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A review of the applications composite materials in wave and tidal energy devices

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ABSTRACT: The use of marine composite materials, especially Glass Reinforced Polymers (GRP), offer many advantages such as low weight (for transport, installation, and operation), durability (fatigue and corrosion), low maintenance and ease of producing complex seamless forms. This paper presents an overview of the applications of composite materials to wave and tidal energy devices. It identifies the main shapes of components used and the main types of loading so as to identify representative components in composite materials that are worthy of further study in order to produce optimised structural designs that can be applied for these type of devices. The paper also reviews various research studies concerning the developments of the composite material solutions for these types of devices. General considerations about the study of composite materials in the floats of wave energy converters are also presented.

1 INTRODUCTION

The generation of energy from ocean waves offers huge potential. However the production of ocean energy is still in its early stages with Wave Energy converters (WECs) perhaps the least developed of all. To date most research effort has been focused on evaluating various and varied device technologies, about which have been written a number of review articles (e.g. Drew et al, 2009, Falcão, 2010, Guedes Soares et al. 2012). Tidal energy is a more developed technology when compared to wave energy, where the leading players are already testing full scale prototypes (EIT, 2016) and a number of review articles have also been written on tidal energy (e.g. O'Rourke et al. 2010, Uihlein et al. 2016).

The cost of wave and tidal energy is currently high compared with other mature technologies (e.g. wind energy) and so it is important for the success of these technologies to achieve a reduction in the Operation and Maintenance (O&M) costs. The access limitations for O&M is already an issue for the offshore wind industry and will also be a challenge to wave farm developments in offshore wave climates (O'Conner et al. 2013). Therefore, the duration and frequency of maintenance activities should be minimized and material selection may play an important role in this. A number of recent reports and articles stress the need for further research into more detailed design areas, with the need for the development of 'new' material solutions often being highlighted (e.g. EIT, 2016).

Traditional welded steel construction has been used up to now, but the use of marine composite materials, Glass Fibre Reinforced Polymers (GFRP) and Carbon Fibre Reinforced Polymers (CFRP), offer many advantages such as low weight (for transport, installation, and operation), durability (fatigue and 'corrosion'), low maintenance and ease of producing complex, seamless forms. Some studies highlight the design potential of composites (e.g. Kleschinski & Müller 2006) for ocean energy but work considering composites for marine energy is both scarce and scattered widely through the literature.

Hence, in order to facilitate further research in this area this paper provides a brief summary of the wave and tidal energy prototypes which use composite materials in their structures (Section 2), and a summary of the existing research concerning relevant aspects (such as deformability under slamming loads, blade shape and material behaviour, sea water aging and fatigue) of the relevant types of marine composites for wave and tidal energy (Section 3). In Section 4, general comments of the study of composite materials in the floats of WECs are outlined.

2 COMPOSITES UTILISATION IN WAVE AND TIDAL ENERGY CONVERTER PROTOTYPES

The known advantages of the use of composite materials for wave and tidal energy have led to their use in a large number of prototypes structures. Concerning WECs, composite materials have been used for a wide range of different technologies (singe-body heaving, fully submerged heaving, pitching, bottom-hinged systems), and for tidal energy converters they are used fundamentally on current turbines. The main prototypes using composite materials for WECs and tidal turbines are presented in Section 2.1 and 2.2 respectively.

2.1 *WECs prototypes utilizing composite materials*

In point absorbers, i.e. an absorber with horizontal dimensions smaller than the wavelength oscillating in heave (Falcão, 2010), composite materials have to date been used for the device's floaters. Examples are E-glass/polyester floats of the F0[3] prototype (SEEWEC, Blommaert 2009) and the CorPower Ocean prototype (CorPower Ocean, Composite Solutions). Composite materials have been also used for the floaters of pitching devices, such as in the structure of the StingRAY prototype (Columbia Power Technologies), and in the Wavestar prototype (Wavestar A/S), where the semi-hemispherical buoys were manufactured using GFRP (Marquis et al. 2010). In the case of the fully submerged heaving buoys of the Archimedes Wave Swing system (Teamwork Technology, Prado 2008) Kevlar and rubber composites were used (Marsh 2009).

For bottom-hinged systems (with a buoyant flap at the sea bed oscillating in pitch mode, Falcão 2010) composite materials have been used for the flaps, for example on the WaveRoller (AW-Energy Oy) and by Resolute Marine Energy (Resolute Marine Energy, Eric Greene 2016). Other projects include the use of composites on overtopping devices, in particular on the seawall (Buccino et al. 2015).

2.2 *Tidal energy prototypes utilizing composite materials*

To date, composite materials have been used mainly in tidal current prototype turbines, for example SeaGen (Marine Current Turbines Ltd.). The blades have a hollow intermediate-modulus unidirectional carbon fibre composite box spar along with carbon ribs and an E-glass fibre composite envelope which is bonded to this carbon fibre skeleton (Marsh, 2009). The blades of the original precursor 'Seaflow' were produced by hand lay-up, but Seagen specifies pre-pregs (using an epoxy matrix chosen for its mechanical and hydrolysis resistant properties) which oven cured at 80°C under normal atmospheric pressure, throughout. All parts were moulded to their final net shapes, avoiding the need for machining after demoulding and blades were protected against the sea environment using gel-coat & antifouling coatings. Special attention was paid to the blade root since underwater rotors are subject to very high root bending moments without the centrifugal relief that wind turbines benefit from. GFRP fairings were also used on the cross-arms that support the twin turbines, and in the top housing (Marsh, 2009).

The CoRMaT prototype (Nautricity Ltd.) consists of two contra-rotors which drive a contra-rotating electrical generator. The 4 m blades of the turbines were manufactured by Airborne using a 'one-shot' (vacuum assisted) resin transfer moulding, or (VA)RTM technology whereby the part is made in one piece 'eliminating the need for shell-bonding and thereby the risks caused by adhesives, of which the long-term reliability in seawater conditions is uncertain' (Airborne 2016a,b). Similarly, the Tocardo T100 turbine (Tocardo International BV), a relatively small structure suitable for river currents and inshore tidal currents (Coppens 2014), was manufactured with a 'one shot' (VA) RTM process (Airborne 2016c).

All structural elements of the SeaUrchin turbine 2 kW prototype are of composite materials. A sandwich structure of thin glass fibre shells made of glass fibre/vinyl ester resin were filled in-situ with a cellular epoxy foam system, to give the required global rigidity. Ashland's Hetron 922 epoxy vinyl ester was chosen for its high corrosion resistance to marine environments as well as for its mechanical properties. Glass fibre was selected for cost reasons. A finite element analysis (FEA) helped define the lay-up consisting of chopped strand mat (CSM), woven roving (WR) and unidirectional (UD) reinforcements (Reinforced Plastics 2013). The TidGen Device (ORPC, Reinforced Plastics 2012), uses carbon fibre composite turbines constructed by Hall Spars, who draw from their expertise in designing spars and rigging for high performance superyachts.

The turbine blades of the HDRITZ HYDRO Hammerfest HS 1000 (ANDRITZ HYDRO Hammerfest) were constructed from Gurit's wind energy range including SparPreg™ and SPRINT™. The high degree of curvature together with significant laminate thicknesses required the development of new processing and manufacturing techniques, and in order to ensure a 25 year design life, 'the design process included a material test programme of over 1,000 individual coupons to ensure that the materials properties in both dry and seawater saturated conditions were well understood in order to provide confidence in the blade integrity even after long term immersion in this aggressive environment' (Gurit 2016).

The innovative GFRP turbines of the OpenHydro Open-Centre Turbine (Openhydro, Marsh 2009) are manufactured using Diab structural cores (Diab 2016).

3 COMPOSITE MATERIALS RESEARCH FOR WAVE AND TIDAL ENERGY

Despite of early stage of the technological development of marine energy devices, some relevant studies regarding composite materials have been completed and those concerning wave and tidal energy are presented below in Sections 3.1 and 3.2, respectively.

3.1 *Composite materials for wave energy*

Most of the work on composites for WECs was carried out within the SEEWEC project (SEEWEC) and concerned the slamming wave impact on composite axisymmetric buoys of a point absorber WEC (Blommaeart 2009, Blommaeart et al. 2009 and Van Paepegem et al. 2011). Two different production methods, filament winding and resin infusion (produced by different fabricators), were used to give monolithic and sandwich GFRP structures. The deformation of these structures under extreme slamming events was studied numerically and experimentally. It was found that, although not complying with the DNV standard (Classification Notes No. 30.5 "Environmental Conditions and Environmental Loads" Section 6 "Wave and Current Loads", March 2000) which assumes rigid behaviour, these structures withstand well the elevated slamming loads. Various buoy shapes were analysed and evolved; egg-like, tulip and finally short cone/cylinder/cone (Van Paepegem et al. 2011).

In the numerical approach first the local fibre orientation was optimised using commercial filament winding software in terms of manufacturing process, then the fibre orientations and ply thicknesses were evaluated using FEA. For a buoy with a height of approximately 4 m, slamming loads according to the DNV standard were taken into consideration and the conclusions were that:

- Breaking wave slamming is more severe than bottom slamming,
- A monolithic skin of filament wound GFRP should be very thick and hence expensive,
- A sandwich structure would be sufficiently robust but would also increase costs.

Experimental tests were developed to measure actual peak pressures. Laboratory-scale tests compared solid and hollow cylinders, the latter suffering a peak pressure of less than half that of the former. Numerical models gave good agreement with these small-scale tests (Van Paepegem et al. 2011).

Large 1:3 scale tests (height and diameter of 1.75 m) were made to compare two E-glass/polyester buoys; one of PVC foam sandwich (designed using the Tsai-Wu failure criterion together with the calculated DNV pressure), and one of monolithic lay-up (designed using the Tsai-Wu failure criterion but with an applied pressure of 50% of DNV value). Three types of test were developed; (i) fatigue tests simulating breaking wave slamming under 1-year storm conditions with a constant pressure in accordance with the DNV standard, (ii) slamming tests in a ship canal, and (iii) static fracture tests. The main conclusions were that:

- The measured local peak pressures are much higher than those of the DNV standard,
- Fracture tests were in a good agreement with the predictions using the Tsai-Wu criteria.

In a study of material aspects of the design of a buckling diaphragm WEC, Le et al. (2015) recognise that fibre reinforced plastic composites are a better choice than steel for marine structures because of their light weight and their high corrosion resistance and fatigue strength, and state that, 'Therefore a lighter structure can be made for the same loading conditions. This will reduce deployment costs and maintenance costs due to better corrosion resistance.'

3.2 *Tidal energy studies on composite materials*

Various aspects of the use composite materials for tidal turbines have been investigated, including the interaction between blade shape and material behaviour, seawater aging, and fatigue, as discussed in the following sections.

3.2.1 *Blade shape and material behaviour*

Grogan et al. (2013) presented a combined hydrodynamic-structural methodology for the design of a tidal turbine at a commercial scale. The strain distribution along the blade span was investigated with comparative tests between unidirectional GFRP and CFRP. An iterative process was developed in order to increase the thickness of the blade until the maximum strain became less than the failure strain. CFRP gave significant lower strains relative to GFRP leading to weight gains.

Improvements in the performance of the turbine can also be obtained by taking advantage of the ability of composite materials to give passive hydrodynamic performance adjustments with changes in tidal current velocity. This is achieved through tension-twist and bending-twist coupled asymmetric lay-ups to automatically depower the blades via increased twist as they become increasingly loaded, and has produced promising results for turbine performance (Nicholls-Lee et al. 2013, Li et al. 2016).

3.2.2 *Sea water aging*

Due the very aggressive environment in which tidal turbines must work is important to take into account the effects of sea water aging of composites. Boisseau et al. (2012) studied three types of GRP epoxy laminates (17 m diameter E-glass with P196 sizing from OCV Reinforcements, Advantex® glass (20 m) and the HiPer–tex™ glass (17 m) from 3B and OCV) which were tested in order to evaluate diffusion kinetics and effects of wet ageing on the mechanical quasi-static properties at different aging periods. The type of glass fibre did not significantly affect the diffusion behaviour. The mechanical behaviour was evaluated with four-point bending tests of three infused composites at different ageing periods at 60ºC in order to evaluate the effects on failure stress.

The tests revealed that sea water aging has a large influence on the flexural failure stress; a large reduction (from 40% to 56%) of the quasi static composite flexural strength and a change in the failure mode from compressive to tensile was seen after long aging periods.

Another study characterized and modelled the long term behaviour of different carbon/epoxy composites for tidal turbines (Tual et al. 2015) using accelerated seawater aging tests. Carbon/epoxy laminates made using three production methods (autoclaved pre-preg, RTM and vacuum infusion) were studied: Infused and RTM materials were aged at 60 ºC and Pre-preg material at 80 ºC. Mechanical tests were performed to characterize the elastic properties and also to evaluate the Interlaminar Shear Stress (ILSS). It was concluded that thickness and fibre orientation had little influence on the kinetics of water diffusion, but that both manufacturing process and matrix type did affect both the kinetics of water absorption and the degree of water saturation. There was also a severe reduction in failure strength (from 20% to 40%), but no significant effect on the elastic modulus and toughness. ILSS tests revealed that interfacial adhesion in all three carbon/epoxy composites was affected by sea water ageing.

Dawson et al. (2016) studied the effect of the test environment variables; temperature, conditioning medium (natural seawater or deionised water), and pressure, on the seawater-ageing of pre-preg and infused glass / epoxy composites in terms of laminate weight gain and mechanical properties. A fatigue test was also developed for the infused laminate which is discussed further in section 3.2.3. 'Advantex' fibres were used and panels manufactured by vacuum infusion and using prepregs oven-cured under vacuum between a flat tool and a plate; with a final cure for both materials at 80ºC. The main conclusions were that:

- After 2 years of immersion at different temperatures (4º, 25º, 40º, 60º, 80ºC) the temperature accelerated the weight gain of all specimens, and prepreg laminates took more time to saturate than did the infused ones. Importantly, the temperature should be limited carefully in order to avoid excessive degradation effects.
- Specimens conditioned in deionised water achieved a greater weight gain than those conditioned in seawater,
- Conditioning at high pressure (500 bar) did not significantly affect the weight gain of wither type of laminate.
- Ageing in natural sea water and deionised water severely reduced both the tensile and interlaminar shear strength, and this effect was stronger for deionised water.

Davies (2014) highlights what may be a weak link in the structure of a tidal turbine; the effect of seawater ageing of the adhesives used to bond together the separate components.

The field of seawater ageing of marine composites in general is applicable here but too broad to be include in this paper, and so the reader is directed to Davies & Rajapakse (2014) for further information.

3.2.3 *Fatigue*

The fatigue of tidal energy converters was studied by Boisseau et al. (2013), where infused GRP epoxy laminates (E-glass, Advantex® glass and HiPer-tex™glass fibres) were studied under cyclic loading in both air and also in circulating sea water at 60ºC. Four point flexure tests on 'dog-bone' specimens were developed and it was seen that:

- Fibre sizing considerably affected the fatigue performance,
- Fatigue life was significantly lowered by ageing
- Ageing changed the failure mode from compression to tension
- Matrix type is of particular importance to fatigue behaviour.
- Fatigue behaviour was little influenced by the medium (i.e. air or water). Similarly, Dawson et al (2016) concluded that testing an Advatex glass laminate in air or seawater did not affect the tensile fatigue strength.

Fatigue of composite tidal turbines was also considered by Davies et al. (2013) using a four-point flexure test for quasi-unidirectional infused E-glass/epoxy GRP and unidirectional pre-preg CFRP epoxy in seawater at 60º C. The GRP composite again suffered a significant reduction in fatigue life after ageing with an associated change in failure mode from compressive to tensile. For the CFRP laminates interlaminar shear failures led to a significant reduction in fatigue life. The important influence of the quality of the manufacturing process was also highlighted two batches of nominally identical GFRP were manufactured and tested in sea water with the same cyclic four-point flexure test set-up. The interlaminar shear stress results were much poorer for one of the batches, showing that the manufacturing process should be very well controlled.

Harper et al. (2015) studied the fatigue delamination of turbine blades, proposing a methodology to analyse the delamination using numerical modelling of the growth of interfacial cracks along different interfacial planes, for quasi-static and fatigue loads.

Again, the field of fatigue of marine composites in general is applicable here, but far too broad to dis-cuss in detail here, and the reader is directed to Bois-seau and Peyrac (2015), Poodts et al (2013) and Mil-ler (2000) for further information.

4 STUDY OF COMPOSITE MATERIALS IN FLOATS OF WECS

As previously noted, composite materials could play an important role in wave and tidal energy converters, however a lack of information still remains relatively to the mechanical strength of composite materials under the wave loads high exposure and still there are few studies regarding the suitable material properties (e.g. fibre orientation, matrix, sandwich cores) to be selected.

Regarding to the study of composite materials in WECs and in particular in the floats of the devices, the physical principle of the WEC introduces different degrees of complexity in the design of float structures, e.g. relatively low motions of the moored spar buoy of the floating oscillating water column (essentially immersed vertical cylindrical bodies), to the moderate motions of pontoons of pitching devices (essentially horizontal floating cylindrical bodies) and to the possible high vertical motions of point absorbers in which due to resonance optimal conditional it may happen that floaters have too high vertical displacements and move out of the water impacting it at entrance (Wang & Guedes Soares 2014). The slamming analysis besides be crucial for the integrity of the structure can reduce significantly the power absorption (Backer et al 2009) and so their effect should be carefully analysed. The buoys of these devices are subjected to external pressure from waves and also are subjected internal pressure due the water ballast on buoy, used to reduce the natural frequency of buoy to be in resonance with waves.

The modelling of the mechanical strength of the shell, plate and beam elements of the composite structure (bending, torsion) requires numerical and experimental approaches. The Finite Element Method can be used to model the stresses, deflections of the composite structures while the survivability of the composite structure can be analysed with composite failure criteria (e.g. Tsai-Hill, Tsai-Wu Kaw, 2006) and in accordance with standard classification society regulations (DNV 2012, 2013, 2014). Experimental analyses are required to test the material properties and also to determine the survivability of the structures at a scale model.

For components that are submitted to bending forces (e.g. pontoons of pitching devices) or impact loads (e.g. points absorbers) sandwich structure per-haps is the suitable construction while for structures which are submitted to lower loads (e.g. immersed vertical cylindrical bodies) laminated construction can be eventually used. The GFRP and CFRP are perhaps the suitable composite materials to be studied. Their use concerns which parameters should be used such as material fibres (e.g. E-glass, S-glass), resin matrices (e.g. polyester, epoxy), and structures (e.g. laminated plates of various different fibre orientations and thicknesses; sandwich panels with different cores).

5 CONCLUSIONS

Wave and tidal energy technologies are still at an early stage of development (perhaps tidal energy is around 15 years behind wind energy, and wave energy is another five years behind that, according to Marsh, 2009) and most research still concerns proof of concept studies rather than more in-depth design orientated investigations. However, it is clear that as the technology matures, the choice of materials will be fundamental to any design choices to be made.

Composite materials show great potential for this emerging market due to advantages such as resistance to the marine environment and fatigue, light weight and ease of forming seamless complex shapes; a point reinforced by the fact that Gurit (already a leading composite materials supplier to the wind energy sector) has formed a dedicated Ocean Energy team to focus on developing the potential for composites within the emerging wave and tidal (Marsh, 2009).

A number of prototypes of both wave and tidal energy devices use composites materials on their structures, such as the floats and flaps of WECs and fundamentally for the turbine for tidal devices, and some specific research studies have been undertaken. Most of the research on composites for WECs considers slamming loads on deformable structures which may be considered for new design codes for wave energy, and that concerning tidal energy considers the interaction between blade shape and material behaviour, seawater aging, and fatigue.

However, more research specifically concerning the application of *marine* composite materials to tidal, and especially to wave energy conversion technology (for example, concerning the effects of long-term immersion in seawater under cyclic loading) is required before they can be confidently used commercially over economically viable lifetimes. This research is needed to enable the use of (and further development of) relevant standards and guidelines in order to commercially implement this technology.

It is clear that there is an opportunity for new innovations and improvements to ocean energy technology design that may only become feasible with the introduction of the use of composite materials.

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