure contact (Left image: contact on end, right image: end and inner wall contacts).
Fig. 4	500mm inner diameter carbon/epoxy cylinder with composite dome in pressure vessel before implosion test.
Fig. 5	40 mm thick carbon/epoxy composite cylinder before implosion test.
Fig. 6	Example of inner wall mid-length strain recordings during implosion test showing mode 2 buckling.
Fig. 7	Instrumented glass/epoxy cylinders for long term immersion tests at 2500 meter depth, and example of inner wall mid-length strains versus immersion time.
Fig. 8	Impact damage in carbon/epoxy cylinder wall.
Fig. 9	Influence of impact damage on implosion pressure, glass/epoxy cylinders.
Fig. 10	General view of SEPCOMP subsea oil separation system, designed by Doris Engineering.

Fig. 11	FE analysis of SEPCOMP cylinder
Fig. 12	Composite versus metal design, SEPCOMP
Fig. 13	Collapse failure mode of steel/composite hybrid cylinder under hydrostatic pressure.
Fig. 14.	Post-test FE analysis of hybrid tube collapse.

Table Caption List

Table 1 Comparison of glass/epoxy mechanical properties determined using different methods (t: tangential, r: radial, a: axial)

Table 2 Collapse pressure (bar) for different types of end closure.

Material	Ultrasonic wave speed	Vibration analysis	Mechanical test	Model
E_t (MPa)	33250	29100	27700	25330
E_r (MPa)	20500		18960	15470
E_a (MPa)	22140	18520	17410	14040
ν_{rt}	0.121		0.139	0.128
ν_{ar}	0.320		0.275	0.256
ν_{at}	0.277		0.460	0.627
G_{ar} (MPa)	7000	7500		5360
G_{at} (MPa)	11960	12200		12700
G_{tr} (MPa)	7780	7600		5340

TABLE 1: COMPARISON OF GLASS/EPOXY MECHANICAL PROPERTIES FROM DIFFERENT TEST METHODS (t tangential, r radial, a axial)

	Contact on end	Contact on inner periphery
FE linear	477	598
FE Non linear	340	440
Test result	345	436

TABLE 2: COLLAPSE PRESSURE (BAR) WITH DIFFERENT TYPES OF END CLOSURE.

FIGURE 1. – EXAMPLES OF COMPOSITE CYLINDERS BEFORE AND AFTER TEST

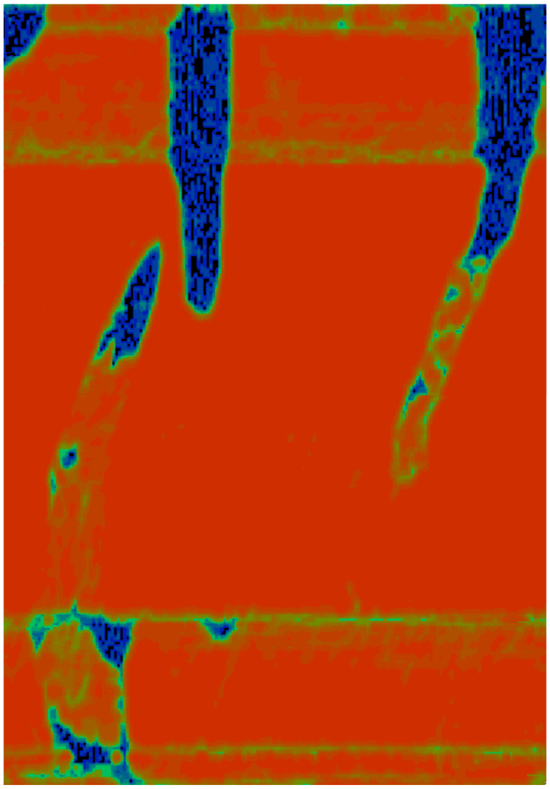

FIGURE 2. - ULTRASONIC C-SCAN INSPECTION MAP OF THICK (50 mm) CARBON FIBRE/EPOXY FILAMENT WOUND CYLINDER. VERTICAL DIMENSION IS CYLINDER LENGTH (300mm). DELAMINATIONS IN BLUE.

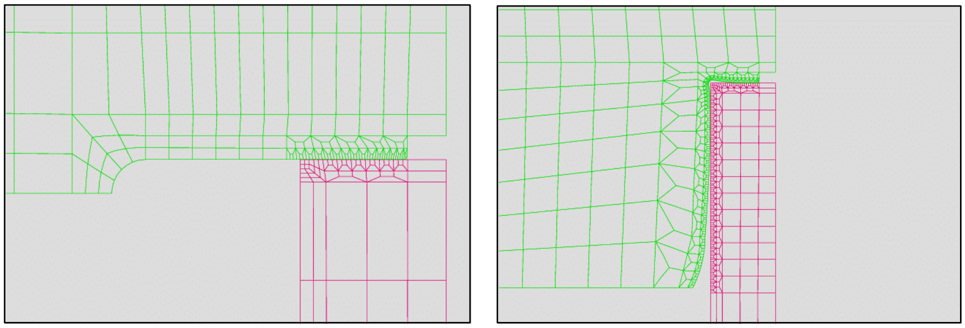

FIGURE 3. FE MODELS OF CYLINDER END CLOSURE CONTACT FOR TWO DESIGNS (LEFT IMAGE: CONTACT ON CYLINDER END, RIGHT IMAGE: END AND INNER WALL CONTACTS).

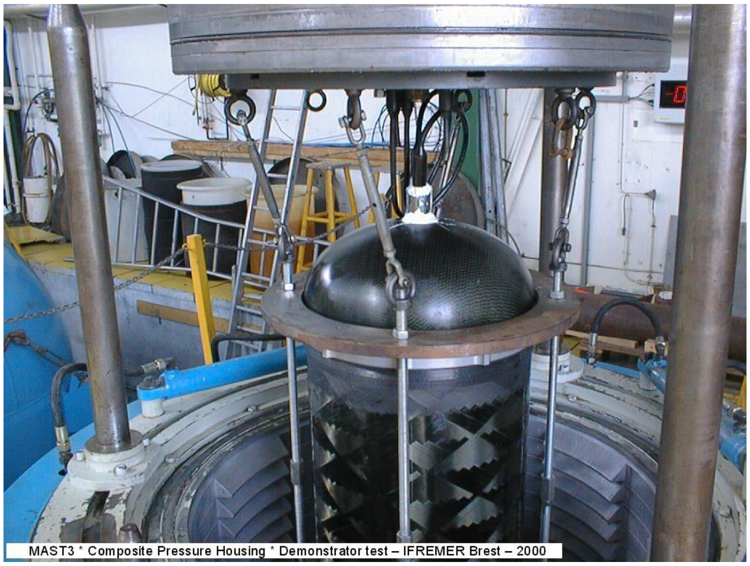

FIGURE 4: 500 MM INNER DIAMETER CARBON/EPOXY CYLINDER WITH COMPOSITE DOME IN PRESSURE VESSEL BEFORE IMPLOSION TEST.

MAST3 * Composite Pressure Housing * Demonstrator test – IFREMER Brest – 2000

FIGURE 5: 40MM THICK COMPOSITE CYLINDER BEFORE IMPLOSION TEST.

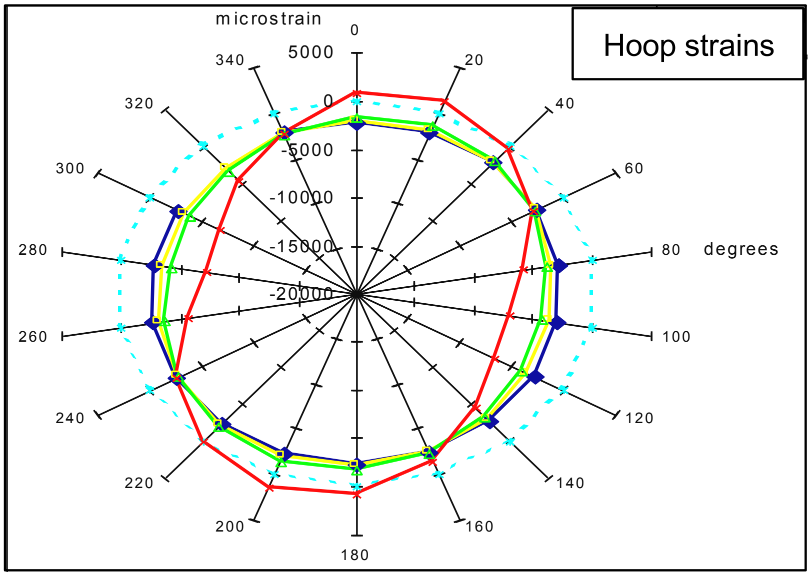

FIGURE 6: EXAMPLE OF INNER WALL MID-LENGTH STRAIN RECORDINGS DURING IMPLOSION TEST SHOWING MODE 2 BUCKLING.

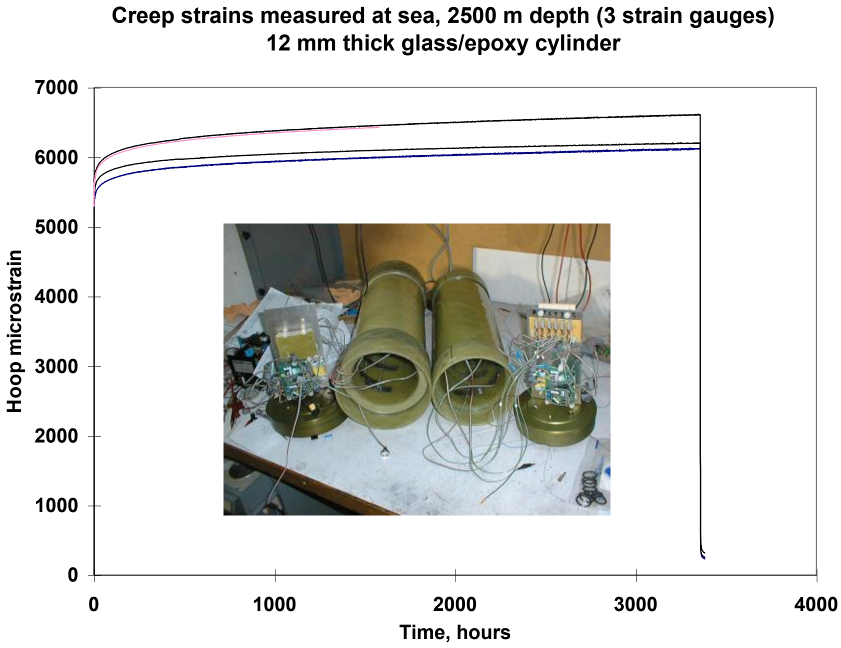

FIGURE 7: INSTRUMENTED GLASS/EPOXY CYLINDERS FOR LONG TERM TESTS AT 2500 METER DEPTH AND EXAMPLE OF INNER WALL MID-LENGTH STRAIN DATA VERSUS IMMERSION TIME.

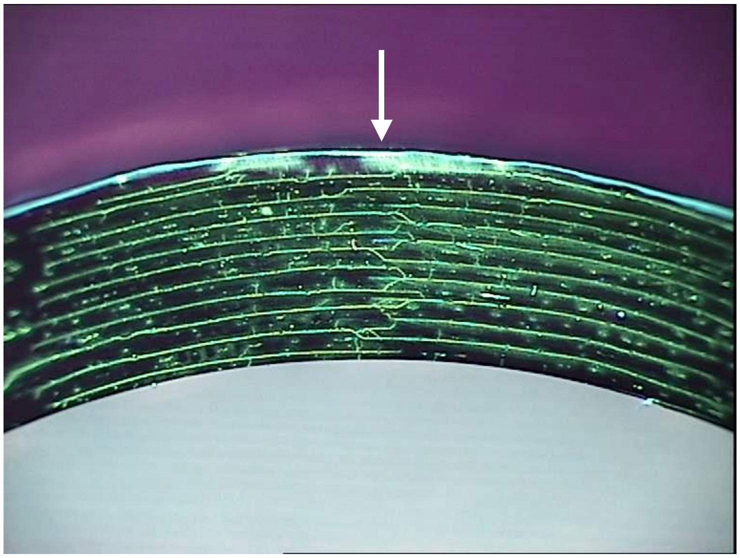

FIGURE 8: IMPACT DAMAGE IN CARBON/EPOXY CYLINDER WALL.

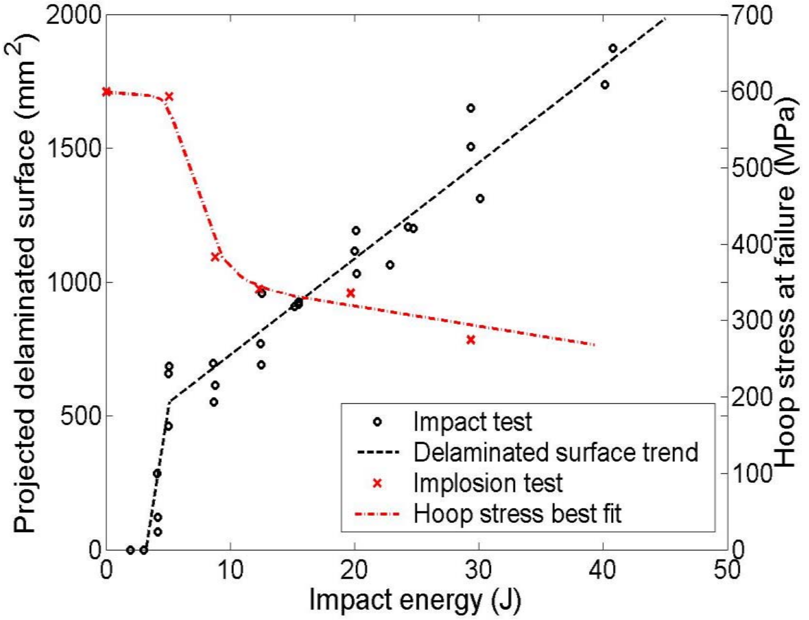

FIGURE 9: INFLUENCE OF IMPACT DAMAGE ON IMPLOSION PRESSURE, GLASS/EPOXY CYLINDERS

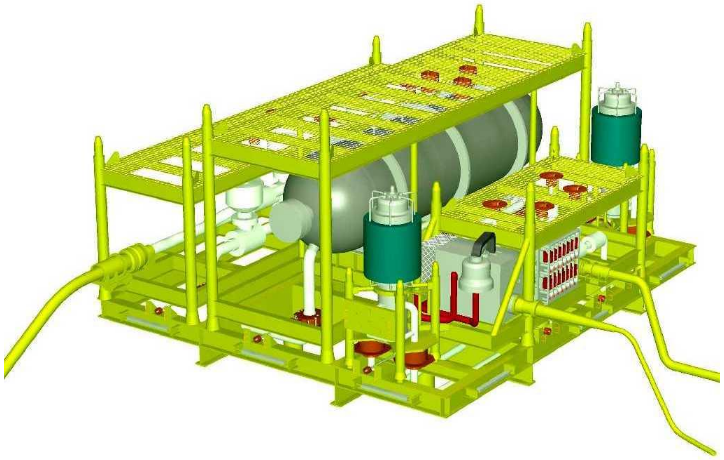

FIGURE 10: GENERAL VIEW OF SEPCOMP SUBSEA OIL SEPARATION SYSTEM DESIGNED BY DORIS ENGINEERING.

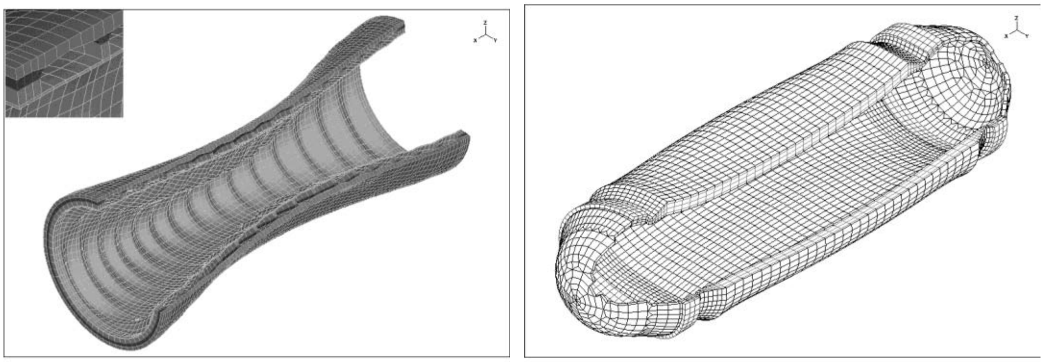

FIGURE 11. FE ANALYSIS OF SEPCOMP CYLINDER.

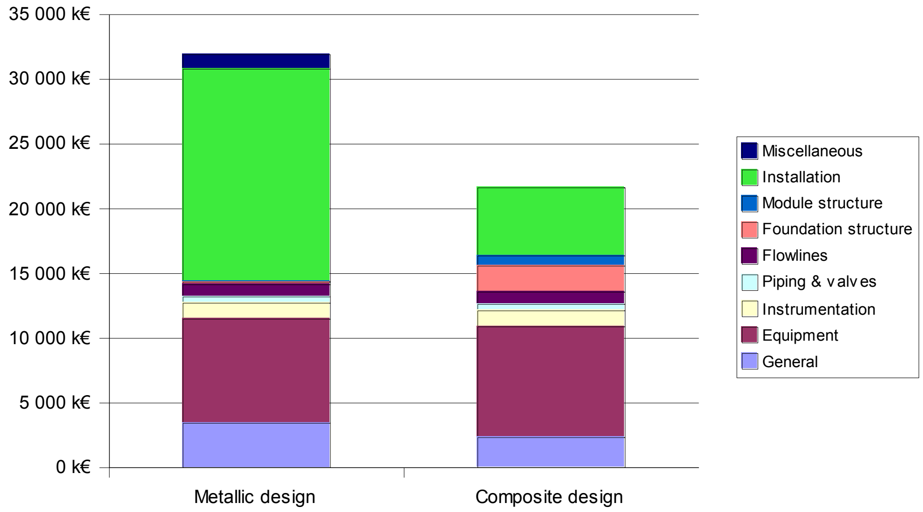

FIGURE 12: COMPOSITE VERSUS METALLIC DESIGN, SEPCOMP

FIGURE 13: COLLAPSE BUCKLING MODE OF HYBRID STEEL-COMPOSITE TUBE UNDER HYDROSTATIC PRESSURE.

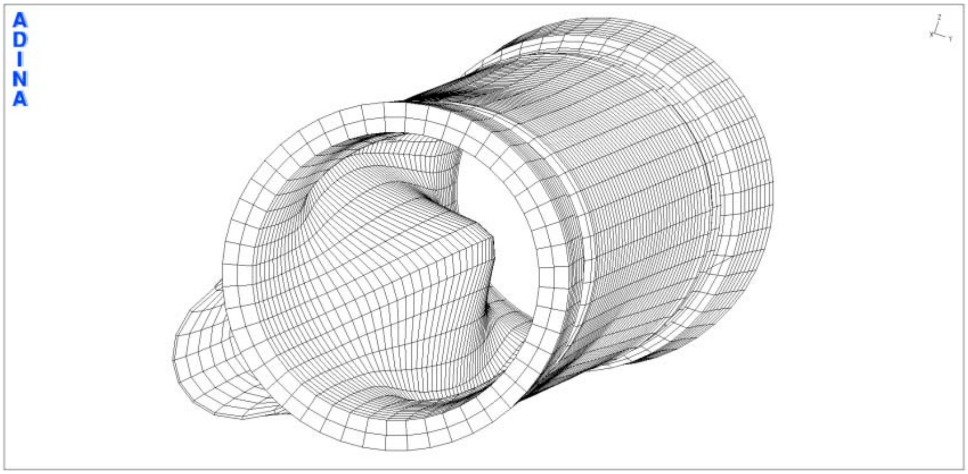

FIGURE 14: POST TEST FE ANALYSIS OF HYBRID TUBE COLLAPSE.