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Conceptual design of a composite pressure hull

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ABSTRACT

Composites are an attractive material for pressure hulls because of their high strength and low density. This paper presents a history of composite pressure vessel hull development over the last 50 years and uses the lessons learnt, to develop a composite pressure hull concept for a shallow diving hull, or buoyancy device. This is done by evaluating several concepts modelled using Finite Element Analysis for weight and other criteria. A converged solution is developed and further analysed for sensitivity to geometric imperfections. These imperfections are shown to have a significant effect on the collapse depth of the composite pressure hull.

1. Introduction

A composite is a name given to a material made up of two or more different materials, which when combined exhibit properties that exceed those of the individual constituent components. Examples of composite materials include, concrete, plywood, bone and Carbon Fibre Reinforced Plastic (CFRP) (Jones, 1999). In this paper, a composite is assumed to be a Fibre Reinforced Plastic (FRP), which comprises of fibres in a plastic matrix. The fibres are assumed to be glass or carbon and can be short loose strands, long continual fibres, or woven fabrics. The matrix is typically a thermosetting plastic e.g. polyester, vinyl ester or epoxy, or thermoforming plastic e.g. Polyether ether ketone (PEEK), polythene or Acrylonitrile Butadiene Styrene (ABS).

Composite materials are being increasingly used instead of traditional metals, particularly in aerospace and automotive applications, with the latest generation of airliners the, Airbus A350 XWB and Boeing 787 Dreamliner, being over 50% composite (Boeing, 2011). Composites are used for their relative light weight, high specific stiffness and much improved corrosion resistance over metallic structures (Smith, 1990). Because they can also be designed to deliver operationally significant signature management improvement, composites are increasingly used in naval ships and submarines (Mouritz et al., 2001).

Composite maritime structures are not new. Composites have been used by the US Navy for small patrol vessels since the mid 1940's (Mouritz et al., 2001). The Royal Navy launched the first all composite hulled ship, HMS Wilton, in 1973. It served for 21 years (Smith, 1990). The all-composite Hunt class vessels launched in 1979 are still in service today as is the subsequent Sandown class, (Mouritz et al., 2001) and could potentially continue in service for many years to come. The use of composites for submersible pressure hulls was first proposed in the 1960 s. The high strength and low density of composites result in a low weight to displacement ratio. This means they have a greater collapse depth for a given weight to displacement ratio or a reduced hull weight for a given operating depth compared with submarine steels, titanium and aluminium alloys, allowing them to dive deeper, have a larger operating range or carry a heavier payload (Smith, 1991; Hom, 1969).

Investigations into the suitability of composites for submersible pressure hulls can be found in the literature dating back to the mid-1960 s (Smith, 1991). Hom describes early studies by the Naval Ship Research and Development Centre where filament winding was used to produce Glass Fibre Reinforced Plastic (GFRP) pressure hulls (Hom, 1969). Development of design rules for composite pressure hulls was performed at the Admiralty Research Establishment (ARE) in Dunfermline in the 1980's (Mouritz et al., 2001) followed up by participation in a series of European experimental test programmes on composite deep diving submersibles, EC Brite-Euram, EUCLID and MAST I, II and III (Graham, 1995, 1996; Cook, 1998).

There have been many other studies looking at the design of composite pressure hulls for commercial and military purposes and for deep and shallow diving vessels. Some have been purely theoretical (Ross, 2006), while others have been mostly numerically focused on optimising the lay-up (Messager et al., 2002; Fathallah et al., 2015). Several studies have focused on replicating the tests of small scale experimental loading (Hernández-Moreno et al., 2008; Hur, 2008; Moon et al., 2010; Lee et al., 2013) and some have been conducted on reduced scale hulls in open water (Carvelli et al., 2001).

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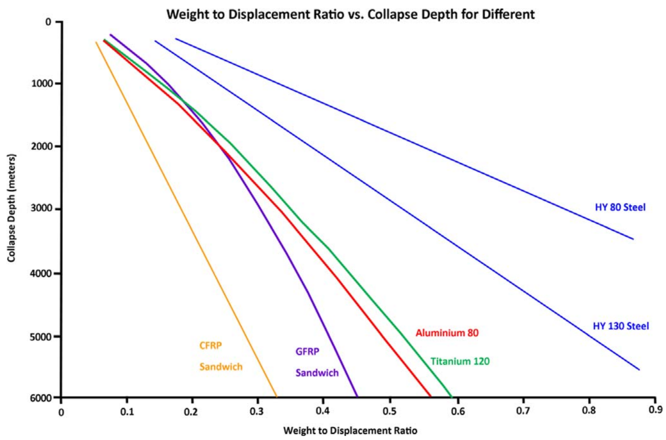

Fig. 1. Collapse depth vs. weight/displacement ratio for stiffened cylinders (ARE)

1.1. Composite submersible pressure hulls

Submersible pressure hulls manufactured using composites have significant advantages over metallic pressure hulls due to their high stiffness to weight ratio, low density, corrosion resistance and ease of forming into complex shapes (Pattison, 2001). In order for submersible vessels to float they need to be buoyant. Changing the weight of the submersible, then allows the vessel to submerge and change depth in a controlled manner (Smith, 1990). In order to compare different structural materials for a pressure hull, the ratio of weight/displacement (W/Δ) is often used, (Smith, 1990), (Pattison, 2001). Ideally the pressure hull structure should have minimal weight for a given displacement whilst achieving a hull density as close to that of sea water as possible. This allows for a higher payload or a longer range for a given pressure hull (Smith, 1990). This is often plotted as collapse depth vs. W/Δ for a visual comparison of structural materials, (Smith, 1990), and (Smith, 1991) and (Pattison, 2001), as shown in Fig. 1 for composite sandwich panels compared with metals commonly used in pressure hulls.

They also have reduced through life costs and maintenance requirements (Smith, 1990). Composites also offer the potential for increased stealth (Mouritz et al., 2001) as there is scope for incorporating damping, decoupling and anechoic characteristics to improve the acoustic stealth (Smith, 1990). They also offer inherently reduced magnetic and electrical signatures, particularly for GFRP (Boeing, 2011) this has recently been demonstrated for wind turbines (QinetiQ, 2009).

There are disadvantages to using composites too. The CAPEX costs of mandrel or moulds and associated costs are typically more expensive than for a metal fabrication. When comparing metallic and composite pressure hulls, metallic structures generally undergo plastic deformation prior to final failure; whereas, composites often undergo sudden and irreversible failure due to the compressive external loading (Reddy and Miravete, 1995). They also suffer from poor interlaminar strength, meaning damage will readily propagate under this compressive out of plane load. The materials themselves, particularly the resin systems, are also toxic, particularly when uncured (Pattison, 2001). Composite laminates are also susceptible to creep behaviour meaning the structural properties can change over time (Mouritz et al., 2001). This can be further affected by immersion in water, and the uptake of water by the laminate can degrade the material properties over time. Composites, notably Carbon Fibre Reinforced Plastic (CFRP), are known to have a poor tolerance to damage, particularly impact damage due to poor intralaminar strength (Davies and Olsson, 2004) and the nature of the out of plane compressive loading will readily propagate delaminations caused by the impact. This can be mitigated by making the outer layers of the laminate from GFRP which is more damage tolerant than CRFP (Kane et al., 2004). Composites are prone to local variations in stiffness of the laminate due to thickness variations, resin rich regions or other manufacturing variations usually caused by uneven fibre distribution (Messager, 2001).

Whilst composites themselves are extremely corrosion resistant, CFRP is electrically conductive, so any metallic structure in electrical contact with the CFRP will corrode (Stevenson and Graham, 2003), thus CFRP should be electrically isolated.

A traditional steel pressure hull consists of a cylinder stiffened with 'T-shaped' ring frames, and the principal structural strength design drivers are frame size, frame spacing and plate thickness (Stevenson and Graham, 2003). A composite pressure vessel has a more flexible approach as the properties of the composite laminate are anisotropic and can be tailored by varying the angle of the fibres in each ply of the laminate (Smith, 1990). For example the shear stiffness of webs or stiffeners can be increased by adding fibres at ± 45° (Smith, 1991), whilst theoretically, each ply can have a different fibre angle, and the angle can vary infinitely between 0° and 180° . Laminates for pressure vessels are typically stacked sequences of two or three fibre orientations. This has been ± 55° (Graham, 1995, 1996; Cook, 1998) or a 0°/90° layup (Hur, 2008), (Carvelli et al., 2001), or some variation of this replacing the 0° fibres with another angle 30°, 45°, 50°, ± 55° or even 60° (Moon et al., 2010; Lee et al., 2013), or Quasi-Isotropic (QI) layups, 0°/ ± 45°/90° (Livingstone, 2002). There are obvious issues when filament winding a structure in winding the fibres at 0° along the length of the cylinder, so a purely 0°/90° layup should be avoided for a filament winding approach. Using a hand layup approach with pre-preg materials draped over a mandrel as in (Hur, 2008), it is possible to create a 0°/90° layup. Studies have been performed to look at optimisation of the stacking sequence for composite pressure hulls, and whilst these were found to be dependent on the loading and fibres and resin system, (Fathallah et al., 2015) a lay-up of predominantly 90° degree fibres with some off axis fibres close to 0° degrees, was considered optimal. For example $[90^\circ_3/15^\circ_2/90^\circ_2]$ was 40% more stable under external buckling pressure than a $[\pm 55^\circ_N]$ layup (Messager et al., 2002).

In the same way that the lay-up of composites can be tailored for a given stiffness requirement, composite structures allow a number of different approaches to load carrying. These include monolithic skin structures, (Graham, 1995, 1996) and (Hur, 2008) T-stiffeners such as those used on metallic pressure hulls, blade stiffened, or use top hat stiffeners (Mouritz et al., 2001), Fig. 2.

Sandwich structures are also commonly used for composite pressure hulls to provide stiffer sections to resist bending and buckling with a lower weight increase over monolithic structures (Graham, 1996), (Lee et al., 2013). These sandwich structures consist of skins of GFRP or CFRP with a core of foam, balsawood, Nomex or aluminium honeycomb or top hat stiffeners.

It has been proposed, Fig. 3, that modular composite hull forms could be used to create customised pressure hulls configured to suit the vessel or purpose, and that these could tailor the material properties and geometries to avoid the stress concentrations that typically occur when joining the hemispherical end onto the cylinder of a pressure hull, (Smith, 1990), (Ross, 2014).

The desired size and operating depth of the pressure hull can also have an influence on the geometry and material choices. Deep diving vessels are typically unmanned, small diameter thick walled monolithic CFRP (Livingstone, 2002) containing only instrumentation. Larger diameter manned shallow depth vessels typically require ring-stiffening or sandwich construction to prevent buckling (Stevenson and Graham, 2003) and are often made of GFRP sandwich construction (Carvelli

Fig. 2. a) T-stiffener, b) Blade stiffener, c) Top hat stiffener.