FULLY SUBMERGED COMPOSITE CRYOGENIC TESTING

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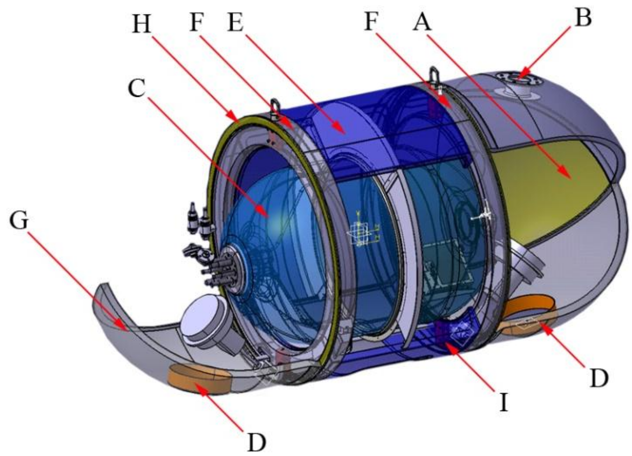
1 General Introduction

New methods for marine salvage and decommissioning of structures in the open sea are continually being sought in order to improve control and lower operational costs [1]. The concept design of a lightweight, cryogenic, marine, heavy lift, buoyancy system has been investigated [2]. The objective is to be able to raise or lower high mass objects controlled solely from a surface support vessel. The overall design concept and associated system development issues have been discussed previously. A number of the sub-systems in one complete buoyancy system involve considerable design and development, these include: structural design of the buoyancy chamber, mechanical systems to control and connection to the lift device, the cryogenic system itself and overall process control systems. The main area of concern in the design process is the composite cryogenic Dewar. This is required to operate not only at temperatures as low as -196°C but also to withstand pressure differences exceeding 35bar. As such the composite materials have to perform in a very aggressive environment. This work details a method for fully submersed composite cryogenic testing in order to qualify the materials for use in the Dewar of the buoyancy system.

2 The Buoyancy System

2.1 Overall

The DSR (Deep Sea Recovery) buoyancy system is a composite, modular structure that has been designed to lift heavy loads from the deep sea with a high level of remote control. It has a modular design such that components can be replaced/upgraded without having to construct an entirely new vessel. The modularity also enables the system to be transported more easily. The DSR buoyancy system is illustrated in Figure 1 [3]. The lift process is governed by the production of Nitrogen gas, which is released into the buoyancy chambers to create lift.



A – Buoyancy Chamber
B – Gas release valve
C – Dewar
D – Open bottom
E – Central membrane
F – Structural rings with lift attachment points
G – Caisson shell
H – Face seal
I – Dewar bracket supports

Fig. 1: The DSR Buoyancy System

The central part of the buoyancy device is the cryogenic Dewar. The Dewar holds liquid nitrogen (LIN) at -196°C and ambient pressure. The cryogen is heated to produce Nitrogen gas at the ambient temperature and pressure which is then released into the buoyancy chambers. This gasification process provides a measure of buoyancy control alongside that of the top valves. The Dewar is shorter and broader than conventional containers, with the axis parallel to that of the caisson. This results in the stronger domed ends providing much more effective structural support than in a conventional configuration.

2.2 The Dewar

The Dewar is required to carry a volume of LIN to a depth of 350m. At an absolute minimum it will be required to operate at pressures exceeding 35bar and temperatures down to -196^{o}C. It consists of an inner chamber which contains the LIN, a vacuum cavity for insulation, and an outer skin which must withstand the ambient pressure. In the event that the buoyancy system is inadvertently taken to a depth exceeding 350m, for example on an uneven seabed, the design pressure has been taken to be 40bar (400m). The LIN is forced out of the Dewar as a result of a pressure build system which results in the internal pressure of the Dewar being 2 bar above the ambient pressure at any depth. Figure 2 shows the Dewar without the caisson. It is formed of a two part carbon outer casing enclosing the steel lined, fiberglass wrapped inner container.

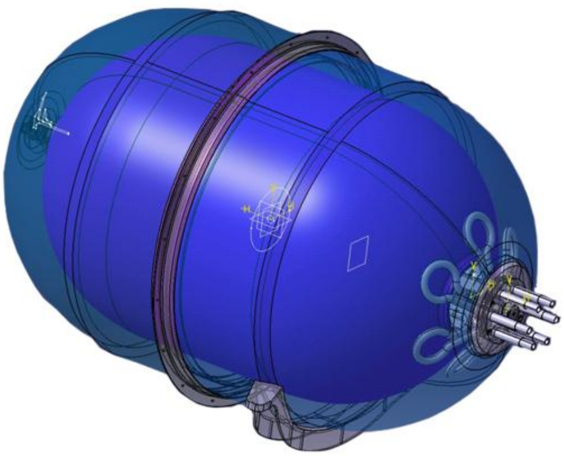


Fig. 2: The Dewar

One of the main factors governing the whole buoyancy system is the overall system mass; the lighter the system, for a fixed volume in the buoyancy chambers, the larger the payload that may be lifted. One area in which much mass can be saved is the Dewar. Conventional Dewars are constructed of stainless steel which, in order to withstand the pressures that the system is to operate at, would need to be very thick. Instead the inner vessel of the Dewar is to be made out of S2 fiberglass wound over a thin steel liner. The liner not only acts as a mandrel, but also prevents gas seeping through the composite layers, making the inner vessel a Composite Overwrapped Pressure Vessel (COPV). It should be noted, however, that the liner is not an integral structural part of the Dewar and the inner vessel would still have a safety factor of five without it. The fiberglass overwrap is to be placed using Automated Fiber Placement (AFP) which ensures that the fibers are located in an optimal arrangement to spread the load distribution, therefore minimizing the amount of material required. The coefficient of thermal expansion of the S2 fiberglass and resin is relatively similar, meaning that when LIN is introduced to the steel liner it should not shrink a large amount compared to the overwrap, minimizing any possible gap.

The outer vessel of the Dewar must withstand a large compressive pressure which composite materials are not generally suited to; however, it has been found that the use of T700 carbon fiber pre-preg at a thickness of 14mm through the middle section and 10mm at the hemispherical ends provides the required strength without the need for an inner liner. This reduces the mass of the vessel by several hundred kilograms. The thickness discrepancy between the ends and middle of the outer vessel is due to the inherent stability of the hemispherical shape when compared to the cylindrical mid-section under external pressure loading. The structure has polar boss openings at both ends for the pipe work for filling and emptying, safety release valves and the pressure build system.

3 Dewar Testing

3.1 Initial Tests

With the Dewar operating at temperatures as low as -196^{o}C, and parts of it in contact with the LIN, thorough testing of components and the whole entity is essential. The steel liner is to be constructed by a company specializing in cryogenic Dewars from standard materials and as such does not require coupon testing. The composite materials, however, have not been used as part of a cryogenic system before and therefore a series of tests have been proposed in order to qualify the materials for use in the Dewar construction.

Initially coupons of the specific materials were provided and tested at room temperature and pressure at the University of Southampton. These tests comprised of both static and cyclic tensile tests. The results of these tests were to provide a basis of comparison for the tests of specimens at lower temperatures. The next stage involved testing some specimens at a low temperature in an insulated chamber, Figure 3.

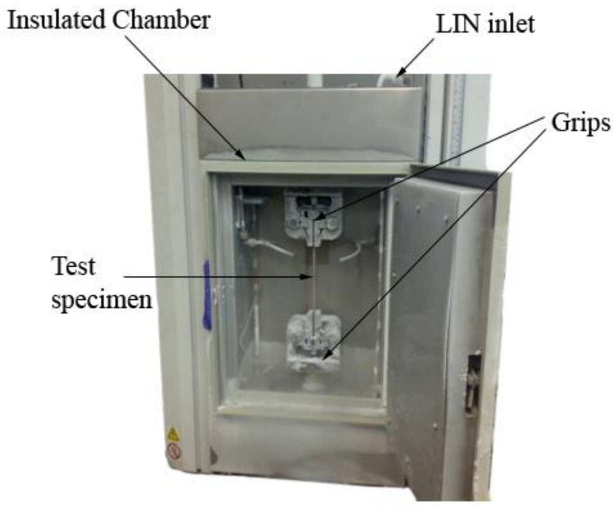


Fig. 3:Initial cryogenic test setup

This system was limited in that the lowest temperature that could be reached was around -165°C, over 30°C warmer than the Dewar will be subjected to. Problems were also encountered with the specimen grips seizing at these low temperatures. To start with a group of specimens were simply placed in the insulated chamber, none in the grips, and the whole system cooled to as low a temperature as possible. Once a suitable temperature had been reached the intention was to place a cold specimen in the grips and carry out the tests.

This method has the advantage of time, insofar as all of the specimens are already cold before testing. At the very low temperatures, however, the grips had seized up and therefore a sample could not be fitted into them. The system was allowed to thaw, a single specimen placed in the grips, and then the whole system re-cooled. This was an incredibly time consuming method of testing as it involves the entire test setup being cyclically thawed and chilled for each individual specimen. Three tests were carried out using this method at a temperature of -165°C. Of these three tests one specimen failed at the end tabs and the other two slipped out of the grips. The specimen that failed at the end tabs failed at a load of 24kN; this compared well to the room temperatures tests which all failed near a load of 25kN.

A single test is not enough to make design decisions on and as, in retrospect the jaw grips are not suitable for such low temperature testing, and as such a second system for fully submerged cryogenic testing was developed.

3.2 Fully Submerged Testing

The second experimental setup allowed the samples to be pinned at the lower end therefore allowing samples to be tested quickly without the whole system being thawed to allow for specimen removal. Figure 4 illustrates a model of the test setup, and Figure 5 a sample in-situ.

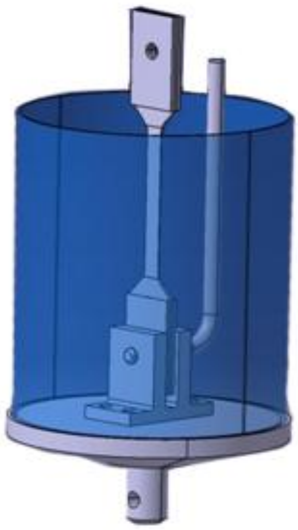


Fig. 4: Experimental setup for fully submerged tests

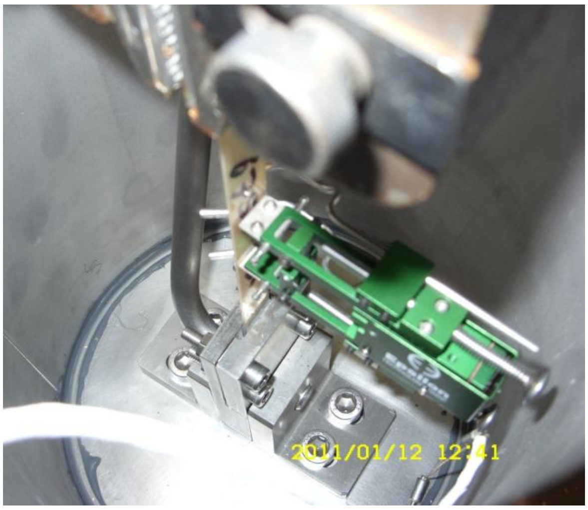


Fig. 5: Specimen in place with extensometer

Each individual sample was inserted into the bucket with an extensometer and a thermocouple attached, and pinned at the lower end. The long handled pin used at the lower attachment point was such that, when the bucket was full of LIN, one sample could be removed and another inserted without having to empty and refill the setup. The upper set of grips were then lowered and the sample clamped at the top. The samples were enclosed in an insulated bucket which was then filled with LIN, Figure 6.

Fig. 6: Specimen under test submerged in LIN

Each sample had a cross-section of 15mm x 1mm and was tested at 2mm/min (crosshead controlled) in accordance with the ASTM D3039 test standard [4]. The specimens were constructed from MTM®44-1 resin with reinforcements of UD S2 fiberglass. MTM44-1 [5] is a high-performance, toughened epoxy matrix system optimized for low-pressure vacuum-bag Out-of-Autoclave processing. It offers low density and good Tg retention under wet conditions and a high level of damage tolerance – thus making it particularly suited to the deep sea environment. The extensometer used was an Epsilon 3542-025M-010-LT – a 25mm gauge length, ±10% strain, low temperature specific thermocouple.

Initially problems were encountered during the pure tensile testing as the specimens tended to pull free of the upper grips. Cyclic testing was carried out at 4N, corresponding to an operating pressure of 35bar for the Dewar in service, over 10 cycles. The samples were then allowed to thaw and were tested to destruction at room temperature. When compared to room temperature testing of similar samples, those that had been cryogenically cycled performed well with a failure of 26kN compared to a maximum of 27kN at room temperature, Figure 7. The lower failure load of the second cryogenic sample was caused due to failure at the end tabs, not complete sample failure.

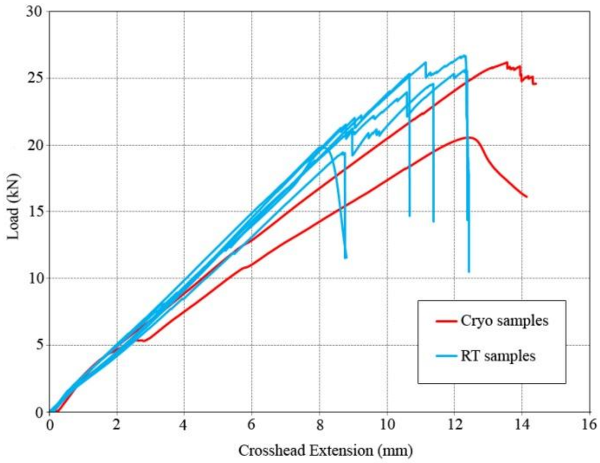


Fig. 7: Failure loads of room temperature and cryogenic specimens

Micrographs of the two cryogenic specimens were taken at a magnification of 200x. The resulting images for both specimens are shown in Figures 8 and 9. It can be seen that no micro-cracking was observed to occur despite the samples being cycled whilst submerged in LIN.

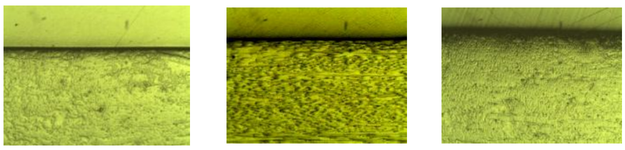


Fig. 8: Micrographs of Specimen 1 – 26kN failure

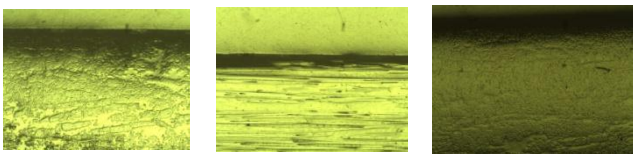


Fig. 9: Micrographs of Specimen 2 – 21kN failure

The test setup was then altered such that the sample was pinned at both the top and bottom. This arrangement prevented the samples being pulled out of the grips at the top when loaded, and thus enabled tensile testing to be carried out under full submersion in LIN. Further specimens were tested using this system and the results illustrated in Figure 10.

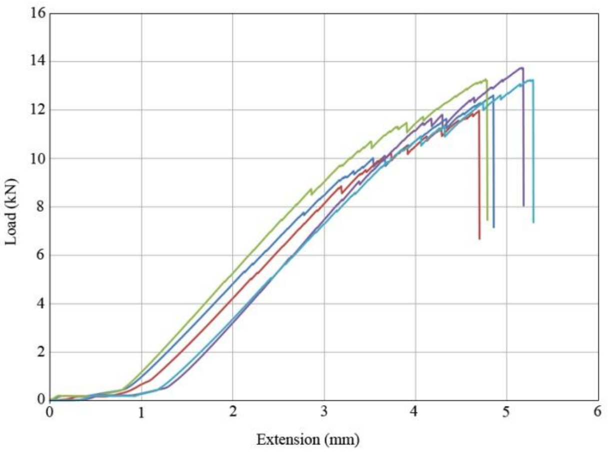


Fig. 10: Failure loads of further cryogenic specimens

All of the samples from the second set of sully submerged testing failed due to the sample pulling free of the end tabs at the top where the hole for the pin created a stress raiser, Figure 10. Comparing Figures 7 and 10 it is apparent that the sample in the first set of tests that failed in a similar manner to those in the second tests, at the end tab, failed at a higher load – 25kN compared to 12-14kN. This it thought to be due to the differing testing scenarios; where the first set were cyclically loaded under full cryogenic submersion, but then underwent tensile testing at room temperature after thawing, and the second set were subjected to full tensile testing whilst submerged. The different attachment mechanism also affected this failure load, with the introduction of the hole as a stress raiser.

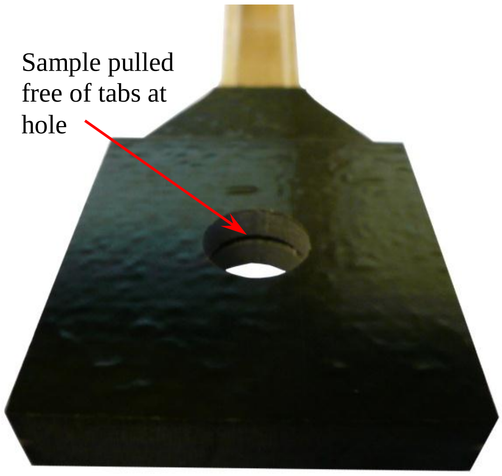


Fig. 10: Failure loads of further cryogenic specimens

It is thought that using the same material for the end tabs as in the sample would benefit the test setup by negating the use of adhesive between the end tabs and sample.

Conclusions

The DSR buoyancy system contains a composite cryogenic Dewar holding LIN. The Dewar has to operate at temperatures as low as -196°C and at pressures exceeding 35bar. A method for fully submerged cryogenic testing of composite specimens has been presented. The initial samples performed well when compared to similar specimens tested at room temperature. No micro-cracking was evident despite cyclic testing at cryogenic temperatures.

Tensile testing under full cryogenic submersion was achieved through a modified test setup; however, the hole for the top pin created a stress raiser and each sample failed due to being pulled out of the top end tab.

Overall, while minor adjustments to the sample/end tab layup are required, the method for fully submerged cryogenic testing of composite specimens was considered to be a success.

References

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