Advanced Concrete Engineering - WEC (ACE-WEC)

WES Structural Materials and Manufacturing Processes Stage 1 Public Report

Quoceant Ltd

wave energy SCOTLAND

This project has been supported by Wave Energy Scotland

1. Project Introduction

This Wave Energy Scotland (WES) supported project into structural materials and manufacturing processes was undertaken to assess the application of novel fibre-reinforced concretes manufactured using additive techniques (3D printing) to produce low-cost structures for WEC prime mover applications.

The project team consisted of two project partners and three sub-contractors, which brought together a wide range of world-class skills and experience in the fields of wave energy, concrete technology, offshore design and risk management. The project team is as follows:

- Quoceant Ltd, Project Lead – Quoceant are specialists in marine energy and technology innovation. The team all previously worked together on the Pelamis Wave Power project and have amassed a combined experience of over 150 years in the marine sector. Quoceant provide independent, expert engineering consultancy services to a range of organisations working in the wave, tidal and wider marine energy sector.
- Concrete Technology Unit, University of Dundee, Project Partner – The Concrete Technology Unit (CTU) at the University of Dundee is a leading centre of excellence in the field of cement sciences and concrete technology. It specialises in sustainable materials and durability performance and has extensive experience of designing concrete mixes for the marine environment.
- INNOSEA, Project Sub-contractor – INNOSEA offers engineering technical consultancy and support services by being a specialized pure-player on offshore wind and marine renewables. INNOSEA is committed to apply the best practices to overtake technical hurdles and provide its clients with the best engineering and solutions and services.
- Black & Veatch, Project Sub-contractor – Black & Veatch has been consulting on marine energy since 1976, and in the past 10 years has provided rigorous technical and evidence-based analysis to the most seminal wave and tidal stream/range projects which have sought to commercialise the marine energy sector
- David Kerr Engineering Consultant, Project Sub-contractor – Civil & Structural Engineering Consultancy, specialising in offshore structures for renewable energy.

The project indicated that fibre-reinforced concretes provide a viable construction material for wave energy converter (WEC) structures, and manufacture using additive methods provides the potential for significant cost savings against more traditional steel and conventional concrete designs. Demonstration of the material and manufacturing methods are required to support the conclusions reached by the project and to provide additional refinement to both structural designs using the concrete and manufacturing methods and the cost estimates for accurate calculation of the Levelised Cost of Energy (LCoE) for different wave energy convertor solutions.

2. Description of Project Technology

Concrete is an established construction material and is well suited to the marine environment. It has a low base material cost, a well-established supply chain, has excellent fatigue performance and does not corrode in saltwater.

There are multiple offshore applications that use conventional concrete manufacturing methods, ranging from small fishing vessels through to enormous gravity base structures for production oil rigs. While conventional concrete is still a low-cost material there are areas of cost associated with traditional methods that can be removed through use of different concrete mixes and cutting-edge manufacturing methods.

The use of fibre reinforced concrete potentially allows the elimination of internal steel rebar cages which are primarily used to support any tensile loading experienced by the structure. These cages can be costly and time consuming for complex designs due to high numbers of man-hours required to construct and assemble the units. They also enforce certain construction limits on the concrete as they require protection from corrosion, achieved through the use of significant concrete coverage around the steel bars.

The use of fibre reinforced concretes also allows the possibility to reduce and / or eliminate the use of prestress in a concrete structure through increased capacity during ultimate limit state loading. Prestress is a recognised method of placing a concrete structure into a compressive stress state to minimise tensile stresses in the structure, and hence avoid cracking during load. However, it can be an expensive process and adds complexity to the structure as it often requires additional internal ducting and rebar reinforcement. Fibre reinforced concretes potentially allow this cost centre to be reduced through better tensile capacities, in particular in the post-crack initiation phase, which would allow a small degree of cracking in the structure to be permissible.

The use of 3D printing presents the opportunity to remove the requirement for formwork and falsework to manufacture concrete sections. This eliminates tooling cost from construction, minimises any void or poor compaction risks associated with complex formwork and allows almost total flexibility in design. This can mean that very complex, optimised shapes can be produced or that the design can be altered for different structures (or different evolutions of the same structure) with no cost penalty other than material usage. The ability to produce more complex shapes allows greater ability to optimise material use which further minimises cost. Additional potential benefits to using this method are the ability to vary the material properties within the structure by varying the concrete mix during the printing process. This could result in high-strength concrete in areas of local load, with cheaper standard concrete in other regions of lower load, thereby further optimising the cost of the structure.

3. Scope of Work

The scope of the project was to:

- Review of the current state of the art for both fibre-reinforced concretes and 3D printing (additive manufacturing) techniques to establish a baseline for the technologies, and highlight areas of uncertainty in the current materials and methods for WEC applications

- Design and analyse (at high level) several different WEC types to investigate the use of advanced concretes and manufacturing methods to produce a viable structural option for the selected WEC structures

- Investigate the current methods and facilities for additive manufacture of concrete structures in the United Kingdom and further afield, including site visits to relevant academic and industrial facilities where possible

- Provide high-level cost calculations for the selected WEC structures to enable comparative levelised cost of energy calculations to be performed. This allows the cost-effectiveness of the material to be compared against more conventional options to consider the cost benefits for any WEC structure manufactured using this method

4. Project Achievements

The project initiated with an extensive literature review to establish the current state of the art for fibre reinforced concrete and additive manufacturing of concrete structures. This produced a significant amount of information on similar reinforced concretes which suggested that performance gains could be achieved over traditional concrete methods. The review did not discover research work on the specific concrete considered in this project that could be directly used in the structural design phase, but it did eliminate non-steel fibre reinforcement options from further consideration.

The additive manufacturing methods were further researched in later work packages, with site visits to relevant industrial and academic centres. This included the Loughborough University 3D Concrete Printing centre, which is at the cutting edge of additive manufacture of concrete structures for both construction and architectural projects. Discussion with the experts indicated that there were no barriers to manufacture using the considered concrete material, although it was noted that modifications to their printing system and testing methods would be required to achieve optimal results. Further research has also indicated that additive manufacture of houses in some instances already uses fibre-reinforced concretes, however the details of this are unknown.

Figure 1 Sample 3D printed concrete slab sections indicating layered construction and intricate slab curvature (courtesy of Loughborough University 3DCP Centre)

To assess the applicability of the material / manufacturing combination a wide range of WEC types were considered as candidates for further structural design work. The selection of 5 different WEC types, including an attenuator, submerged pressure differential, rotating mass and 2 oscillating surge types were then used as test cases to produce representative structural designs using fibre reinforced concrete.

The designs were produced using sets of design load cases, including ultimate and fatigue limit state conditions, with load and geometry information being provided by the WEC developer. From this a structural solution was developed for each of the WEC types. Conventional calculations and finite element methods were used in the development of the solutions, which allowed the combination of multiple loads into a single structural model. In some instances, minor modifications to the structures (when compared to an equivalent steel design) were required, however through discussion with the contributing developers any modifications were noted to not significantly affect the WEC performance.

The designs produced were at a high level and further work would be required to produce more detailed designs prior to considering manufacturing a prototype concrete device, however the work showed that there were no immediate issues with the development of a concrete option. Further refinement of both the material properties and of the WEC designs, specifically to suit concrete manufacture could improve the designs and produce more efficient structures than those developed.

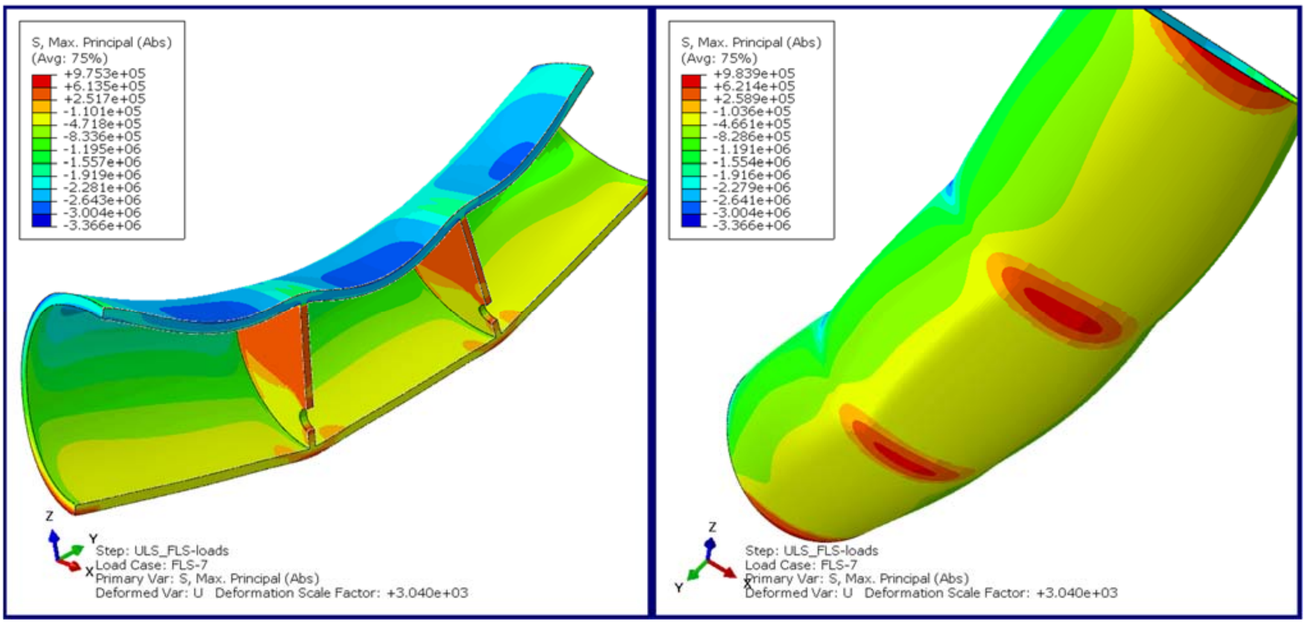

Figure 2 Typical finite element analysis of a concrete hull structure

The developed WEC structures were used to provide material and construction costs to enable a set of comparative LCoE calculations to be produced. These calculations are not absolute figures as only the structural subsystem CAPEX input was modified, with all other LCoE cost contributors remaining as the typical values assigned by WES.

These structural designs were, where possible, compared to a conventional construction method, either a steel fabrication or a conventional concrete design, and in some instances both steel and standard concrete cost models were produced. Cost projections were also produced based upon recognised learning rates and likely uncertainty values to provide a wide spread of estimates. A short sensitivity study was also performed to assess the effect of possible device performance uplifts (due to the flexibility in structural form) and operations and maintenance variation for a single WEC type.

In all cases the designs produced using the advanced concrete combined with 3D printing manufacture produced lower cost options than the traditional methods. This showed that for WEC prime structural applications this material and manufacturing combination presents an opportunity to reduce structural CAPEX, and hence lower the LCoE rate for a given WEC type. It should be noted that further qualification is required on both the structural designs and cost estimates to calculate accurate LCoE rates, however as a comparative study clear benefits are demonstrated in the results. Reductions in LCoE ranged from between 9% up to 45% for the different WEC options when compared to a steel baseline, and the sensitivity study indicated that further improvements up to a 20% reduction in LCoE may be possible through increased device capacity factor as a result of optimised structural forms.

Part of the project was to investigate the performance of the fibre reinforced concrete beyond the material elastic limit. This intended to use a concrete-specific material model (the concrete damaged plasticity model) in a finite element package to assess the behaviour of the concrete during typical ship impact events. Standard concrete material coefficients were established however attempts to modify the standard material model to represent a material with the anticipated response of fibre-reinforced concrete were unsuccessful.

A short sensitivity study was performed on the material model, which illustrated that small modifications to represent low fibre-content reinforced concretes were possible without generating modelling errors, and analysis of basic beam tests using these modes indicated that even for low-fibre content concretes there were performance gains. These gains illustrated that there is potential in the material that can be taken advantage of for structural designs, however it also shows that to properly investigate and represent the material a specific set of validated material properties will be required.

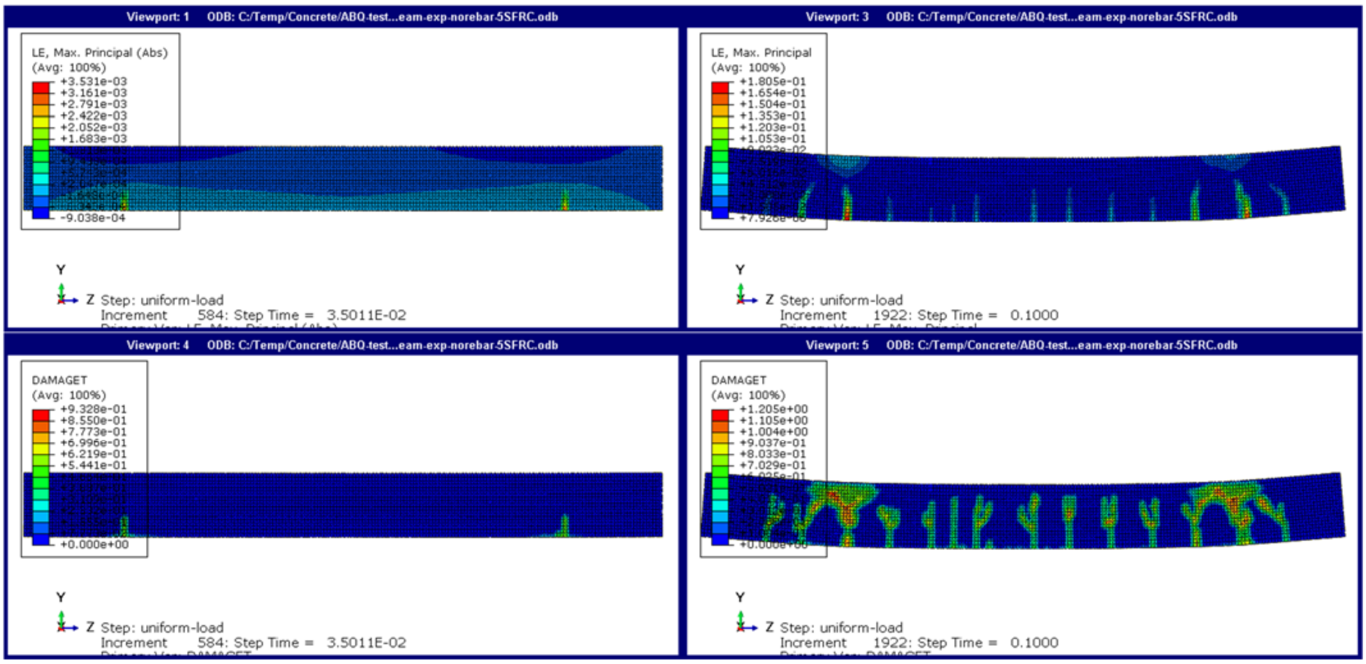

Figure 3 Sample illustration of fibre reinforced concrete beam illustrating strain and crack development

5. Applicability to WEC Device Types

Any WEC that includes a large rigid structural prime mover or component(s) is a potential candidate for the application of advanced fibre-reinforced concrete. This includes all the basic WEC types such as Attenuators, Point Absorbers, Oscillating Surge Absorbers, Rotating Internal Mass etc.

Using currently available printing equipment, WECs that have smaller prime movers, or have structures that can easily be reduced into segments present the best near-term options for production using additive manufacture. While there is no theoretical limit to the size of device that can be produced, there will be real-world upper limits with regards to printing machine cost, concrete printing and setting rate (which affects the ability of the structure to form into a homogenous part without slumping) and structural handling requirements post-manufacture.

WEC structures that are also complex in shape will experience a greater benefit through the ability to produce hydrodynamically optimised shapes without any cost penalties associated with conventional concrete production.

6. Communications and Publicity Activity

Presentation on project progress at the Wave Energy Scotland Conference, Edinburgh, November 2017.

Application to present a short talk on the project at All-Energy 2018 conference and trade show.

Project article on Quoceant website, describing the project and project team.

Various press releases at project inception for example:

https://tidalenergytoday.com/2017/01/18/presenting-wes-funded-wave-energy-materials-rd-projects/

https://www.hydroworld.com/articles/2017/01/wave-energy-scotland-announces-it-will-invest-us-3-7-million-in-10-wave-energy-projects.html

http://www.waveenergyscotland.co.uk/news-events/3m-investment-in-wave-energy-projects/

7. Recommendations for Further Work

The additive manufacture of concrete structures is a relatively immature technology, with most of the research remaining in an academic field with only a few commercial small-scale operations focussing on the construction of houses. Therefore, further research should initially be directed towards the additive manufacture of concrete structures.

Initially, investigation of the base material as produced by a 3D printer should be examined to better quantify the material properties. The concrete mix used in additive manufacturing is not identical to conventional mixes, and the inclusion of fibre reinforcement will also require investigation. A detailed understanding of the as-printed material properties, including the potential to affect material directional properties through fibre alignment should be established, and this will enable more representative WEC structures to be created. This investigation should be conducted through the printing of multiple test samples for laboratory testing to provide statistically significant results regarding the behaviour of the material for both ultimate and fatigue performance.

Additionally, further investigation should be performed to establish the costs for set-up of a 3D printing facility capable of manufacturing significantly-sized concrete structures. Understanding the likely costs and facility requirements is important to provide more accurate costing estimates for WEC developers, and to provide accurate costs for detailed LCoE calculations. This should include CAPEX costs for the printer, anticipated costs associated with operation and maintenance, printing rates for continual operation and setting times (if any) for completed concrete structures. It should also provide an estimate of any additional facility requirements and the number of staff required to operate the printer. As the costs for the supply of the concrete base materials are well understood these do not require further investigation.

Finally (prior to moving to construction of an actual full WEC structure) the manufacture of a representative (large) structural detail using fibre reinforced concretes and additive manufacturing should be produced. This is required to demonstrate the capability and to provide an indicative test of the material and manufacturing process. This could demonstrate several discrete features, such as concrete with varying strengths, concrete with properties that vary with direction, ability to print complex optimised forms and the ability to print onto structural load connection points i.e. steel mounting plates. Validation of the structure should be performed through laboratory load testing of the test piece and comparing the test results against a structural model. This would provide further confidence in both the material and manufacturing process before applying the material to actual WEC designs.

8. Useful References and Additional Data

https://www.dundee.ac.uk/engineering/research/research-groups/concretetechnologyunitctu/

Concrete Technology Unit, University of Dundee.

http://www.lboro.ac.uk/enterprise/3dcp/ Loughborough University 3D Concrete Printing website

https://www.quoceant.com/projects Quoceant projects website including short article on this project

http://www.offshorerenewables.ac.uk/ Offshore Renewables Institute (ORI).