Advanced concrete materials for offshore floating structures

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Abstract- Reinforced concrete (RC) is particularly suited for use in the offshore environment and can be more cost effective than using materials such as steel. However, the demands of wave energy converters (WECs) can be difficult to overcome using conventional RC techniques, for example: the minimum wall thickness requirement can make RC structures too heavy for floating WECs with tight buoyancy constraints; post-tensioning is required to prevent concrete cracking which can significantly increase costs; and large, multi-axial dynamic loading regimes can lead to complex reinforcement requirements. This paper investigates the potential for advanced fibre reinforced concretes to overcome these issues, by reducing the need for internal reinforcement; reducing the wall thickness and overall structural mass; and increasing the permeability of the material in the cracked state, which could remove the need for post-tensioning. If advanced concrete mixes can be successfully exploited they offer a significant benefit for floating wave energy converters and other offshore structures. The potential for the use of these materials is investigated through a case study, looking at the design of a Node structure, which is the main buoyancy element of the WaveNET array developed by Albatern. The paper compares the benefits of fibre reinforced concrete designs against baseline designs using conventional materials using finite element models, and shows that fibre reinforced concrete materials can be used to eliminate the requirement for internal reinforcement and post-tensioning required for conventional RC structures, reduce overall structural mass, and lower CAPEX costs.

Keywords- Offshore floating structures, reinforced concrete, fibre-reinforced concrete, CAPEX costs

I. INTRODUCTION

The levelized cost of energy (LCoE) for wave energy needs to reduce to make wave power technologies competitive within the overall energy market. One potential area for cost reduction is the use of cheaper materials such as reinforced concrete (RC) which is particularly suited for offshore structures, as the material has a high resistance to corrosion, a low susceptibility to fatigue failure and offers good strength and stiffness properties at a low unit cost. However, use of the material in the wave industry has currently been limited to nearshore bottom fixed structures such as the Limpet due in part to the demands of wave energy devices which can be difficult to overcome using conventional concrete techniques. In particular:

- Concrete structures tend to be large, with minimum section thicknesses dictated by construction practicalities and durability concerns. This can be an issue for floating structures which need to remain buoyant;
- Concrete is designed to crack under tension to transfer the tensile forces to the internal reinforcement, which can lead to durability issues and leakage. Offshore structures often require post-tensioning to keep the structure in compression, which can significantly increase the capital costs.
- Many wave energy devices need to resist large multi-axial dynamic forces which can lead to complex reinforcement requirements, which is a high cost item for reinforced concrete structures.

This paper investigates the potential for advanced steel fibre reinforced concretes to overcome these issues. Two different types of concrete mix are considered. The first is an Ultra-High-Performance Fibre Reinforced Concrete (UHPFRC) mix with up to 10 times the tensile capacity of plain concrete, which could be used to eliminate the need for internal reinforcement, thereby reducing the wall thickness and overall structural mass. The second is a lower strength Strain Hardening Cement Composite (SHCC) material which exhibits post-cracking strain hardening behaviour, with peak tensile strengths approximately double that of plain concrete. For this type of material, the strain hardening phase is characterised by the formation of multiple micro-cracks before crack localisation. Theoretically the permeability of cracked SHCC materials is the same as the un-cracked material providing that the width of the micro-cracks is kept below a critical value. If this behaviour can be successfully exploited it could have significant benefit for floating wave energy structures and other offshore structures subject to low tensile stresses, as this could remove the requirement for post-tensioning.

The potential for the use of these materials is investigated through a case study, looking at the design of a Node structure, which is the main buoyancy element of the WaveNET array developed by Albatern. The paper compares the benefits of fibre reinforced concrete designs against baseline designs using conventional materials using results from finite element models and code based structural design methods, and shows that UHPFRC and SHCC materials could successfully be used to eliminate the requirement for internal reinforcement and post-tensioning, and reduce overall structural mass.

II. CASE STUDY OVERVIEW

A schematic of the 12S WaveNET array developed by Albatern is shown in Figure 1. This is a multibody array, made up of Node elements and interconnecting Link Arms, connected with articulated joints which house the Power Take Off (PTO) systems.

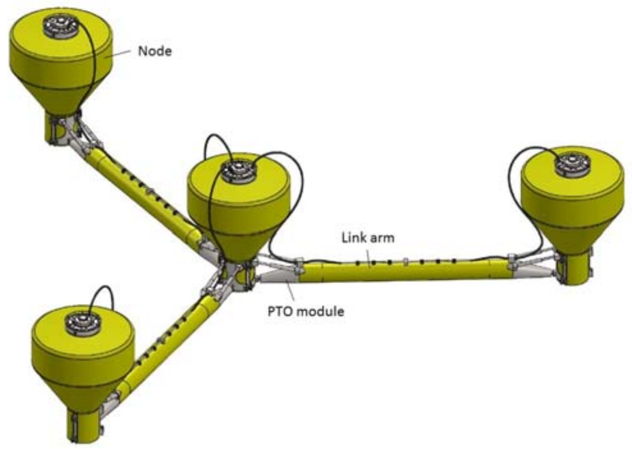

Figure 1 : Schematic overview of 12S WaveNET array

Initial internal studies have shown that reinforced concrete is the preferred material for use for the Node structure, as it offers many techno-economic advantages over other materials such as steel. However, the preliminary design process has highlighted areas where the use of advanced concrete may provide additional benefits, for example:

- UHPFRC could be used in areas of high tensile stress to reduce or eliminate the need for internal reinforcement, and reduce wall thickness and overall structural mass.
- SHCC concrete mixes with enhanced post-cracking properties could eliminate the potential for the development of through thickness cracks, and hence remove the need for post-tensioning

To investigate the potential for these materials, design options have been developed and compared against a baseline reinforced concrete design to see the impact on overall weight, material quantities and cost. These designs are discussed in section IV.

A. Scale effect

In addition to the 12S array as shown in Figure 1, Albatern's growth plan was to develop the WaveNET system on different scales to meet the requirements of different energy markets [1]. This paper also investigates the benefits of using advanced concrete materials at different scales, by looking at design options for a node structure in a "6S" array, which is half the physical size of the 12S, and is developed for off-grid markets such as aquaculture. A comparison of the 12S and 6S array parameters is shown Table 1.

Table 1: Characteristic parameters of WaveNET array scales

Parameter	12S	6S
Rated power per unit	75kW	7.5kW
Design Hs	14m	7m
Distance between nodes	12m	6m

At the 6S scale, it is not possible to use conventional RC for the Node structure due to overall weight and buoyancy constraints. However, fibre reinforced concretes can be used, as thinner wall sections can be achieved. At this scale, advanced concrete materials are therefore compared to steel and Glass Fibre Reinforced Plastic (GFRP) designs. These design options are discussed in Section V.

III. MATERIAL PROPERITES

A. Baseline materials

Depending on the scale, baseline designs are based on a C50 concrete mix with properties as given in DNV-OS-C502 [2], S355-J2 mild carbon steel [3], or a GFRP sandwich construction as described in [4].

B. Advanced concrete materials

Fibre reinforced concretes (FRC) include discrete fibres within the concrete mix to improve the material behaviour, particularly in the post-cracking phase under tensile loads. FRC has increased ductility compared to conventional concrete due to the capacity of the fibres to bridge crack faces. The mechanical characteristics of FRCs vary depending on multiple factors, including (amongst others) fibre volume fraction (v_f), fibre shape, length and aspect ratio, as well as the exact nature of the underlying concrete mix. In general, FRC mixes can be classified as either Steel Fibre Reinforced Concrete (SFRC); Strain Hardening Cement Composites (SHCC) and Ultra High Performance Fibre Reinforced Concrete (UHPFRC). The properties for each are summarised in Table 2.

Table 2: Fibre Reinforced Concrete (FRC) classifications

Type	Typ. v_f	Description
SFRC	<2%	Mix characterised by post-cracking strain softening behaviour, with peak tensile strengths the same as plain concrete. Typical compressive strengths ≤ 50MPa.
SHCC	1.5-2.5%	Mix characterised by post-cracking strain hardening behaviour, with moderate residual tensile strengths up to 2x that of normal strength concrete. Peak strength achieved at high strain levels (4-5%). Typical compressive strengths 50 - 100 MPa
UHPFRC	up to 5%	Mix characterised by immediate post-cracking strain hardening behaviour, with high residual tensile strengths up to 10x that of normal strength concrete. Peak strength achieved at low strain levels (0.5-1%). Typical compressive strengths ≥ 100MPa.

This paper focusses on SHCC and UHPFRC mixes with strain-hardening behaviour, which have increased tensile strength compared with conventional RC. Typical stress-strain curves for these materials are shown in Figure 2. SHCC1 and SHCC2 relate to two different mixes, giving an indication of the range of mechanical properties that can be achieved

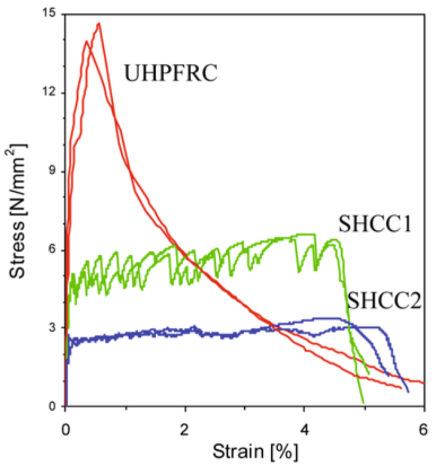

Figure 2 : Typical uniaxial tensile behaviour of different fibre reinforced concrete types [5]

As well as increased peak strengths, one of the major advantages of FRC over conventional RC is the improved cracking behaviour; as steel fibre transfer tensile stresses across cracks, this leads to a reduction in crack widths, therefore improving durability. In addition, SHCC materials are characterised by the formation of micro-cracks before crack localisation, keeping the material permeability low even at relatively high strain levels. The permeability of SHCCs has been investigated by several authors, with the general conclusion being that cracked SHCC has the same permeability as the un-cracked material providing that micro-cracks remain below approximately 60µm [6, 7, 8]. The benefits of using SHCC as a method of seepage control has been recognised by various authors for structures such as tunnels [9], dams [10] and buildings [11], but there is limited research relating to its use in watertight offshore structures, which are subject to more dynamic loading regimes. Low permeability in the cracked state is a particularly useful property and could provide significant benefits for floating wave energy converters and other offshore structures. Thus, the use of SHCC in watertight dynamic structures is an area which warrants further research. For this paper it is assumed that SHCC materials do indeed remain watertight through the strain-hardening phase and can therefore tolerate low levels of tensile stress without the risk of developing through thickness cracks.

The fib Model Code [12] categorises FRC mixes in terms of compressive strength f_{ck}, and residual strength values f_{Fts} (for serviceability loading), and f_{Ftu} (for ultimate loading). In addition, UHPFRC mixes are defined by the peak strength f_{Pt}. These values are typically determined from standard bending tests for design purposes, but in this paper mechanical design properties as shown in Table 3 have been assumed based on typical properties defined in the literature. While there are many different materials that can be used for fibres, the properties for steel fibres are used in this paper, as this is the most common.

Table 3: FRC mix design mechanical properties

Mix	v_f %	f_{ck} MPa	f_{Rts} MPa	f_{Pt} MPa	f_{Rtu} MPa
SHCC	2.5	80	2.0	-	4.5
UHPFRC	5	150	5.5	21.6	6.6

IV. 12S DESIGN

A. Overview

The node structure is designed to take the load components as shown in Figure 3. Pressure loads are calculated based on dynamic Froude-Krylov pressures in accordance with linear wave theory. The PTO loads come from hydrodynamic and physical modelling carried out by Albatern discussed in more detail in [13]. A number of load cases have been assessed covering Serviceability, Ultimate and Accidental limit states (SLS, ULS and ALS) in accordance with [2], with the appropriate factors of safety applied.

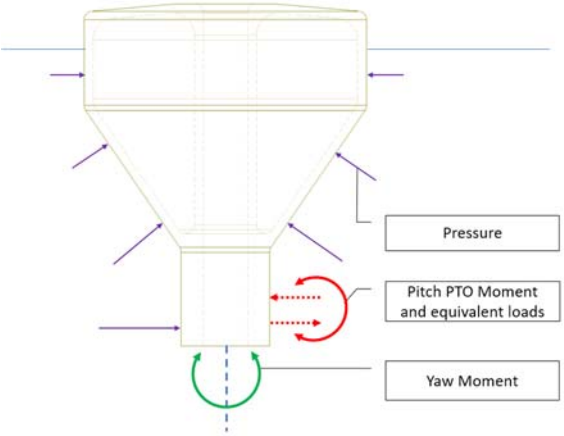

Figure 3 : Node dimensions

Overall dimensions for the node structure and a general schematic of the internal layout are shown in Figure 4. The internal volume is split into two chambers: the top chamber is designed to be fully watertight using post-tensioning of the central column if required to keep the section in compression. Some leakage is allowed in the bottom chamber as it is very difficult to ensure that through thickness cracks will not form in the outer walls in the bottom chamber.

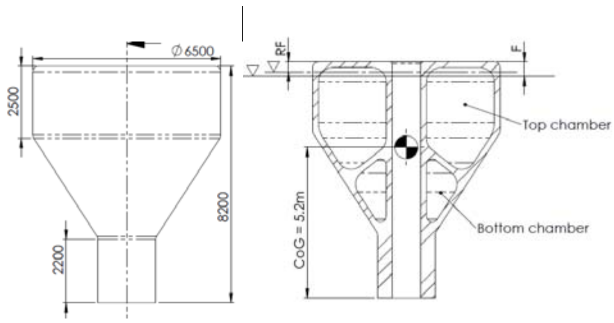

Figure 4 : Node dimensions and internal layout

For design purposes, the section has been split into different sections as shown in Figure 5.

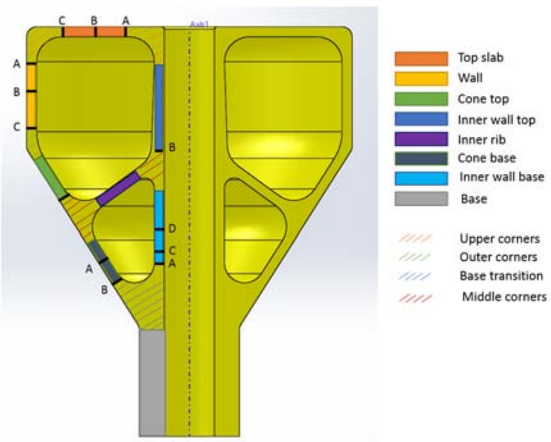

Figure 5 : Node dimensions and internal layout

The design sections fall into three different categories:

- A majority of the structure can be classified as “slab" sections, and designed to resist the applied bending moments and axial forces (with no significant shear forces) in accordance with standard methods as described in design codes such as [2], modified as necessary to allow for FRC materials.
- The varying thickness of the corner and transition sections result in more complex analysis requirements than for the “slab" sections. At this stage it is assumed that the reinforcement requirements for the slabs can be continued through the adjacent corners and transitions, rather than carrying out a separate rigorous analysis, which could lead to less conservative requirements
- The base section is considered as a stand-alone structure, and is designed as a circular column to directly resist the applied PTO bending moments.

Designs have been carried out with the aid of a 3D solid finite element model set up in Abaqus 6.14. A section of the model is shown in Figure 6. The model uses CD820R elements, and assumes linear elastic material properties. While concrete materials (both conventional and advanced) are non-linear, use of linear elastic analysis is standard practice in concrete design, and including full non-linear plastic properties is too complex for this stage of development. Linear elastic analysis gives an upper design solution, as plastic deformations and stress redistribution are not allowed to occur. While this is appropriate at this level of design, the use further non-linear analysis could lead to more economic designs at a later stage.

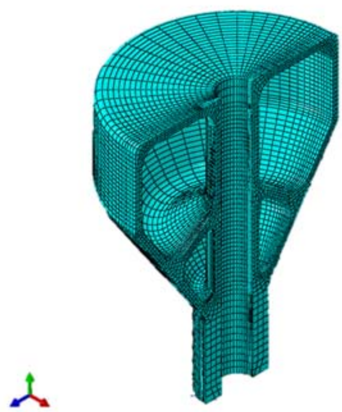

Figure 6 : Abaqus model section

A. Reference concrete design

The conventional concrete design is driven by the following constraints:

- **Minimum wall thickness:** this is a practical constraint, driven by the need to fit in multiple layers of reinforcement, with a suitable concrete cover to ensure reinforcement durability. The minimum wall thickness is taken as 195mm.
- **Crack widths:** cracking in concrete can increase chloride penetration into the structures, leading to corrosion of the internal reinforcement, and can result in leaks, if through thickness cracks develop. The following crack width constraints are imposed (based on the requirements given in [2]) to ensure the durability of the structure:
  - Crack widths are limited to 0.2mm.
  - Watertight sections are designed to have a permanent compression zone to eliminate the possibility of through thickness crack formation.
- **Ultimate capacity:** the structure must be able to resist the ultimate limit state design loads (with a suitable material partial safety factor) without failure.

The final design section thicknesses are shown in Figure 7. 1.5MPa of post-tensioning is required through the central column to keep the walls of the upper chamber in compression.

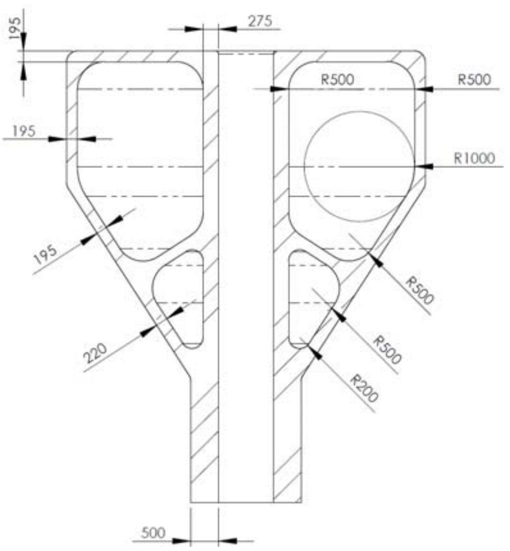

Figure 7 : Reference design dimensions

The reference design highlights the following areas where use of advanced concrete materials may provide additional benefits:

- **Reducing rebar requirements:** There is an area of high stresses at the junction between the base column and the cone section, which results in complex, congested reinforcement (>250kg/m^3) and thicker wall sections which push the structure to the upper limits of buoyancy constraints. This could be improved using UHPRC to increase the tensile strength and ductility of the base concrete material.
- **Reducing wall thickness**: In areas of low stress, the minimum wall thicknesses are the design driver. If FRC mixes were used, it may be possible to reduce the wall thicknesses in these areas, reducing the overall mass.
- **Elimination of the need for post-tensioning**: the tensile stresses that are induced in the watertight chamber are relatively low (~2MPa), therefore it may be possible to use SHCC mixes to increase the permeability of the concrete, and therefore eliminate the need for post-tensioning.

B. Option 1 – UHPFRC

The first design option looks at the potential for using UHPFC with design properties as given in Table 3, to eliminate the need for internal reinforcement. This is possible if the tensile stresses developed in the structure are less than the design strengths of the material. This has been checked by looking at the maximum principal tensile stress (σ_1) in the Abaqus model, with reduced section thicknesses where possible. Table 4 compares this stress with the design limit for both serviceability (SLS) and ultimate loads (ULS). The results show that the principal tensile stress is indeed less than the design limit. These results provide an indication that UHPFRC materials may be used without the use of internal reinforcement, and with reduced section thicknesses as shown in Figure 8.

Table 4: FRC mix design mechanical properties

Limit state	σ_1 MPa	Design limit MPa
SLS	4.4	5.5
ULS	6.6	6.63

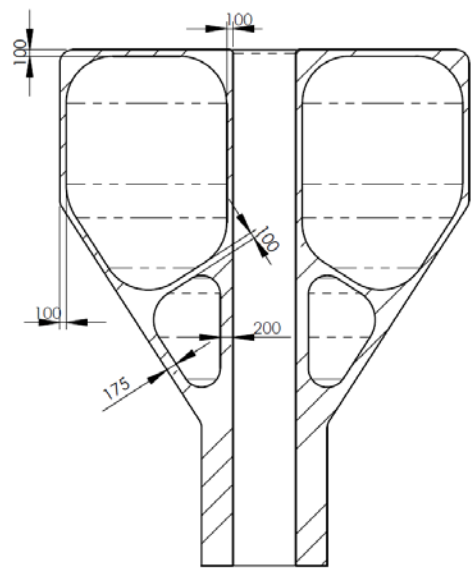

Figure 8 : UHPFRC design dimensions

As for the reference design, post-tensioning is still required to ensure that there is a permanent compressive zone in the upper chamber walls.

C. Option 2 – SHCC

The second design option explores the use of SHCC to eliminate the need for post-tensioning within the structure. It is assumed that this would be possible providing that the principle tensile stress in the upper chamber under the relevant load case is less than the serviceability residual tensile strength for the SHCC material (as given in Table 3). The results from the Abaqus model show that the maximum principal tensile design stress at ULS is 1.9MPa, which is marginally less than the design f_{Rts} for SHCC (2.0MPa), and therefore SHCC can be used without the need for post-tensioning, or internal reinforcement in the upper chamber.

The stresses that occur at the junction between the base column and the cone remain high for this option, and it would be difficult to use SHCC without internal rebar, unless the wall thickness was significantly increased. Therefore, it is preferable to use UHPFRC in this location. This solution gives the final design dimensions as shown in Figure 9. The hatched area shows the approximate extent of the UHPFRC – the exact location of the interface between this and the SHCC would need to be investigated further as part of future design developments.

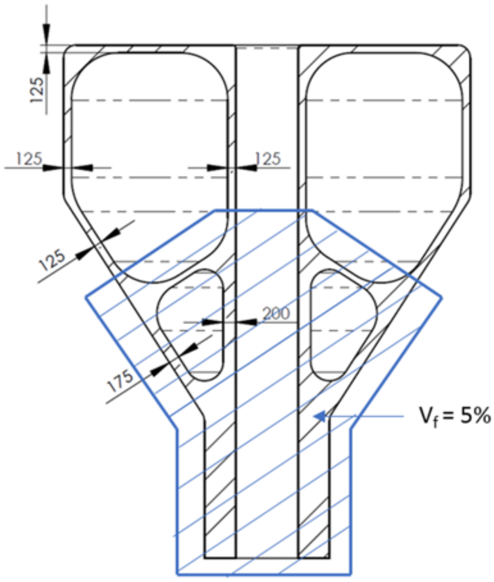

Figure 9 : SHCC + UHPFRC (blue shaded lower area) design dimensions

D. 12S Option comparison

Table 4 shows the material quantities for each of the options. This shows that the reference design is the heaviest, at the upper limits of the buoyancy constraints. Both the UHPFRC and the SHCC option result in lighter sections, and eliminate the need for internal reinforcement, which can reduce overall labour costs and construction time associated with fixing rebar cages. However, the overall steel volume is still greater in both options, compared to the conventional steel option, as a higher volume of fibres is required, compared to the overall volume of steel reinforcement.

Table 5: 12 S Design options material quantities

Quantity	Reference	UHPRFC	SHCC
Concrete mass (te)	109	78	93
Steel rebar (te)	4	-	-
Post-tensioning (MPa)	1.5	1.5	-
Fibre volume (te)	-	12.3	9.5

E. 12S - Cost Estimates

To carry out a quantitative comparison capital costs have been estimated based on the material quantities shown in Table 4. Cost rates are based on industry quotations, literature values and rates provided in construction handbooks such as Spon's [14]. At this level of design there are significant levels of uncertainty associated with the estimates, therefore optimistic and pessimistic costs are shown included. The cost estimates provided in Figure 10 are presented as a multiplier of the baseline cost for the reference option. Conventional concrete is the most well-known material, and therefore the cost for the reference options varies less than for the FRC options.

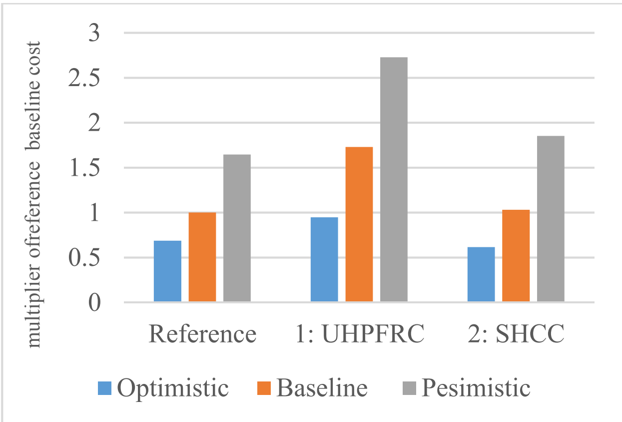

Figure 10 : 12S Option costs as a multiplier of the reference baseline cost

Figure 10 shows that for the baseline cost estimate, the reference design is cheaper than the other options, indicating that where there is a viable conventional concrete design, it is likely to be cheaper than using more advanced materials. However, this does depend on the assumptions made; for example, the optimistic estimate for both the UHPFRC and the SHCC option are cheaper than the reference design baseline cost, with the SHCC option showing a significant reduction, driven primarily by the elimination of the post-tensioning, and to a lesser extent the reduction in labour cost and construction time associated with the removal of the internal reinforcement. Further design refinements may show that the overall volume of fibres can be reduced, or cheaper, lower strength SHCC can be used over a larger area of the structure, making this option more attractive.

V. 6S DESIGN

A. Overview

As discussed in Section II.A, the 6S design is a half scale version of the 12S array. It is not possible to use conventional RC at this smaller scale due to overall weight and buoyancy restrictions; however, it is possible to use an FRC mix. To look at the potential advantage of this against other materials, three designs have been considered:

1. SHCC mix with fibre volume fraction = 2.5%
2. Carbon steel with characteristic yield strength = 355MPa
3. Glass fibre reinforced plastic (GFRP) sandwich construction with characteristic strength = 370MPa, as shown in Figure 11.

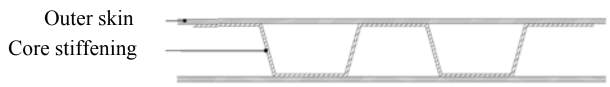

Figure 11 : 12S Option costs as a % of the reference baseline cost

The 6S is ½ the physical dimensions of the of the 12S array (with a length scale L), designed to resist a design wave (Hs) that is ½ the height of the design wave for the 12S structure. Therefore, design actions have been multiplied by a factor of 8 (as the design actions are proportional to □(H. L^2)).

B. SHCC design

The SHCC design has been carried out using the same methodology for the 12S device. The final design dimensions for this option are shown in Figure 12. It can be seen that the use of FRC material allows a much thinner wall thickness than could be achieved using conventional concrete.

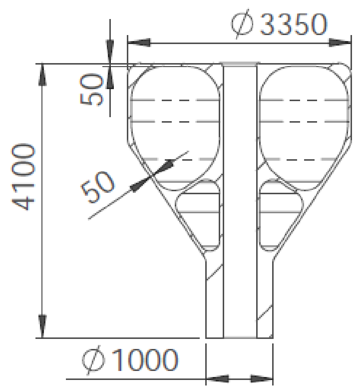

Figure 12 : 6S SHCC design dimensions

C. GFRP and Steel design

For the steel and GFRP options a simple design check has been carried out, based on the combined bending and axial resistance of a particular section. While there are other factors that would need to be considered for a detailed design (e.g. fatigue loading, shear and buckling effects), this gives sufficient information for the preliminary sizing and to allow a comparison between design options. A schematic for an optional design is shown in Figure 13.

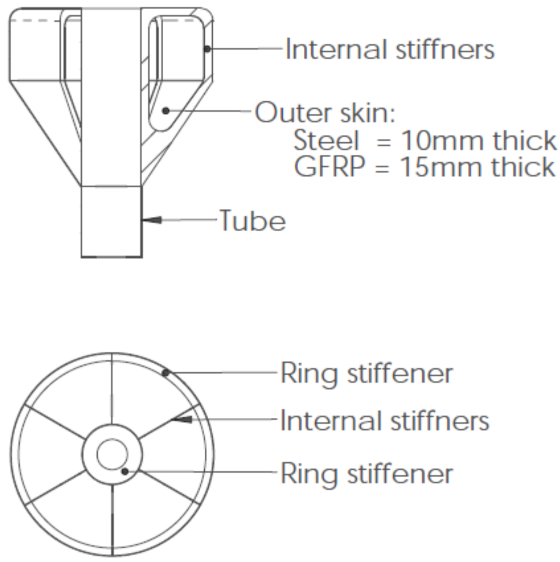

Figure 13 : Steel / GFRP option schematic

D. Option comparison

Cost estimates have been developed based on the quantities given in Table 6. The steel and GFRP options are significantly lighter than the SHCC section, therefore ballast is included to bring all options up to the same weight. The steel option includes a cost for coating as steel is susceptible to corrosion in the marine environment. The cost comparison is shown in Figure 14, with costs presented as a multiplier of the SHCC baseline cost.

Table 6: 6S Design options material quantities

Item	Quantity
SHCC	
Formwork	126 m^2
SHCC	3.9 m^3
Steel fibre @ 2.5%	0.76 te
Steel	
Base tube	1 te
Steel fabrication	3.2 te
Coating	109 m^2
Ballast	5.8 te
GFRP	
Base tube	0.1 te
GFRP fabrication	0.7 te
Ballast	9.2 te

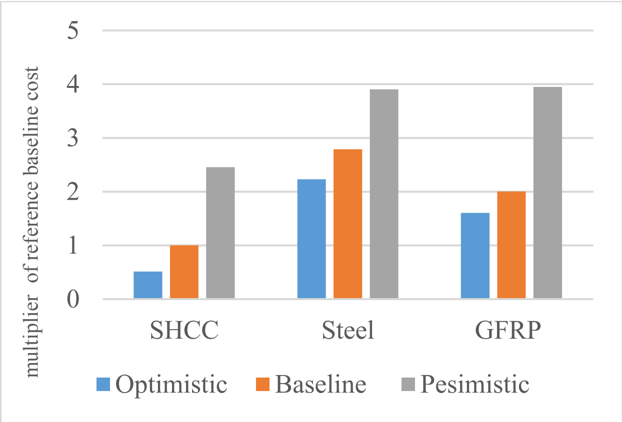

Figure 14 : 6S Option costs as a multiplier of the SFRC baseline cost

Figure 14 shows that the SHCC option is significantly cheaper than either the steel of the GFRP options, even considering the optimistic assumptions. This shows that the use of advanced FRC materials could offer significant benefits in situations where additional constraints exist such as weight and buoyancy restrictions.

VI. DISCUSSION AND CONCLUSIONS

This paper has shown that advanced fibre reinforced concrete materials with increased tensile strength and improved post-cracking behaviour can theoretically be used in place of conventional concrete to reduce structural mass and reduce the need for internal reinforcement. It may also be possible to exploit the superior permeability characteristics of strain hardening mixes to eliminate the need for post-tensioning.

In normal design conditions, where a conventional reinforced concrete solution is possible, this conventional design is likely to be cheaper than using more advanced materials. However, in situations with exceptional design constraints which push the limits of conventional concrete design, FRP materials can offer significant economic as well as technical benefits, particularly when compared to other materials such as steel or GFRP. The cost of FRC materials increases with increasing fibre volume and base concrete compressive strength. Therefore, they offer the greatest cost benefit in situations with low tensile stress, where lower fibre volumes can be used to improve the post-cracking behaviour and permeability, without needing a significant improvement in tensile strength.

The findings of this paper are based on assumptions surrounding the behaviour of FRC materials which would need to be proved through a material testing programme. The paper provide justification for such a programme to be carried out, as if FRC can be successfully exploited for dynamic, floating, watertight structures this could have significant benefits both for wave energy converters and other structures in the wider offshore industry.

ACKNOWLEDGMENT

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REFERENCES

[1] Albatern Ltd "Technology Development" http://albatern.co.uk/wavenet/technology-development/

[2] DNV, "DNV-OS-C502 Offshore Concrete Structures," 2012.

[3] BSI, "BS EN 10025-1 Hot rolled products of structural steels, General technical conditions", 2004

[4] Pelamis Wave Power, "WEC-main body structural design and materials selection", (V/06/00197/00/00/REP - DTI URN 03/1439). 2003.

[5] G.P.A.G van Zijl, W.P Boshoff, "Mechanisms of creep in fibre-reinforced Strain-Hardening Cement Composites (SHCC)" in Crrep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures, Tanabe Ed. London: Taylor & Francis, 2009.

[6] Michael D Lepech and Victor C Li. "Water permeability of engineered cementitious composites". Cement and Concrete Composites, 31(10):744-753, 2009.

[7] C-M Aldea, Surendra P Shah, and A Karr. "Permeability of cracked concrete. Materials and structures", 32(5):370-376, 1999.

[8] Gideon PAG van Zijl. "Durability under mechanical load - micro-crack formation (ductility)".In Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC)", pages 9-39. Springer, 2011.

[9] B Maidl and J Dietrich. "Verification of serviceability for SFRC in tunnelling". Structural Engineering International, 2(2):114{117, 1992.

[10] H. Liu, Q. Zhang, C. Gu, H. Su, and V. C Li. "Influence of microcracking on the permeability of engineered cementitious composites". Cement & Concrete Composites, 72:104-113, 2016.

[11] J Yu, H Li, C KY Leung, X Lin, J YK Lam, I ML Sham, and K Shih. "Matrix design for waterproof engineered cementitious composites (ECCS)". Construction and Building Materials, 139:438-446, 2017.

[12] Federation Internationale du Beton. "fib Model Code for concrete structures 2010". Berlin, Germany, 2013.

[13] L Barker Ewart, P T Theis, T Stratford, N Barltrop "Optimising structural loading and power production for floating wave energy converters" in proceeding of EWTEC 2017.

[14] Spon's "Civil Engineering and Highway Works Price Book" 2018

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