Materials Landscaping Study

Final Report

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EXECUTIVE SUMMARY

MATERIALS LANDSCAPING STUDY

Wave Energy Scotland commissioned this landscaping study to investigate the materials and production processes available, or potentially available, for wave energy device structural design and in particular the transferability of existing knowledge and capability from other industrial applications. Existing solutions as well as those which hold a significant possibility of contributing to the reduction of costs, and improvement of reliability and performance were considered.

This initial piece of work is a scoping study to explore the use of materials, coatings and structures in the wider engineering and industrial sectors that may be relevant to the progression of wave energy technology.

The functionality of the materials considered such as structural and dynamic characteristics (strength, elasticity/plasticity, fatigue resistance, impact resistance etc.), environmental resistance (wear, corrosion, erosion, bio-fouling etc.), environmental impact, industrial availability/readiness, etc. is also considered in the context of overall suitability for wave energy applications and the reduction in capital costs and maintenance requirements.

The study critically evaluates the advantages and disadvantages of each of the investigated materials, coatings and manufacturing processes, clearly itemising and rating their transferability and applicability for use in the wave energy sector, both from a technological and economical perspective. A rating system is developed, representing the range from immediately transferrable through to unsuitable for transfer via various levels of specified development and/or adaptation. Technology Readiness Levels (TRLs) are used to assess the maturity of the technology solutions considered and ultimately recommended for development.

The Materials Landscaping Team consisted of experts in materials, coatings, joining, design and fabrication, as well as having expertise in marine and offshore structures. The study was led by the University of Edinburgh, with partners RiserTec Ltd, Pelagic Innovation and 38techinsight, and was carried out over a 4 month period from February to June 2016. The Team met regularly with Wave Energy Scotland personnel to discuss findings and to refine the overall approach to the work.

WAVE ENERGY SECTOR NEED FOR MATERIALS AND PROCESSES

Wave energy devices are required to withstand large permanent and variable functional loads as well as environmental and accidental loadings. Commercial devices will be required to withstand some of the harshest conditions possible for many years of operation. Detailed interviews were carried out with 10 WEC device developers, in order to understand the problems faced by the sector in the fields of structural materials and manufacturing processes. Responses were categorized under headings of Construction Cost; Articulation Systems; Environment and Performance.

The highest priority issues identified were the costs of steel and polymer composite structures and the fatigue performance in general of most materials. Medium priority issues identified were transportation and logistics costs, submersible buoyancy, the cost and wear of bearing systems, effects of bio-fouling, device mass and manufacturing of complex shapes. Issues seen as low priority by the industry were load shedding, corrosion protection, UV degradation of materials and effects of transported sediments.

TRANSFER OF KNOWLEDGE AND INNOVATION

To date, most wave energy devices have been painted steel structures, or reinforced concrete, with some sub-structures in polymer composites. Trials of various coating technologies have been carried out across the broader marine energy sector with some concrete, composite and plastic structures being developed, however these opportunities have not been explored in full despite being employed extensively in other industries. A key aim of this study is to identify materials and process technologies that have been employed in other industries and have the capability to benefit the wave energy sector by knowledge transfer into the sector.

The Materials Landscaping Team also considered materials and processes which have not previously been used on wave energy device structures. This was to highlight potential innovative solutions to the issues facing the sector. In all, 61 potential technologies were considered. A detailed downselection process was carried out using a technology rating system, and the list of technologies reduced to 11 for detailed investigation.

1 INTRODUCTION

1.1 PURPOSE

The purpose of this landscaping study is to guide future WES project calls in the areas of materials, coatings and manufacturing processes. This initial piece of work is a scoping study to explore the use of materials, coatings and structures in the wider engineering and industrial sectors that may be relevant to the progression of wave energy technology.

1.2 WES REQUIREMENTS

WES stipulated that the study should encompass:

- Materials - e.g. metals, concrete, composites, rubbers, plastics (e.g. HDPE, GFRP), liquids/gels and flexible membranes (e.g. PVC, PU).
- Coatings - e.g. resins, composites, metallic plating (e.g. Nickel), paints.
- Production techniques - e.g. structural component fabrication/manufacture/construction, component integration, assembly and fastening approaches, coating application techniques.

The full range of known wave energy device types has been considered, including attenuators, point absorbers, oscillating wave surge converters, oscillating water columns, overtopping devices, pressure differential and bulge wave devices.

The physical scope that has been addressed is the main external structure of a WEC. i.e. the prime mover structure and its structural integration and connection requirements, up to the interface with a station keeping system.

The study has critically evaluated the advantages and disadvantages of each of the identified materials, coatings and manufacturing processes, and investigated their transferability and applicability for use in the wave energy sector, both from a technological and economical perspective.

2 PROJECT OVERVIEW

2.1 PARTICIPANTS

The Materials Landscaping Team has been led by the University of Edinburgh, with Prof. Conchúr Ó Brádaigh, Chair of Materials Engineering, taking the role of overall Project Manager and Lead. Conchúr has 30 years experience of materials research, development and commercialisation, focused mainly on fibre reinforced composites. He has been assisted by Dr. Tim Stratford, a Senior Lecturer at the University of Edinburgh and Head of the School of Engineering's Graduate School. Tim has 20 years' experience working in structural engineering with concrete and FRP composites in research and industrial practice. Contractual and financial control at the University has been carried out by Mr. Dave Gunn, who is a Consultancy Manager within the University of Edinburgh's Research and Innovation organisation (ERI).

Also on the team, under subcontract to the University of Edinburgh were RiserTec Ltd (Aberdeen), Pelagic Innovation (Edinburgh) and 38techinsight (Dublin, Ireland). RiserTec were represented in the project by Mr. Jonathan Jury and Dr. John Shanks, who have over 60 years experience in the design and management of riser systems, pipeline and subsea systems, marine structures and offshore facilities design.

Mr. Donald Naylor works as an independent consultant trading as Pelagic Innovation. He has over 18 years of experience in the design, manufacture, installation and operation of powerful equipment for the marine environment, including senior engineering positions at the wave energy developer, Aquamarine Power.

Dr. Seamas Grant works as an independent consultant trading as 38techinsight, and has 35 years experience in R&D in adhesives, sealants and coatings, combined with 15 years experience managing global R&D teams in a large multinational corporation (Henkel / Loctite).

The Materials Landscaping Team is highly qualified, with 4 PhDs and 1 MSc in materials, chemistry, mechanical, civil, structural and ocean engineering. Combined, the group has over 60 years research and development experience in composite materials, adhesives and coatings and over 90 years experience in offshore engineering and Wave Energy Converter (WEC) development.

2.2 WORK PACKAGES

The Materials Landscaping Study has been divided into 5 Work Packages (WPs). These are outlined below.

WP 1. Identifying the critical materials problems facing the sector

Leader: Pelagic Innovation.

WP1 established the basis for evaluation of material suitability and formulated the critical materials problems facing the sector. It took the form of a desk study using publicly available sources. A generic environmental specification was compiled as well as typical structural loading requirements for the different WEC classes. Critical materials problems were formulated based on telephone interviews with industry as well as the team's own knowledge of the sector.

WP 2. Identify potential solutions

Leader: University of Edinburgh

WP2 identified potential solutions to the materials problems identified within WP1. Desk studies were conducted into the major materials areas and formed the basis for population of a wide ranging Potential Solutions list. Brainstorming techniques were used to identify novel solutions that could be developed specifically for the wave energy sector. Also within WP2, an initial screening was conducted.

WP 3. Evaluation of potential solutions

Leader: University of Edinburgh

WP3 completed an evaluation of the screened solutions and down selected a limited number of areas for more detailed assessment. Research was conducted into each of these areas and Technology Summaries prepared. These covered the State of the Art, the opportunities for technology transfer and an assessment of the risks associated with using these materials and processes within the WEC environment/duty.

WP 4. Final report

Leader: University of Edinburgh

The final report was completed in WP 4, including recommendations for future materials development activities.

WP 5. Project Management

Leader: University of Edinburgh

All project and contract management was performed within WP5.

3 ESTABLISHING THE BASIS FOR EVALUATION

3.1 METHODOLOGY

The objective of the first work package in the Materials Landscaping Study was to establish a basis for the evaluation of materials, coatings and manufacturing processes. It also sought to gain an industry-wide perspective on the critical challenges that the sector faces with respect to materials technologies.

Firstly, a generic environmental specification (Appendix 2) was written that provides a consistent and concise reference of typical environmental conditions to which WEC materials are exposed. This document was not intended to be an exhaustive definition of all environmental requirements that may be applicable to specific wave energy technologies, but rather it provides an overall picture of typical conditions.

Secondly, a reference set of the typical structural loads (Appendix 3) was compiled. The purpose of this document was to provide indicative loading scenarios that are likely to influence the material selection and design of WEC structures. It provides an indication of the most significant loading mechanisms and their orders of magnitude.

A parallel landscaping study has been conducted by a different team into the forces acting on WECs. Ideally, the ‘forces’ study would have been conducted in advance and its outputs used as an input to the ‘materials’ study. Project timescales did not permit this. However, our report has been reviewed by the ‘forces’ team and they have had no critical comment to make of it.

Finally, a series of interviews were conducted with the developers of a broad range of WEC types. In total, of 14 companies who were approached, 10 were interviewed. These organizations are predominantly located in the UK and Ireland, with the exception of one Australian and one American organization. Where practicable, face to face meetings were held in preference to telephone calls. An ‘Industry Questionnaire’ (Appendix 1) was used as a guide to the discussions, but it was not enforced as a strict protocol. Rather, the industry representatives were given the freedom to cover the areas of materials and engineering challenge of greatest concern to themselves.

The information gathered during the industry interviews, combined with the existing knowledge of the project team, was used to generate a prioritized set of Materials Problem Statements. These problem statements were then used as the input to the subsequent stages of the project.

3.2 PROBLEM STATEMENT AND PRIORITISATION

The problem statements have been categorized under 4 principal areas: Construction Cost, Articulation Systems, Environment and Performance. Further ‘sub-problems’ are defined within each area.

PROBLEM 1 - CONSTRUCTION COST

Wave Energy devices, capable of extracting significant quantities of energy are physically large, heavily loaded structures. Using conventional materials and construction techniques results in expensive structures that are a major contributor to the manufacturing CAPEX. Additionally, because of their size and weight there are also high costs associated with transporting and installing devices.

Sub problem 1.1; Cost of steel structures

Priority - High

A number, but not all, of the WEC developers do not believe that they will achieve a commercial LCOE through fabrication of their primary structures using traditional techniques and fabrication rates. Many of these companies are investigating concrete as an alternative with a lower basic material cost, or lightweight composites that have inherent corrosion resistance and reduced transportation costs.

An alternative viewpoint is that steel as a raw material has a good cost to strength ratio. The challenge is in unlocking rapid automated fabrication techniques to bring down the fabricated cost per tonne, and in developing joining technologies with superior fatigue resistance such that the strength of the base material can be properly utilized. This would enable lighter, cheaper steel structures.

Sub problem 1.2; Cost of composite structures

Priority - High

Some developers, who had investigated the use of composite (Glass Reinforced Polymer – GRP) materials, had found them to be too expensive for the primary structural components. There were however seen to be a number of technical benefits (e.g. corrosion resistance, complex shapes, light weight) from the use of composites. However, it was felt by other developers who were considering composites that they could offer cost savings at the multi-unit production stage, due to the amortization of one off costs (moulds etc.) but this has not been quantified. Adhesive bonding of composite-to-composite and composite-to-metal joints, rather than mechanical fastening, was seen to be a key enabler to the use of composites.

Sub-problem 1.3; Transportation and logistics costs

Priority - Medium

The costs of transporting and offloading heavy and large structures can be prohibitive. One developer found this to be as significant an issue as the fabrication cost of a steel structure. Modular construction or lighter weight materials were being considered.

Sub-problem 1.4; Fatigue

Priority - High

Waves are oscillatory by nature, resulting in fluctuating forces and stresses in WEC structures. In many instances, it is fatigue resistance that dominates the design rather than the ultimate strength. This pushes up the cost and weight of the structure. The most significant cyclic stress variations typically occur at the wave frequency. The wave period can be in the range of 5-20 seconds (0.2 – 0.05 Hz) which results in around 10^8 stress cycles in a 20 year design life.

Materials, coatings and production techniques are needed that have greater fatigue resistance and can enable the design of cost-effective structures to be balanced between ultimate strength and fatigue considerations.

Better understanding is required of the fatigue properties of candidate materials for the wave energy sector and the improvements that can be realized through new production and quality assurance techniques. Specific data is needed for polymers, polymer composites and adhesive joint fatigue performance when materials are immersed in the ocean environment. Designs should not be constrained by historic standards that may be overly conservative.

One potentially disruptive technology relies on the use of natural rubber. Knowledge of the fatigue properties of natural rubber in tension and the joining technologies is essential for this class of device.

Sub-problem 1.5; Submersible buoyancy

Priority - Medium

A number of devices require buoyancy elements that are either permanently submerged, or may be submerged at times during installation and operation. Typically the depth rating requirement was no more than 2 bar. The cost of submersible buoyancy was perceived as being very high. Some developers are also interested in using low-cost polymers for floating structures, but have found that unreinforced polymers don't have sufficient mechanical properties to resist connection and mooring loads etc.

Sub-problem 1.6; Load shedding

Priority - Low

A characteristic of wave energy is the very large ratio between the average and extreme conditions. It could be desirable for some devices to self-regulate the extreme loads which they experience by modifying their geometry.

Materials (and knowledge regarding existing materials) that enable load shedding designs, without compromising fatigue or ultimate strength would be beneficial.

PROBLEM 2 - ARTICULATION SYSTEMS

Devices that require articulation between structural components are concerned with wear within the articulating interface. As with fatigue, these interfaces can be subject to in the order of 10^8 cycles. Because of their location and the imperative of minimizing through life costs, maintenance free solutions are preferable.

Sub-problem 2.1 – Knowledge of wear characteristics

Priority - Medium

A wide variety of proprietary plain bearing materials are available, but comprehensive and independently verified information on their wear properties is difficult to obtain. Accurate data on how they perform in conditions representative of the environment and duty cycle of wave energy converters is needed.

Rolling element bearings may be an option for WEC systems because despite the slow reciprocating nature of operation that prevents effective hydrodynamic lubrication, the devices may be tolerant to small imperfections in the bearing race, e.g. false brinelling that would be un-acceptable in high speed machinery.

Sub-problem 2.2 – Cost of counter-face materials

Priority - Medium

The wear rates of plain bearings are heavily influenced by the surface on which they are running. In non-corrosive environments, steel shafts can be finished to a smooth finish, but in seawater they will be subject to corrosive attack, creating a rough surface and high wear rates. An approach taken in other industries (oil and gas / defence) is to use corrosion resistant alloys for these counter-face locations. This approach is expensive and a more cost effective solution, perhaps utilizing coatings on a cheaper base material would be beneficial.

PROBLEM 3 - ENVIRONMENT

Wave Energy devices operate on and in highly oxygenated, nutrient rich seawater. Their structures are therefore potentially subjected to corrosion and bio-fouling as well as other environmental effects such as UV degradation and the impact of transported sediments.

Sub-problem 3.1 – Limitations of corrosion protection systems

Priority - Low

A combination of paint coatings and Cathodic Protection (CP) systems (and possibly a corrosion allowance) can be an effective means of mitigating against corrosion on steel structures. However there can be some adverse impacts:

- Additional manufacturing cost
- Performance effects of anodes in the water flow
- Inspection and maintenance requirements

Sub-problem 3.2 – Effects of bio-fouling on performance

Priority - Medium

Some WEC designs are sensitive to the hydrodynamic drag of their surfaces. Bio-fouling creates an increase in the drag resistance of the surface and (generally) a reduction in power capture. Maintenance free methods of preventing bio-fouling would be advantageous.

Sub-problem 3.3 – Effects of bio-fouling on loads

Priority - Low

Bio-fouling can increase the loads on the WEC structure. Firstly, drag loads may be increased which in some instances could impact on the design. Secondly the weight of the structure may be changed potentially causing issues with performance, retrieval operations and even survivability.

Sub-problem3.4 – Effects of bio-fouling on reliability and maintainability

Priority - Medium

In specific areas of a machine, marine growth may affect the reliability (e.g. on bearing systems) or the maintainability (e.g. disconnection systems) of the device. Materials, coatings or physical barriers are required in these areas to prevent local marine growth.

Sub-problem 3.5 – Transported sediments

Priority - Low

Sediment transported in the water column could have a ‘sand blasting’ effect on structures, damaging protective coatings and / or the parent material.

Sub-problem 3.6 – UV degradation

Priority - Low

Floating devices and those located in shallow water are subjected to ultraviolet radiation. Polymer materials that are degraded by exposure to UV need to be protected by coatings or fillers. Maintenance-free solutions are preferred.

PROBLEM 4 - PERFORMANCE

Sub-problem 4.1 – Device Mass

Priority - Medium

The inertial characteristics of wave energy devices are fundamentally linked to their performance. In some instances low inertia is beneficial and lightweight materials offer an advantage. In others, ballast is required to provide adequate inertia and heavy, but cheap materials may be a net benefit to LCOE.

Sub-problem 4.2 – Complex Shapes

Priority - Medium

The shape of structures impacts on how they interact with the wave environment. In some instances it is beneficial to have more complex shapes with features such as rounded corners or double curvature. Trade-offs have to be made between the added complexity and cost of manufacture and the performance benefit. Materials and manufacturing process solutions that are suited to the production of complex shapes may be desirable. Polymer and composite moulding processes may be more suitable than steel fabrication for doubly-curved structures, for instance.

4 IDENTIFICATION, EVALUATION AND DOWN SELECTION OF TECHNOLOGIES

4.1 METHODOLOGY

Having gathered a reasonable perspective on the most critical issues related to structural materials, the Materials Landscaping Team then considered each of the sub-problems in turn and generated a listing of potential solutions to that problem. This activity was completed in a full day brainstorming workshop attended by the complete team. Innovative, as well as conventional methods were explored and an emphasis was also put on technical solutions that exist in other areas but have not been utilized in the wave energy sector.

61 ideas were documented in this session. A high level technology summary (3-4 sentences) was prepared for each of these areas and then a rough screening and consolidation exercise was conducted. This screening process resulted in 40 technologies for further investigation. These were evaluated using two methods. Firstly using a conventional weighted scoring matrix and secondly using a simple 'impact' versus 'risk' estimation.

In consultation with Wave Energy Scotland, 11 areas were selected for a more detailed assessment of their potential application to the sector.

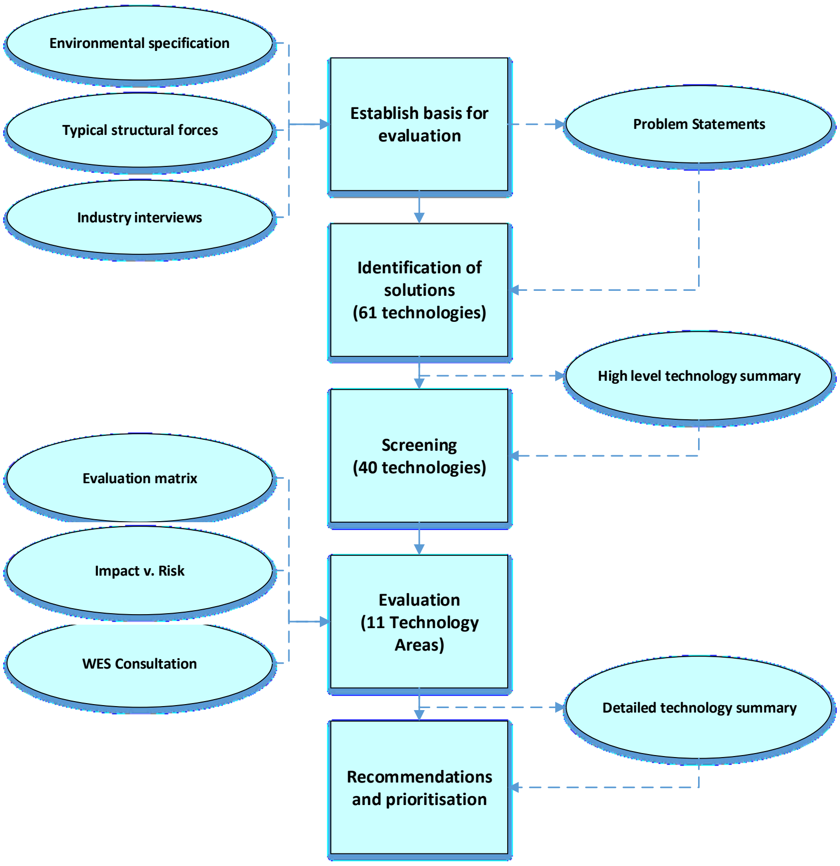


Figure 4.1 - Materials Landscaping Process

4.2 POTENTIAL SOLUTIONS

The 61 identified solutions are listed below and the high level technology summaries are presented in Appendix 4. Subjects that did not pass the rough screening process (Appendix 5) are indicated with a shaded background.

Steel
- Automated Welding
- Design for Fabrication
- Adhesive Bonding
- Rivetting / Spot Welding
- Ductile Iron
- ▨ Steel Casting
- ▨ High Strength Steel
- ▨ Low Spec. Steel
- New Welding Methods

Concrete
- Post-Tensioned Concrete
- Concrete - Durable Connections
- Reinforcement Materials
- ▨ Low Cost Concrete
- ▨ High Performance Concrete
- ▨ Sustainable Concretes
- ▨ Repairability of Concrete Devices
- Novel Production Techniques

Composites
- ▨ Pultrusion
- ▨ Filament winding
- ▨ Thermoset Resin Infusion
- Adhesive Bonding
- Mechanical Joints
- ▨ Composite Repairs
- ▨ Thermoplastic Monomer Infusion
- Polymer/Composite Hybrids

Logistics costs
- Modular Building

Fatigue
- Improved SN Curves for steel
- Optimised welding techniques (incl. prep)
- Composites
- Polymers and Elastomers
- Composite Adhesive Joints

Submersible Buoyancy
- Cargo-Net Loading
- Rotational moulding of plastics plus reinforcements
- Foam sandwich construction

Load Shedding
- Elastomers
- ▨ Shape Memory Alloys

Articulation Systems
- Improved Verified Wear Data
- ▨ Counterface Materials
- Composite Hinge Shafts
- Laminated Elastomers (LECs)
- Composite Springs
- Rolling Element Bearings

Corrosion Protection
- ▨ Cathodic protection / IC Systems
- ▨ Coatings
- ▨ CP Design Tools
- ▨ Emerging Corrosion Protection Techniques
- Erosion Protection Coatings for Composites

Biofouling
- Biocidic Release Coatings
- Foul Release Coatings
- Ecospeed
- Ultrasonic Cleaning (UT)
- Mechanical Cleaning

UV degradation
- ▨ Polyurethane Top Coats
- ▨ Elastomer & Polymer Formulations

Device Mass
- Concretes
- ▨ Pumped Ballast
- Composite Materials

Complex shapes
- Concrete Domes
- Inflatable Bags
- Composite Materials

Novel concepts
- Dielectric Elastomers

Table 4.1. Potential Materials and Processes Solutions Considered

4.3 DOWN SELECTION OF POTENTIAL SOLUTIONS

Following the rough screening process, the remaining technologies were evaluated. In a first stage, the evaluation matrix presented below was used to rank them. This was completed independently by each member of the team and the results aggregated.

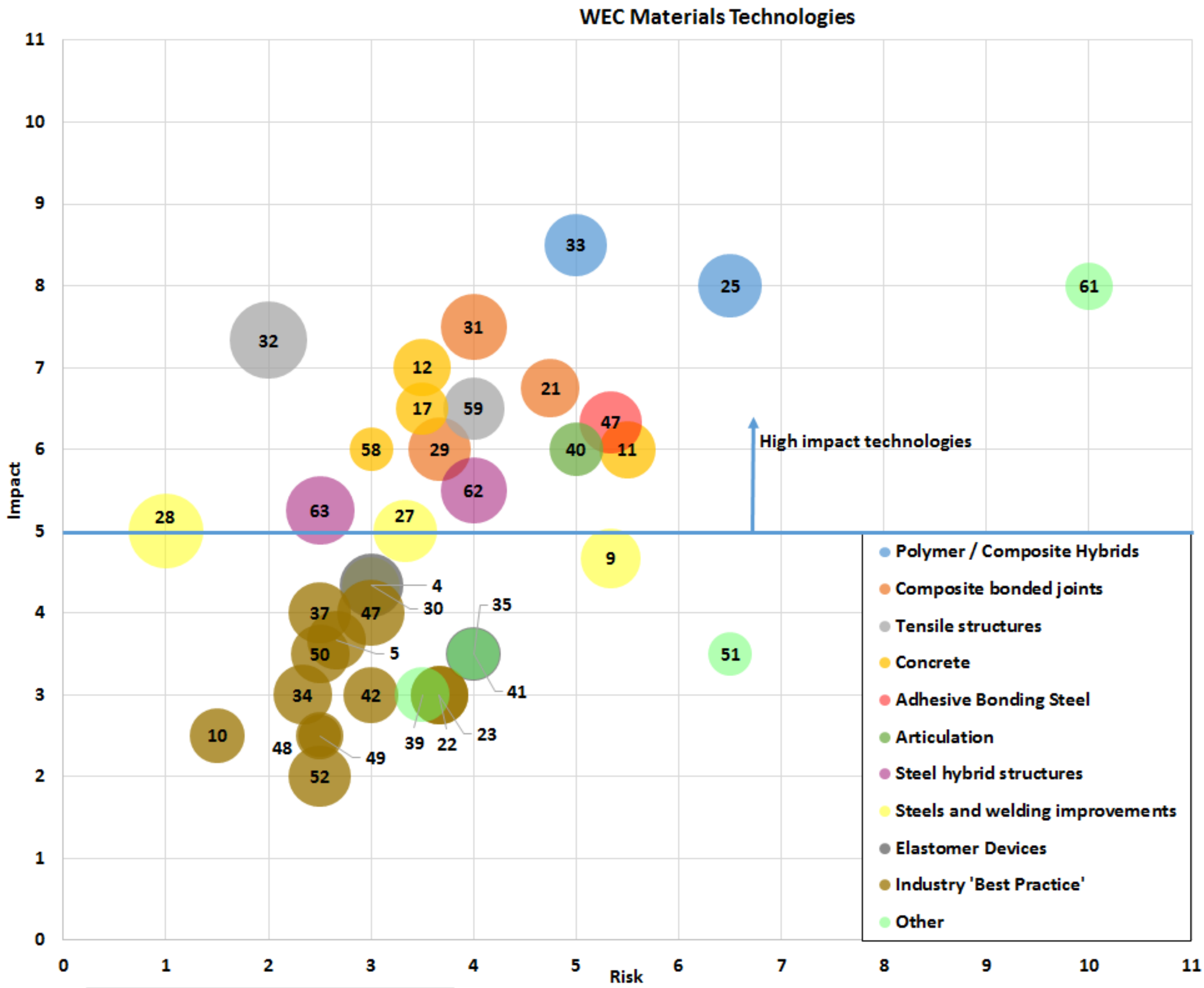
Attribute	**Scoring Guide**		**Weighting**
Manufacturing Cost	1=Expensive,	5=Cheap	x 2
Material Cost	1=Expensive,	5=Cheap	x 2
Capital Cost (NRCs)	1=Expensive,	5=Cheap	x 1
Maintenance & Repair	1=Difficult	5=Easy	x 1
Joining (To self)	1=Poor Quality / Difficult	5=Excellent Quality / Easy	x 2
Joining (To Other)	1=Poor Quality / Difficult	5=Excellent Quality / Easy	x 2
Durability / Survivability	1=Poor	5=Excellent	x 1
Logistics / Installation	1=Expensive,	5=Cheap	x 1

Table 4.2. Evaluation Matrix for Downselection of Technologies

In addition to the matrix evaluation approach, a simple, qualitative risk and impact rating (out of 10) was assigned to each technology. Both of these sets of results are tabulated in Appendix 6.

It was discovered that the weighted scoring method generated ambiguous results. Each technology has strengths and weaknesses and so the outcomes are highly dependent on the selection of weightings. It was also noted that the merits of a particular material choice are highly dependent on the specific design under consideration and that being overly reliant on a highly qualitative assessment within this generic landscaping study could be misleading.

The risk versus impact assessment was of more benefit and ultimately was used to guide the down selection of technologies. Results are presented in the bubble chart below. The diameter of the circles in this chart also reflects the score from the matrix evaluation.



Key
3 - Adhesive Bonding
4 - Rivetting / Spot Welding
5 - Ductile Iron
9 - New Welding Techniques
10 - Post Tensioned Concrete
11 - Concrete - Durable Connections
12 - Concrete reinforcement Material
17 - Novel Production Techniques
21 - Adhesive Bonding
22 - Mechanical Joints
23 - Composite Repairs
25 - Polymer / Composite Hybrids
27 - S-N curves - steel
28 - Optimize welding techniques
29 - Composites (fatigue)
30 - Polymers and Elastomers (fatigue)
31 - Composite Adhesive Joints (fatigue)
32 - Cargo Net Loading
33 - Rotomoulding Plastics + reinforcement
34 - Foam sandwich construction
35 - Elastomers (load shedding)
37 - Improved wear data
39 - Composite Hinge Shafts
40 - Laminated Elastomerics
41 - Composite Springs
42 - Rolling Element Bearings
47 - Erosion Protection Coatings - Composites
48 - Biociic Release Coatings
49 - Foul Release Coatings
50 - Ecospeed
51 - Ultrasonic Cleaning
52 - Mechanical Cleaning
58 - Concrete Domes
59 - Inflatable Bags
61 - Dielectric Elastomers
62 - Hybrid Steel / Polymer / Composite
63 - Hybrid Steel / Concrete

Figure 4.2 – Bubble Chart of Potential Solutions Shown on Impact Vs Risk Axes

In consultation with WES, it was agreed that the landscaping study should focus on the technologies with a high impact score. A further exercise of consolidation into slightly broader subject areas resulted in the 11 areas shown in Table 4.3 for detailed assessment.

It was also noted by the team that many of the technologies in the lower left quadrant (low risk / low impact) of the bubble chart could be regarded as 'industry best practice'. Whilst there may not be a great deal of research and development required in these areas, it would be of benefit to the community to ensure that technology developers are aware of best practice in these areas and have ready access to comprehensive and marine-specific design information.

Letter	Potential Technology Solution	Initial Weighted Score (out of 60)	Initial Risk Assessment (1 = Low Risk, 10 = High Risk)	Initial Impact Assessment (1 = Low Impact 10 = High Impact)
A.	Rotationally Moulded Polymer and Composite Hybrids	43.0 42.5	6.5 5.0	8.0 8.5
B.	Adhesive Bonding of Composites	40.0	4.0	7.5
C.	Tensile Structures	53.0	2.0	7.3
D.	Concrete Structures	39.0 39.0	3.5 5.5	7.0 6.0
E.	Adhesive Bonding of Steels	42.3	5.3	6.3
F.	Articulation using Laminated Elastomeric Composites	37.0	5.0	6.0
G.	Concrete – Steel Hybrids	46.8	2.5	5.3
H.	Polymer and Composite - Steel Hybrids	45.3	4.0	5.5
I.	Steels and Welding Improvements	41.0 42.7 51.0	5.3 3.3 1.0	4.7 5.0 5.0
J.	Elastomers	43.3	3.0	4.3
K.	Dielectric Elastomers Generators	32.5	10.0	8.0

Table 4.3. Downselected Technology Groupings and Scores

5 TECHNOLOGY SUMMARIES IN HIGH PRIORITY AREAS

A technology summary for each of the down selected technology areas is presented in this section, covering the technology state of the art, technology transfer, maturity and risk. These reports form the source of the recommendations presented by the materials landscaping team.

5.A ROTATIONALLY-MOULDED POLYMER AND COMPOSITE HYBRIDS

5.A.1 TECHNOLOGY – STATE OF THE ART

Rotational Moulding

Rotational moulding is a technology that involves the processing of plastic materials particularly suited to the manufacture of large hollow shapes. The actual process itself is relatively simple: the mould is like an empty shell that rotates slowly within a hot air oven on one of more axis of rotation. The material within the mould melts to a fluid like substance and adheres on all of the inner surfaces of the mould. The rotational moulding process is suitable for complex forms and large parts.

It finds its origins in slip casting production methods and has been used as a plastic forming method since the early 1940s [1]. While it was originally used mostly for producing children's toys, it has been adapted as a major manufacturing method for the production of fuel tanks, canoes, boats, air ducts and automotive parts, offering significant advantages over similar processing methods such as injection moulding and blow moulding. The lack of applied pressure minimises the residual stress build up in the plastic part while the use of a powder polymer material removes costly preforming processes from the production cycle.

The rotational moulding process is conventionally contained within a large heating oven and can be broken down into four major steps as outlined in Figure 1 [2]. In Step 1, the hollow metal mould is charged with the powder for forming the part. The amount of powder inserted into the mould is controlled by the internal volume of the mould and the desired wall thickness of the part, with the volume of the part and the density of the powder used to determine the required mass of polymer powder needed. In Step 2, the mould is closed and heat is applied as the mould rotates biaxially causing the powder polymer to melt and stick to the mould surface. The rotational speed used here is

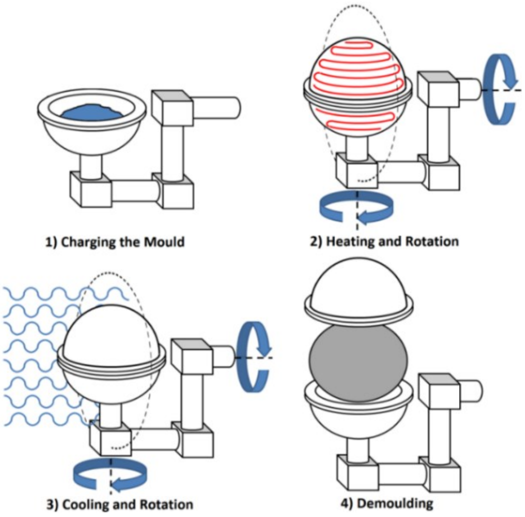


Figure 5.1. An outline of the main steps in the rotational moulding process [2]

quite low ($\approx$ 12 rpm) as the heated tool surface is the driving force behind wall thickness build up and not centrifugal force. The speed of each axis can also be altered to control wall thicknesses in different locations of the part as the time spent passing through the powder pool at the bottom of the mould during heating also controls the part thickness.

Advantages of Rotational Moulding

There are many benefits to using rotational moulding in making plastic products such as: it is suitable to both small and large parts as well as simple and complex designs; the process is excellent for the production of goods that require inserts of different sizes and material types; parts can be produced with no flow lines, ridges or signs left from extrusion of the part; metal inserts can be moulded directly into the part and articles may be produced with a wide range of surface finishes, decorations and details; control of the wall thickness of your part as well as the opportunity for multi coloured or multi layered materials.

Rotational molding is a processing method for producing seamless, stress-free, one piece hollow products that have significant advantages compared to traditional methods (extrusion or injection molding) such as fewer design constraints, lower capital investment costs, and greater flexibility [1]. The rotational molding industry has grown 10–20% in the past few years. Raw materials such as polyethylene (PE), polyamide (PA), acrylonitrile-butadiene-styrene polymer (ABS), polycarbonate (PC), high-impact polystyrene (HIPS), and polypropylene (PP) are currently used in rotational molding. PE represents about the 85% of the total processed material.

Large Product Sizes with Rotational Moulding

In terms of considering the production of large polymer structures for possible use in wave energy converters, the overriding advantage of rotational moulding is its capability to make very large hollow plastic structures which are ideal for floats and other hollow stuctures in wave energy. This is because the mould tooling is unpressurised and the plastic covers the inside of the mould in a stress-free coating-type process. Figure 2 shows some very large water tanks, up to 30,000 litres in capacity, which have been moulded inexpensively using standard rotomoulding equipment [3, 4].

Figure 3 shows what seems to be the largest rotational moulding machine in the world. A Chinese company (Wenling Rising Sun Rotational Moulding Technology Co. Ltd.,) says it has made the world’s largest rotational molding machine for a customer in Canada [5]. The gigantic machine — measuring 6.5 meters in diameter, 27 meters in length, 17 meters in width, and 8 meters in height — traveled across the globe and now is used to rotomould storage products. It had a price tag of 1.8 million yuan ($281,000).

In reality, the only limitation on the size of plastic products that can be rotationally moulded is the size of the moulding machine, ovens and tooling. New developments such as direct electrically-heated tooling [6-8] means that heating and cooling ovens do not have to be used. This will allow the development of even larger moulding machines in the future, where the only limitation will be the size of the mould tools.

(a) *(b)*

Figure 5.2. Large rotationally-moulded polyethylene products (a) 30,000 litre water tank from Bushmans Tanks, Australia (Ref. 3], diameter 3.92m, height 2.87m; (b) 30,000 litre water tank from Tanks-Direct in the UK [Ref. 4], diameter 3.45m, height 3.65m, retail price £3,900 inc. VAT

Wenling Rising Sun Rotations Moulding Technology Co. Ltd.

Figure 5.3. The gigantic rotomoulding machine measures 6.5 metres in diameter, 27 metres in length, 17 metres in width and 8 meters in height. [from Ref. 5]

Disadvantages of Rotational Moulding – Limited Materials and Mechanical Properties

The main limitation of rotational moulding is the limited choice of polymers that can be moulded using the process (PE, PP, PA, ABS, PC and HIPS). The industry is dominated by PE, and table 1 shows the relative performance in terms of stiffness (modulus) and strength of these materials, in comparison to commonly-used metals like aluminum and steels.

Material	**Modulus**	**Strength**
	(GPa)	**(MPa)**
Steel [9]	203.0	600-2000
Aluminium [9]	75.0	70.0-80.0
Low-Density PE [10]	0.2	10.0
High-Density PE [10]	1.2	32.0
PP [10]	1.5	33.0
PA-66 [10]	2.8	70.0
ABS [10]	2.2	38.0
PC [10]	2.8	65.0

Table 5.1. Properties of polymers used in rotational moulding, compared to steel and aluminium [from Refs 9 and 10]

As the table shows, the strength and stiffness properties of HDPE, the most common material used in rotational moulding, are between one and two orders of magnitude less than those of steel. Other polymers that can be rotationally-moulded such as PP, PC and ABS do not possess much higher properties than HDPE. Though HDPE has excellent resistance to seawater, its low stiffness in particular makes it susceptible to deformation and creep under high loadings over a long period of time.

The most common approach in polymer moulding to achieving an increase of stiffness and strength is by incorporation of short or long reinforcing fibres of glass or carbon in the polymer, via compounding, extrusion or milling. However, the literature shows that despite many efforts [11-13], it has proved very difficult to incorporate meaningful amounts of reinforcing fibres into the polymer during rotational moulding. Problems associates with fibre reinforcement in rotationally-moulded polymers include poor adhesion with the polymer, poor dispersion of fibres, excessive voids in the polymer wall and poor surface finish [12]. Recent efforts towards incorporation of natural fibres such as abaca, cabuya, sisal and banana fibres [14, 15] have led to some successes in producing void-free mouldings with good surface finish, but the maximum increase in mechanical properties has been of the order of 100% only, still leaving a significant gap between the properties of rotomoulded polymers and steels, for instance.

There is a clear need for other methods of reinforcement of rotationally-moulded polymers, using perhaps in-mould positioning of pre-consolidated composite or metal structures which would be over-moulded during the process; or post-moulding reinforcement methods such as thermal welding [16] or tape-placement [17] of thermoplastic composites.

5.A.2 TECHNOLOGY TRANSFER

Rotational Moulding of Marine Products

The most relevant rotational moulding sector for technology transfer into wave energy is the manufacture of marine and aquaculture structures. Rotational moulding of Polyethylene (PE) products is widely used for marine products, such as buoyancy modules, clamps, saddles, centralisers and spacers for oil and gas risers (Figure 4), buoys and modular buoys, drill riser buoyancy, riser towers and floats. Balmoral Offshore Engineering [18] make buoys "typically constructed from a rigid polyurethane foam core, cast around a central steel tension member that is reinforced with a glass reinforced polyester skin. The buoys are clad in a resilient polyethylene layer which is externally coated with a tough abrasion resistant polyurethane elastomer skin." This is an example of hybrid marine structures based on the rotational moulding process for polyethylene.

Figure 5.4. Rotomoulded polymer buoyancy modules for oil and gas risers generally consist of an internal clamping system and syntactic foam buoyancy elements. The buoyancy elements are supplied in two halves incorporating a moulded internal recess that is configured to transfer the forces from the buoyancy to the clamp and subsequently the riser. [from Ref. 18, Balmoral Offshore Engineering]

The use of syntactic foams is for deep water applications (1,000 feet depth or more). Less expensive foams such as closed-cell polyethylene, PVC-based copolymer or polyisocyanate foams [19] can be used for depths that WECs will operate at (100 feet depth or less).

Rotational moulding of polyethylene is also widely used for aquaculture structures. Rotational moulding of Polyethylene (PE) products is widely used for fish farm tanks, pontoons, containers, crates, pallets and insulated fish and cooler boxes [20, 21, 22]. These structures can be large and quite complex in shape and have demonstrated a 20-year lifetime in the ocean.

Until recently, there have been no examples, however, of hybrid reinforcement processes using either thermoplastic or thermosetting composites, being employed with rotational moulding in the marine or other sectors. In 2015, French multi-national energy company, Total announced that "Total has developed a new technology to produce, in the rotomolding process a multilayer structure combining a Carbon or a FG composite, or any type of composite system layer together with one or more thermoplastic layers" [22].

5.A.3 MATURITY AND RISK

The TRL level of rotational moulding for wave energy converters can be estimated, depending on whether the moulded components are non-structural (lightly loaded) or structural (i.e. heavily loaded).

Non-Structural (Lightly Loaded)

For lightly loaded marine components such as floats and other buoyant structures, the TRL for rotationally-moulded polymers, in particular HDPE is 9 (actual system proven in operational environment.

Structural (Heavily Loaded)

For heavily-loaded marine components, there has been no technology demonstrated that will allow enable high long-term mechanical performance in rotationally-moulded structures, via incorporation of fibre or polymer composite reinforcement. Examples shown above of hybrid structures (polymer, steel and fibre-reinforced composites) in the oil and gas field could form the basis for some developments in more heavily-loaded wave energy device structures. Accordingly the TRL for heavily-loaded structures is between 2 and 3 (TRL 2 – technology concept formulated; TRL 3 – experimental proof of concept).

The principal technical risks are as follows:

- It may not be technically feasible to reinforce rotationally-moulded structures with fibre-reinforced structures.
- It may not be economically feasible to do so in any case.
- It may not even be technically feasible to reinforce rotationally-moulded structures with steel structures.

5.A.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

Rotational moulding is a very cost-effective method of producing large hollow polymer structures, which can be largely automated. Raw material prices for rotomoulding powders vary from a baseline £1/kg for polyethylene (HDPE) to 15% more for polypropylene (PP) powders, and £4-£5/kg for Nylon-6 (PA-6) powders and as high as £10/kg for Nylon-11 and Nylon-12 powders [23]. Given that the rotomoulded polymers will have to be locally reinforced with glass or carbon fibres, or with pre-consolidated thermoplastic composites, in order to take the high loads transferred by PTOs, tethers and other fixings in WECs, the prices of these composites need to be taken into account also, with typical prices of £5/kg for a commingled glass fibre PP and £20/kg for a CF/PA-6 material.

Assuming that 30% of the weight of a hybrid glass fibre composite/polymer structure is in a thermoplastic composite and 70% in un-reinforced polymer, this would yield an average material price for a PP rotomoulded/glass-fibre hybrid structure of £2.30/kg. Addition of metal fixings and loading points could increase the average material price to £3/kg. The moulding process is relatively inexpensive, but will have to be developed to incorporate the composite reinforcement. Allowing for materials to constitute 70% of the fabricated cost of the final product would suggest that a fabricated hybrid rotomoulded composite structure could be produced for in the region of £4.3/kg, or £4,300 per tonne.

Assuming a baseline figure of £4,000 per tonne of fabricated steel construction in the UK, the fact that the hybrid composite/polymer structure would have a density of approx. 1,500 kg/m3, compared to the metal structure at 7,800 kg/m3, even allowing for double the wall thickness in polymer/fibre compared to the steel would give an equivalent price of £4,300 x 1500 x 2 / 7,800 = £1,653/equivalent tonne. This would give a CAPEX saving of approx. 58%. Savings in logistics due to modular, lighter weight construction and lifting could raise the CAPEX savings to the order of 60%. Operating costs could also be reduced by lower maintenance as polymers and composites do not corrode in seawater.

It should be noted that, due to the novelty of the proposed process and the fact that WECs would be re-designed to take advantage of a validated new technology, there is no way to predict with any accuracy the potential CAPEX cost savings that could be achieved. The replacement of a steel fabricated floating structure with a rotomoulded polymer/composite structure will also depend on the material and structural properties available from the new process. Potential savings of 50% could, however, be aimed at.

5.A.5 RECOMMENDATIONS

Rotational moulding of polymers has many advantages over other manufacturing processes, in production of large, hollow, lightweight, corrosion-resistant and inexpensive floating structures. There is a rich heritage of use of rotomoulded polymer structures in the marine sector, in particular for buoys, tanks and flotation devices in both the oil and gas and aquaculture sectors. However, the mechanical properties of commonly-used polymers for rotational moulding are not high enough for consideration for heavily-loaded WEC structures with current technologies.

In this perspective, critical materials and process issues that need to be addressed are:

- Development of methods of incorporating pre-manufactured fibre-reinforced composites or metals into the rotational moulding process, via an overmoulding step.
- Development of post-moulding reinforcement methods such as thermal welding or tape-placement of thermoplastic composites.
- Re-design of WEC structures to take advantage of existing rotational-moulding possibilities as a cost-saving exercise i.e. by re-reorientation of load paths through steel skeleton structures, leaving floating structures less heavily loaded.
- Re-design of WEC structures to make possible use of hybrid moulding processes based on rotational moulding or polymers with composite and/or steel reinforcement.

5.A.6 REFERENCES

1. R. J. Crawford and J. L. Throne, "Rotational Molding Technology", William Andrew Publishing and Plastics Design Library, USA (2002).
2. R. J. Crawford and M. P. Kearns. "Practical Guide to Rotational Moulding", Rapra Technology Ltd., Queen's University Belfast, UK (2003).
3. Bushmans Tanks, Australia, http://www.bushmantanks.com.au/water-tanks/t6500-30000l-storm-water-tank
4. Tanks Direct, UK, http://www.tanks-direct.co.uk/30000_litre_water_tanks?gclid=CjwKEAjw0pa5BRCLmoKIx_HTh1wSJABk5F_44lOGVjaX7L-A__Bvafz7lDw3AmtDqtvhmCXGyVT6pxoCuxPw_wcB
5. Plastics News, "Rotomoulding a very big future", September (2015) http://www.plasticsnews.com/article/20150909/NEWS/150909932/rotomolding-a-very-big-future
6. M. Kearns et al, "Comparison of cycle times and heating efficiency for direct electrically heated and conventional gas fired rotomoulding machines", Rotation Magazine, Vol. 13, No.6, pp. 18-25 (2004).
7. B.R. Murray et al, "Void Distributions and Permeability Prediction for Rotationally Moulded Polymers", Proceedings of the Institution of Mechanical Engineers, Part L, Journal of Materials: Design and Applications, Vol. 229, No. 5, pp.403–418 (2015)

8. Persico Ltd., “SMART Leonardo Technology”, http://www.leonardosmart.com/
9. W.D. Callister, “Materials Science and Engineering, An Introduction”, 7th Edition, Wiley (2007).
10. R.J. Crawford, “Plastics Engineering”, 3rd Edition, Butterworth-Heinemann (1998).
11. F.G. Torres and C.L. Aragon, “Final product testing of rotational moulded natural fibre-reinforced polyethylene”, Polymer Testing, Vol. 25, pp. 568–577 (2006)
12. Paul Betschart, “Strengthening Rotationally Moulded Products: Development of a Rotomouldable Thermoplastic Composite”, MSc Thesis, University of Waikato, New Zealand (2008).
13. Rubén H. López-Bañuelos et al., “Rotational molding of natural fibers and polyethylene composite materials”, SPE Plastics Research Online (July 2012), accessed on http://www.4spepro.org/view.php?source=004326-2012-07-03
14. Z. Ortega et al, “Rotationally moulded natural fibre reinforced polyethylene”, RotoWorld Magazine, accessed on https://rotoworldmag.com/rotationally-moulded-natural-fibre-reinforced-polyethylene/
15. P. Nugent, “Rotational moulding: new materials, new horizons”, Association of Rotational Moulders (ARM) Annual meeting, Chicago, USA, October (2014).
16. A. Yousefpour et al, “Fusion bonding/welding of thermoplastic composites”, Journal of Thermoplastic Composite Materials, Vol. 17, No. 4, pp.303-341 (2004).
17. White papers: Accudyne Systems Inc., 2016. Accessed at http://www.accudyne.com/white-papers.htm
18. Manuplas Products, http://www.manuplas.co.uk/rov-auv-buoyancy
19. Balmoral Offshore Engineering, http://www.balmoral-group.com/balmoral-offshore/
20. PartnerPlast Marine Subsea Group, http://partnerplast.no/Activa/information.html
21. JFC Marine, http://www.jfcmarine.com/aquaculture/water-storage-tanks/
22. E. Maziers, “Total gives a new spin to rotational moulding”, ARMO 2015: International Rotational Moulding Conference, Nottingham, UK, September (2015)
23. Private Communications from Dr. Mark Kearns, Polymer Processing Research Centre, Queens University, Belfast, Northern Ireland, June 2016

5.B ADHESIVE BONDING OF COMPOSITES

5.B.1 TECHNOLOGY – STATE OF THE ART

Composites are widely used in the marine environment. Glass reinforced polyester resins are used in small boats and ships while carbon fiber filled resins are favoured in fast craft and racing yachts. There is also increasing use of composites in offshore applications (composite risers) and in offshore wind and tidal turbines (blades). Use of composites in WEC devices is still rather limited but there are certainly advantage to be gained from the benefits of strength, stiffness, light weight and corrosion resistance. Several device designs involve elements which are totally submerged while others are designed to float in the splash zone. Modular construction of WEC devices will necessitate assembly and joining of composite components to composites and other materials.

Two methods are commonly used to join composites

a) Co-bonding is the process where two laminates, one of which is cured and the other uncured, are bonded together in the step in which the second laminate is cured
b) Secondary bonding is the process where an adhesive is used to bond two cured laminates together or to bond laminate to another substrate (wood, metal, plastic, glass)

This section of the report will discuss the secondary bonding of composites.

Davies has provided a concise summary of the adhesive bonding of composites particularly in small boat assembly [1]. In larger boats, composites are used mainly in high speed passenger and car ferries, patrol and rescue ships and smaller naval ships. Adhesive bonding of composites in shipbuilding applications is covered by a wide range of standards [2, 3, 4, 5, 6, 7]. All of these standards provide details about construction, qualification of adhesives etc. but in general there are reservations expressed about adhesive joints in critical areas in direct contact with seawater.

"The use of bonded joints is subject to the approval of the Society. Bonded joints are not accepted for transfer of the global loads on the hull or on joints the failure of which would compromise the watertight integrity of the vessel." [Ref 2, Pt 3, Chpt 4, Sec.8].

Composite materials are used in military applications, particularly on mine countermeasure craft, high speed craft, submarine periscope fairings and more recently in superstructures. Some of the key challenges of typical sandwich T –joints and composite superstructure to steel hull joining in military applications are outlined in [8]. The French navy have implemented such a superstructure for the helicopter hanger on the La Fayette class frigate and the details of the steel to composite joint are discussed by Boyd [9].

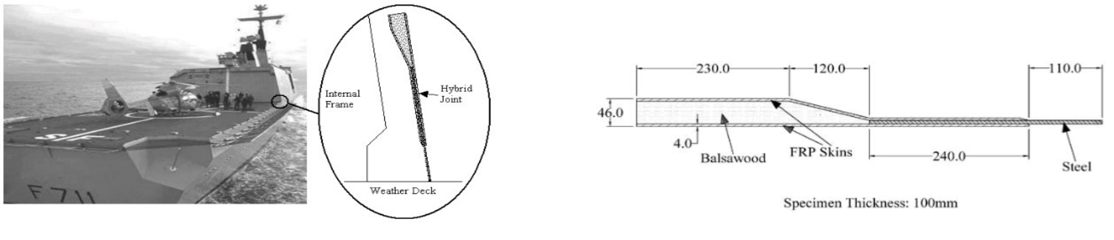


Figure 5.5. Helicopter hangar (left) on the French La Fayette class frigate and (right) details of hybrid joint used [from Ref 9]

The Bondship project was a major European initiative to introduce adhesive bonding into shipbuilding for joining lightweight materials. The project ran from 2000 to 2003 and involved a consortium of research organisations, designers, material suppliers, shipbuilders, ship-owners and operators. The major output was a set of guidelines [10] which sum up all the steps necessary to design, build, inspect and repair all types of bonded joints in ships. In the summary of the reports they indicate one of the major issues with adhesive bonding:

- ***Long-term performance**: This document is based on the assumption that the long-term performance of a bonded joint cannot be reliably predicted from the results of accelerated ageing tests. Therefore, requirements to the resistance of the joint are combined with requirements that limit the consequences of failure of the joint and that it must be possible to repair the joint using an approved repair method.*

There are a number of reports [11] of the use of composite patches for repair of cracks in superstructure of ships with successful experience over a 15 year period reported in one publication [12]. A joint industry project was run for a number of years to develop guidelines for bonded patch repairs of Floating Production and Storage Offshore (FPSO) structures. These bonded repairs allow postponement of emergency repairs by welding until the next planned maintenance, minimizing interruptions in daily operation. An overview of the process is provided by Echtermeyer et al [13]. A Recommended Practice document has been issued by DNV [14]. These repairs can be used in contact with seawater but the Recommended Practice excludes Class III repairs *(Repairs where sufficient documentation is provided to quantify with confidence the reliability of the repair for the intended service life of the structure*). In the guidance note it is stated "*Due to the limited service experience that currently exists with bonded repairs, the long term reliability of repairs cannot be quantified with sufficient confidence using accelerated tests".*

A more recent publication [15] provides a comprehensive review of adhesive bonding in marine applications and describes all aspects of the subject. It is a particularly good reference point for the fabrication and testing of composite/composite and composite/metal joints in the marine environment.

All of the information available suggest a high level of confidence in the performance of composite/composite and composite to metal joints in the marine environment but a high degree of reservation concerning situations where load bearing joints are directly exposed to seawater where there is a requirement for a long service life. This is certainly influenced by the fact that ships and boats are manned and any failure in the integrity of a joint below the waterline presents a danger of loss of life.

5.B.2 TECHNOLOGY TRANSFER

Composite bonding is widely used in aerospace/aircraft, wind, automotive and transport areas. The information available in each of the areas is extensive. This section will focus on a few industry segments that provide particularly relevant information that could be transferred to the fabrication of WEC devices containing composites.

Aerospace /Aircraft

Some aircraft manufacturers have made extensive use of adhesive bonding for metallic substrates. Recently, composites use is increasing and composite/composite and composite/metal bonding applications are increasing. Aerospace adhesives are heat cured and have requirements for high glass transition temperature (Tg) and good humidity tolerance. These products will not be applicable to composite bonding in WEC device applications, but aerospace manufacturers have considerable experience of the importance of good surface preparation for composite substrates, and this information would be transferrable to the use of composite bonding in WEC devices [16]. Portable atmospheric plasma sources are now available and this technique has been shown to enhance adhesion and durability of composite bonds [17]. Considerable strides have been made in the inspection of composites and composite bonds and techniques like pulsed ultrasonic scanning, thermography and shearography are now available [18].

Wind Energy

Wind turbine blades are now the largest composite parts reproducibly manufactured. Large numbers of turbines are now operating on land and offshore and a considerable amount of data has been gathered on their operation in a wide range of environmental conditions. Wind turbine blades use adhesive bonding to assemble the various components. A schematic of the typical blade design and construction methodology is shown in the illustration below [19].

Adhesives are used to bond both halves of the clamshell to the main spar or shear webs. Requirements for these joints are well understood, and design and modeling programs are available [20]. A number of suppliers have products available, some with GL approval, in a range of different chemistries. [21,22,23,24]. Though these blades operate offshore, there is no requirement for direct contact with seawater and the fatigue loads will differ from those experienced with Wave Energy devices Technology developed in this mature industry would provide an excellent starting point for serial manufacture and assembly of WEC devices using Composite adhesive joining. Technology is also being developed for in-situ inspection of wind turbine blades which could be applied to the inspection of other large composite constructions.

Tidal turbines

Tidal turbines are a new technology with a wide range of devices under development. Some of these use composite rotors and adhesive bonding. Unlike other composite applications, tidal turbine blades are in direct contact with seawater. A recent review [25] describes the technology of advanced fiber reinforced composites for tidal turbines. DNV GL have now issued a standard for tidal turbines [26] that includes adhesive bonding and suggests test programs, though it still cautions that bonded joints should be durably sealed against the sea water environment and that degradation of the joints in long term exposure to seawater should be considered as part of the design process by determining/estimating a knock down factor. The standard lists partial safety factors for bonded joints.

5.B.3 MATURITY AND RISK

Adhesive bonding of composites is now a mainstream technology in manufacturing.

- Surface preparation methods are available and well understood
- Adhesive products suitable for bonding all materials and combinations are available
- Application and cure systems are available
- Data is available for the performance of adhesive bonds in harsh environments
- Recommendations are available for bond design
- Test and inspection methods are available
- Suppliers are well established and have appropriate manufacturing and quality assurance systems in place

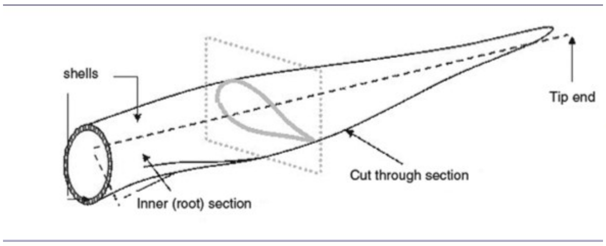


Figure 1. Simplified diagram of a wind turbine blade.

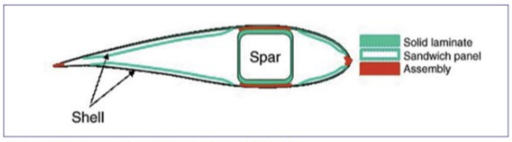


Figure 2. Blade of one-piece construction: cross-section of Figure 1.

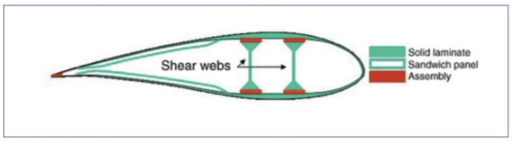


Figure 3. Blade of two-piece construction: cross-section of Figure 1.

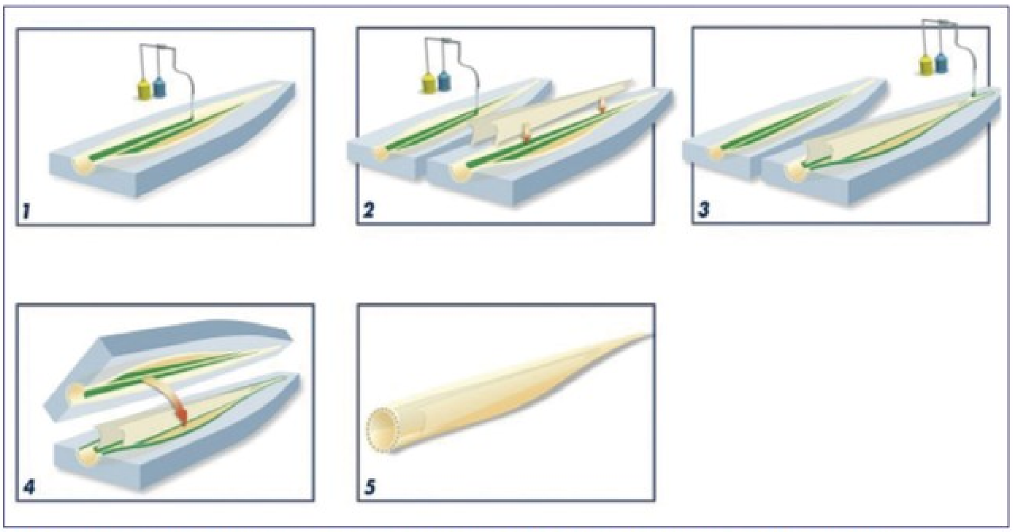


Figure 5: Five-step bonding process for a wind turbine blade. 1: Adhesive is applied to the first shell in the fixed part of the mould, and to the second one, at the root end of the blade. 2: The internal parts (spar or shear webs) are lifted into position. 3: Adhesive is applied to the top of the spar or shear webs for the second shell bonding. 4: The second shell is lifted over onto the spar or the shear webs. 5: The mould is closed.

Figure 5.6. Wind Turbine Blade Design and Adhesive Bonding [from Ref 19]

This technology is now mature. However, to date there is no experience with direct bonding of composites in WEC device environments. We would judge that the technology is at TRL level 6 in WEC devices, WEC devices operate in the submerged and splash zones and this is a different environment for bonded joints than that experienced by tidal turbines. WEC devices are subject to fatigue loading and are expected to have a lifetime of 25 years. Unlike ships and boats, WEC devices are not manned so a higher level of risk can be taken with adoption of bonding, however there is also less opportunity to detect failure before it becomes catastrophic. This situation is addressed in a publication by Weitzenbock and McGeorge [27]. The paper discusses the dilemma posed by our inability to predict the long term performance of adhesive joints in the marine environment and suggests a risk based approach to design.

Joints on the dry side of WEC devices will be subject to unusual fatigue loading. Fatigue studies of composite to composite and composite to metal joints have been carried out, but not with the frequency and amplitudes experienced in WEC devices. There are very few fatigue studies available for composite joints in seawater. WC de Goeij et al reviewed composite joint cycling under cyclic loading in 1999 [28]. In 2002, Liechti et al studied the fatigue crack growth of adhesively bonded joints at several temperatures in air and salt water [29]. Salt water led to a decrease in threshold values and an increase in crack growth rates. This study was carried out with an unusual set of composite materials and at elevated temperatures. Bernasconi et al studied the fatigue behavior of thick composite laminated bonded to composite and to steel with 3M 9323 [30]. They studied the effect of shape of joints and overlap length. They also discussed modeling the joints, but no exposure to seawater data was presented. Boisseau et al have studied the fatigue behavior of composite specimens in seawater [31]. Different matrices and reinforcements were studied but no bonded joints. The paper does present a lot of experimental information which would be useful in setting up tests of bonded composite specimens. Zhang et al looked at the fatigue performance of pultruded composite specimens bonded with Sika 330 epoxy adhesive at various temperatures in air and at 40˚C, 95% RH [32]. Increased temperature shortened the fatigue life and this was exacerbated by the presence of humidity.

The DURACOMP program [33] ("Providing confidence in durable composites") is underway, coordinated by Warwick University. Its aim is to address the concern about the durability of composites in a 50 year+ infrastructure environment. A study of environmental aging of bonded T-joints is included in the scope, but no results have been published on this to date.

5.B.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

Adhesive bonding is the most effective method for composite part assembly. Surfaces must be prepared for bonding either by removal of peel ply or mild abrasion and cleaning. This will add to the material costs. Additional capital costs will be incurred as a result of the purchase of adhesive dispensing equipment and curing/clamping systems particularly for large structures. If heat curing is required, capital costs relating to oven or other type of contact heating systems will be incurred. All of these costs will be specific to the type of assembly being bonded but the equipment can then be reused for other projects. Typical structural adhesive prices will vary depending on supplier, volumes, packaging and technology. Generally, pricing will follow the pattern 2K PU< 2K Acrylic< 2K Epoxy and average cost of adhesive would be approx. £8/kg. Some 2K acrylic adhesives are flammable and this will require a flameproof assembly area. Many of the products have a strong odour and this will necessitate provision of adequate ventilation during application and cure.

Adhesive bonding of composites will only be used in WEC devices if the use of composite materials instead of traditional materials such as steel is deemed to be cost-effective. Pultrusion is the most cost-effective method of production of large volumes of composite materials, with continuous-length profiles available in sheet, bar, L and I-sections and enclosed shapes such as tubes and box-sections. Pultruded glass-fibre isopthalic polyester sheets and bars are available in small volumes for approx. £4/kg, though this could be expected to drop to £2.50/kg for large volumes [34]. More specialized, marine-resistant glass-fibre reinforced vinyl-ester resins can also be pultruded, with current material cost estimates of £7/kg, though this would be expected to decrease at large volumes [35]. Assuming that adhesives will make up 5% of the weight of the structures would yield an average material cost of £4.20/Kg, and allowing for other consumables (e.g. application aids) that might be necessary would bring material costs to approx. £5/kg. Assuming that the adhesive bonding of a large composite structure would yield a process where the materials constituted 50% of the cost of the fabricated structure would yield a fabricated cost of £10/kg or £10,000/tonne.

Allowing for 1.5 times the wall thickness in glass-fibre vinylester pultrusions than the equivalent steel construction, and a material density of 1900 kg/m3, compared to a steel density of 7,800 kg/m3 would result in an equivalent cost of £10,000 x 1900 x 1.5 / 7,800 = £3,653/equivalent tonne. Assuming a typical baseline cost for fabricated steel structure of £4,000/tonne would give a CAPEX saving of 8.6%. Savings in logistics due to modular, lighter weight construction and lifting could raise the CAPEX savings to the order of 15-20%. Operating costs could also be reduced by lower maintenance as polymers and composites do not corrode in seawater.

It should be noted that, due to the fact that large scale adhesive bonding or pultruded composites has not yet been demonstrated in any industry, there is no way to predict with any accuracy the potential CAPEX cost savings that could be achieved. Potential savings of between 10 and 20% could, however, be aimed at.

5.B.5 RECOMMENDATIONS

If composites are to be used with maximum benefit in WEC devices, it is necessary to establish a suitable joining technology. Adhesive bonding offers the best possibility for joining. Based on published information and best experience in industry, the effectiveness of adhesives in joining composites in not in doubt. It is necessary to establish the capability of adhesives to join composites to composites and composites to metals in a WEC device environment. A wide range of adhesive products are available in many technologies. Joint designs are well understood and documented in the various standards and the Bondships Guidelines. Suitable materials could be selected based on the composites to be bonded and the device environmental conditions, temperature, humidity, stress/strain, fatigue, sunlight exposure/salt.

The question which needs to be addressed is: can joints be constructed with adequate environmental resistance to provide survivability for WEC devices ? The study should focus on the wet side (in direct contact with sea water), the dry side (within the sealed area of the device) and the splash zone (the breaking wave area). Areas to be explored would be:

a) The benefit of surface preparation of composites – abrasion, primers, plasma.
b) The effect of bond gap variation.
c) Cure conditions – room temperature vs slightly elevated temperatures e.g. 60˚C.
d) Performance of the assembled joint in fatigue and impact and in particular in fatigue in direct contact with seawater.
e) Development of sealing strategies to protect load bearing joints in critical areas from ingress of seawater.
f) Establishment of test protocols which allow assignment of realistic design safety factors.
g) Development of predictive models.

Unlike the situation for adhesive bonding of metals , where the basic energetics of the polymer/substrate interface predisposes the joint to eventual failure in water (though the timescale for good joints may be long enough to ensure survivability for 25 years), there is no similar predisposition for adhesive/composite joints. Thus there is a better expectation that a stable situation will eventually develop and be maintained.

5.B.6 REFERENCES

1. Marine Industry , Peter Davies , in Handbook of Adhesion Technology , L M F da Silva , A Ochsner and R D Adams (Eds) , Springer Verlag , 2011, pp. 1237-1262.
2. DNV. Rules for the classification of high speed and light craft.
3. DNV. OS-C501 Composite components.
4. NK Rules for the survey and construction of ships of glass reinforced plastics.
5. NK Guidelines for the use of structural adhesives.
6. ISO 12215 Small craft hull construction and scantlings – Part 6 Structural arrangements and details.
7. Adhesives – Standard for Certification No 2.9 Type approval program NO.1-501-12, DNV (2012).
8. Lightweight construction for advanced shipbuilding, P Noury , B Hayman , D McGeorge and J Weitzenbock, , Proceedings of the 37th WEGEMT Summer School on advanced shipbuilding and shipping – Competitive Shipbuilding ETSIN Spain (2002).

9. Integrity of hybrid steel-to-composite joints for marine applications, S W Boyd, J I R Blake, R A Shenoi, and A Kapadia, Proc. Instn. Mech. Engrs., Vol 218 Part M , J Engineering for the Maritime Environment, Special Issue paper, pp. 235 – 246.
10. BONDSHIP Project Guidelines, J R Weitzenbock and Dag McGeorge, DNV (2005).
11. Use of adhesives in repair of cracks in ships structures, R C Allan, J Bird and J D Clarke, Materials Science and Technology, 1988, 4, pp. 853 -859.
12. Application of bonded composites in the repair of ships structures – A 15 year experience, I Grabovac and D Whittaker , Composites Part A , 2009, 40, pp. 1381- 1398.
13. Bonded patch repairs for metallic structures – A new recommended practice, A T Echtermeyer, D McGeorge, J H L Gave and J Weitzenbock, J. Reinforced Plastics and Composites, 2014, 33, pp. 579- 585.
14. DNV- RP-C301, Design Fabrication, Operation and Qualification of Bonded Repair of Steel Structures, DNV, April 2012.
15. Adhesives in Marine Engineering, Jan R Weitzenbock, Woodhead Publishing, 2012.
16. Adhesively bonded joints in Aircraft structures, L John Hart-Smith, in Handbook of Adhesion Technology, L M F da Silva, A Ochsner and R D Adams (Eds) , Springer Verlag , 2011, pp. 1103 – 1147.
17. New approach to surface preparation for adhesive bonding of aerospace composites: atmospheric pressure plasma. Studies on the pretreatment lifetime and durability of the bondline, J S Serrano, A Urena, S L Urena, T B Valera, Composite Interfaces, 2015, 22, pp. 731 – 742.
18. Non destructive testing broadens its scope, K Mason, High Technology Composites, May 2006.
19. Adhesive for bonding wind turbine blades, K P Subrahmanian and F Dubouloz, Reinforced Plastics, Jan/Feb 2009, pp. 26 – 29.
20. Designing adhesively bonded joints for wind turbines, C Nagel, A Sontag and M Brede in Adhesives in Marine Engineering, Jan R Weitzenbock, Woodhead Publishing, 2012, pp. 46 – 71
21. Huntsman Advanced Materials – Selector guide for the wind industry.
22. Plexus – Wind energy adhesive selector guide.
23. Sika – Wind turbine technologies imagine new solutions.
24. Pioneering product for wind turbine production and repair, www.worldwindtechnologies.com
25. Advanced fiber reinforced composites for marine renewable energy devices , P Harper, S Hallett, A Fleming, M Dawson , in Marine Applications of Advanced Fiber reinforced Composites , J. Graham Jones & J. Summerscales (Eds), Elsevier, 2016.
26. DNVGL- ST -0164, Tidal Turbines, DNVGL, Oct 2015.
27. The designer’s dilemma: how to deal with the uncertainty about the long term performance of adhesively bonded joints, J R Weitzenbock and D McGeorge, Proc. Instn. Mech. Engrs., Vol 218 Part M, J. Engineering for the Maritime Environment, Special Issue paper, pp. 273 – 276.
28. Composite adhesive joints under cyclic loading, WC de Goeij, M J L Van Tooren, and A Beukers, Materials and Design, 1999, 20, pp. 213 -221.
29. Fatigue fracture of fully saturated bonded joints, K M Liechti, G A Arzoumanidis and Soo-Jae Park, The Journal of Adhesion, 2002, 78, pp. 383 -411.
30. Local Stress Analysis of the Fatigue behavior of Adhesively bonded Thick Composite Laminates, A Bernasconi, S Beretta , F Moroni and A Pirondi, The Journal of Adhesion , 2010, 86, pp. 480 – 500
31. Fatigue behavior of glass fiber reinforced composites for ocean energy conversion systems, A Boisseau, P Davies and F Thiebaud, Appl. Compos. Material, 2103, 20, pp. 145 -155.
32. Environmental effects on the fatigue behavior of adhesively-bonded pultruded structural joints, Ye Zhang , A P Vassilopoulos,T Keller, Composites Science and Technology, 2009 , 69, pp. 1022 - 1028.
33. DURACOMP, www2.warwick.ac.uk/fac/sci/eng/duracomp/
34. Private Communications, www.engineeredcomposites.co.uk, June 2016
35. Private Communications, www.exelcomposites.com, June 2016

5.C TENSILE STRUCTURES

5.C.1 TECHNOLOGY – STATE OF THE ART

Several companies use large buoyant systems in the wave energy recovery mechanism and find difficulty in attaching the large required buoyant tanks to the wave device, especially where lightweight materials e.g. polymers/composites require to carry high point loads.

One of the outcomes of a new-ideas session was to use the principle of suitably modified “cargo net” to attach such buoyancy units thereby distributing loading and bringing the point loads back through fibre “warps”.

The technology to achieve this is currently achieved in the fishing industry and also in hot air and weather balloons and lift bags and would require little modification to be used to restrain substantially sized buoyancy units.

The principal benefit of the technology is that it spreads loads in the system getting away from concentrated load paths which are difficult to achieve in composites and uses standard fibre ropes to carry load. The fatigue effect of load cycling in different fibre ropes (such as Dyneema, polyester and aramids) is well understood by rope manufacturers.

The arrangement below can be modified to accept any particular shape which may be defined by the WEC device requirement and different shape and sized nets can be manufactured.

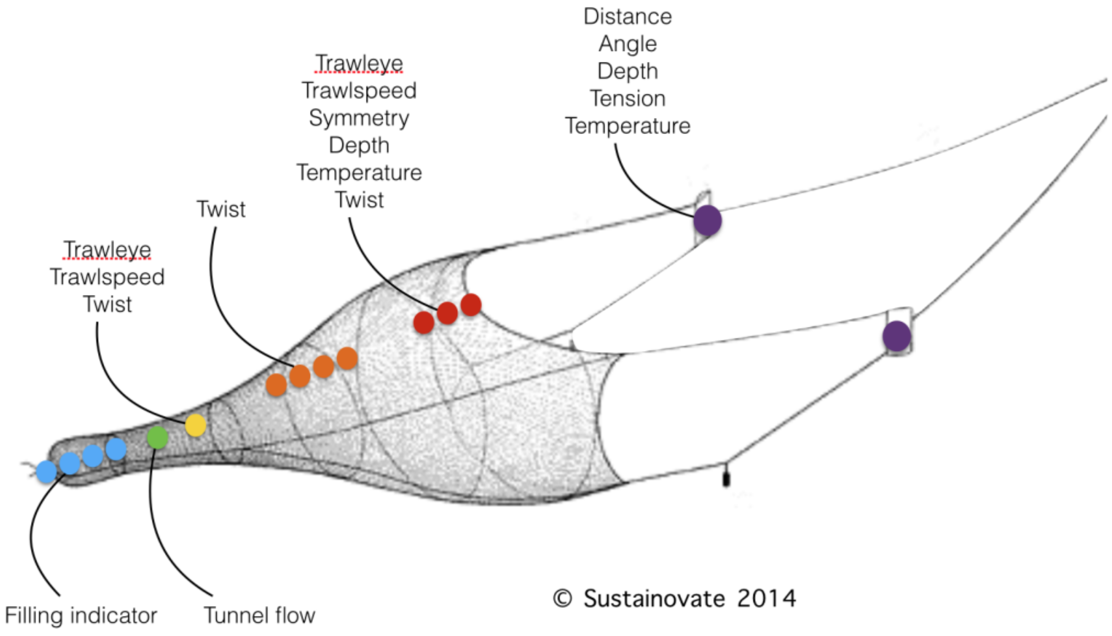


Figure 5.7. Typical Fishing Net Arrangement [from Ref 2]

Other potential sources of buoyancy could include inflatable structures such as lift bags but these would operate in a different manner and are not considered here.

In addition to the net type approach other areas where fibre materials have been used is in the application of Ultra High Molecular Weight Polyethylene (UHMWPE) to provide a distributed load to a large structure so that it can be lifted without providing specific lifting points.

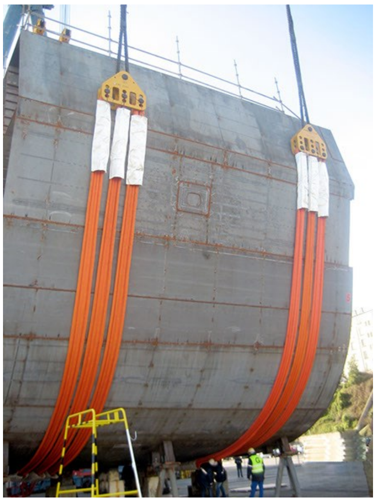


Figure 5.8. Extreema Slings used to distribute loading [from Ref 6]

The principle would be the same for the use of this material perhaps in conjunction with mesh fabrics to use for captivating large buoyancy units rather than trying to build in “hardened” attachment points which would be an obvious fatigue hot spot and is difficult to achieve in designs which may rely on buoyancy from polymer and plastics.

5.C.2 TECHNOLOGY TRANSFER

The technology is currently available in particularly the fishing industry where nets provide the capability of carrying distributed loads up to a warp maximum breaking load of around 144T this, assuming two warps, would allow support of 90T of buoyancy with a FOS of 3. Certainly this would be at the high end of the capacity range [3]. Elsewhere companies are designing and using new materials to spread the load in lifting large and oddly shaped loads [5].

The main integrity issues would be stability of the buoyancy under extreme wave load, installation and long term wear and fatigue however these are issues with existing systems. Certainly fibre rope technology and fatigue issues in fibre ropes are well understood [3] as result of their use in mooring of deepwater FPSO and production platforms in GOM and elsewhere.

Based on a conversation with SICOR, who manufacture fishing nets the principle is feasible, however, factors such as whether the net would be knotted or woven and what rope types (twisted or braided) would be best for long term wear would need to be decided case-by-case. The design procedure is heavily based on operational experience of the behaviour and long term performance of different combinations of the above. The net would be closer to a cargo net than a fishing net and the rope system would need to encompass a “stretcher” section to allow for some elasticity for the extreme loadings expected during storms.

The factors of safety quoted for example in the Extreema slings [6] are much higher than this and the capacity of the slings appears to be far in excess of anything that would be required for the current buoyancy units being proposed in WEC devices.

5.C.3 MATURITY AND RISK

The maturity of the technology is at a minimum of TRL 6 as it is already being used in the fishing industry and the oil and shipping industries. Its application is considered in a slightly different manner however the loadings should not cause any new issues or risks in particular abrasion or behaviour in extreme seas.

5.C.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

The main cost driver with the "cargo net" application is that there is no steel backbone required to allow for the concentrated load connection of tethers and cables. The net effectively distributes the load over the buoyancy. The cost saving is potentially in reducing this requirement and could reduce costs in the range of 10-30% when applied to current arrangements.

5.C.5 RECOMMENDATIONS

To progress the use of this further it is considered that the best approach would be to work with an existing net manufacturer such as SICOR (Aberdeen) and a fabric sling manufacturer like Wilkie to develop typical designs incorporating the most promising materials and fabrics. The proposed design arrangement would then demonstrate how the buoyancy loads can be more easily resisted by the use of these encapsulating systems and what type of devices would most benefit most from this type of application. The project would initially identify the feasibility of the use, then a design for a system specific potential application and then identify the resulting improvements and cost of the system.

5.C.6 REFERENCES

1. Sicor International http://www.sicor-int.com/fishing-marine, trawl net manufacturer, conversation with Gary Mitchell
2. http://sustainovate.com/fisheries/smart-gear/
3. Bridon Fishing and Marine – Trawl Warps - http://www.bridon.com/uk/fishing-and-marine-ropes/trawl-warps/trawl-warp-ropes/dyform-starfish-iwrc/
4. Steve Banfield, "Comparison of Fatigue Data For Polyester And Wire Ropes Relevant To Deepwater Moorings", Tension Technology International, accessed at http://www.tensiontech.com/papers/papers/fatigue_data_comp/comparison_fatigue_data_polyester_wire_ropes.pdf
5. Wilkie Offshore, http://www.wilkieoffshore.co.uk/index.html
6. Lift-Tex Industrie BV, http://www.lift-tex.nl/

5.D CONCRETE STRUCTURES

5.D.1 TECHNOLOGY – STATE OF THE ART

Reinforced concrete is widely used in the construction industry. It is a mature technology used in bridges, tunnels, buildings, marine structures, and offshore structures, and consequently there is a wealth of experience and guidance upon design, durability, and construction methods. However, there is also substantial ongoing research and development in numerous areas, such as high performance concrete, cement-replacement concretes, and replacements for steel reinforcement.

Traditional reinforced concrete technology

Traditional reinforced concrete combines concrete with steel reinforcement. Simplistically, the concrete provides compressive strength, and the reinforcing steel carries tension and (by building it into a reinforcement cage) allows the reinforced concrete to carry bending, shear and torsion (Figure 5.9). The interaction between the concrete and steel, however, is complex: surface texture on the reinforcement enables bond load-transfer between the steel and concrete; the concrete restrains the reinforcing steel to prevent buckling; and the steel confines the concrete to increase its compressive strength and ductility. The internal load carrying mechanisms within a concrete element, whilst complex, are well covered in a variety of design codes, such as Eurocode 2 [1].

Whilst superficially reinforced concrete is often perceived to be a fairly low-tech construction method, it is important to emphasize that structural applications of reinforced concrete are often highly optimized and critically reliant upon correct execution. They rely upon several components, including mix design, detailing (such as bar spacing, bar terminations and cover), and quality control. These are especially important in marine applications; there are numerous examples of reinforced concrete structures that fail due to poorly detailing or construction (e.g. Figure 5.10).

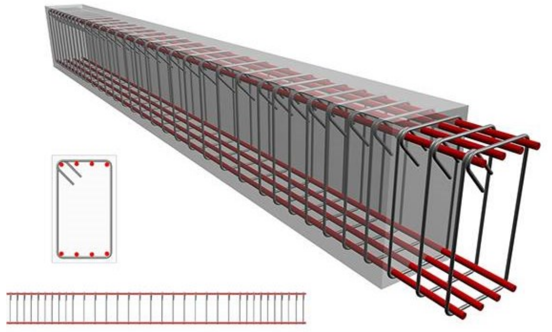


Figure 5.9. Typical reinforced concrete construction (www.buildinghow.com)

Figure 5.10. Example marine reinforced concrete structure suffering from corrosion (www.goldseal.co.nz/marine2)

Durability of reinforced concrete

The concrete also provides an alkaline environment that provides corrosion protection to the reinforcement. The durability of reinforced concrete members mostly depends upon preventing corrosion of the reinforcing steel, which in turn depends upon preventing chloride and carbonation ingress to the reinforcement. Durability consequently critically depends upon the thickness of cover concrete, the permeability of the concrete (which depends upon the mix design), and upon crack widths. Tensile cracks are inherent in reinforced concrete members due to a combination of applied load, concrete shrinkage, and potential freeze-thaw action. If properly designed they are barely visible, and well-established design methods limit their width to provide corrosion protection [2]. Civil engineering projects typically consider design lives of 120 years, and concrete mixes, detailing, and design methods are well established for durable reinforced concrete structures in severe environments including maritime applications [3, 4].

The fatigue behaviour of concrete elements and individual details is covered by S-N curves, such as in Eurocode 2 [1] or as discussed in [5].

High performance concretes

Concrete technology development since the 1970s has enabled the continual development of high-performance concretes (HPC) and high-strength concretes (HSC). Whilst these terms do not have clear definitions, HPCs generally have improved durability and abrasion resistance; HSCs have improved strength, shrinkage and creep [6]. Whilst Eurocode 2 [1] terms concretes with compressive strengths above 50MPa as ‘high-strength’, the definition of what is ‘high-strength’ is rapidly changing; 80MPa or 100MPa are not uncommon in construction projects. Ductal (produced by Lafarge) is an ultra-high performance concrete with compressive strength upwards of 200MPa. The strength and durability of HSC and HPC is a result of concrete mix design and additives to ensure dispersion of the very fine cement particles through the concrete, resulting in reduced porosity [6].

Lightweight and foamed concretes are also available, and the industry is moving towards cement-replacement products that have a lower carbon footprint (but which can have implications for durability).

Prestressed concrete

Prestressed concrete uses high-strength steel tendons (typically 1400MPa) that are tensioned against the concrete. This places the concrete permanently in compression, and results in sections that can carry higher load (for the same section dimensions), and which can be more durable (due to the prevention of crack formation).

Pre-tensioned concrete involves first tensioning the steel tendons, then casting the concrete around the stressed tendons, and transferring the tendon stress to the concrete once it has cured. This usually takes place in precast concrete yards.

Post-tensioned concrete involves casting ducts within the concrete, and the later inserting steel tendons that are stressed and anchored, usually using wedge-action anchors (Figure 5.11). The post-tensioning can be left unbonded, or the ducts filled with a cementious or epoxy grout to give bond. Poor implementation can result in voids in the grout and corrosion of the tendons; however, considerable experience has been gained following failures and inspections of several bridges, resulting in robust methods to ensure durable construction [7]. Post-tensioned concrete is widely used in buildings to enable thinner floor slabs to be constructed.

Figure 5.11. Typical anchorage, tendons, and duct for post-tensioned construction (en.wikipedia.org/wiki/Prestressed_concrete)

Figure 5.12. Segmental, precast, post-tensioned bridge construction (www.bethlehemconstruction.com/sw/concrete/segbridge/)

Connections

Concrete elements can be connected together by leaving exposed reinforcing bars that are cast into fresh concrete. Where steelwork needs to be connected to concrete, or where precast concrete elements are connected together, threaded studs can be cast into the concrete, or tubes cast into the concrete into which bolts and ties are later inserted. Resin anchored fasteners can be drilled into concrete after casting, but care is necessary to avoid damage to the concrete element and to ensure durability.

Very large concrete elements can be joined. For example, segmentally-constructed bridges (Figure 5.12) can use a combination of post-tensioning (through holes in the section wall), mechanical interlock (such as a sawtooth profile on the mating surface), match casting, and/or adhesive bonding.

Offshore structures

Offshore concrete technology is of obvious interest to wave energy devices. The use of concrete in North Sea platforms (Figure 5.13) was enabled first by the development of conventional marine structures, but it was realised in the 1970s that prestressed and high performance concretes would need to be combined to create these substantial concrete structures [6]. The design of offshore concrete structures is covered by DNV [8] and their durability addressed in [9].

Concrete reinforcements

An alternative approach to ensuring the durability of concrete structures is to replace the carbon steel reinforcement with corrosion resistant materials, including stainless steel reinforcement, and fibre-reinforce polymer (FRP) reinforcement. FRP reinforcement includes glass, basalt, aramid, and carbon reinforcement (Figure 5.14); and expect for the latter, these benefit from electro-magnetic transparency as well as corrosion resistance (which can be beneficial near electrical machines). The lack of ductility in FRP reinforcement means that it is most efficient application is when it is prestressed [10]. The corrosion resistance of FRP reinforcement can result in reduced concrete cover requirements in ordinary reinforced concrete and hence thinner sections. There have been successful applications in marine environments, as well as concrete bridge decks that are prone to de-icing salt

Figure 5.13 – Prestressed concrete offshore platform substructures (www.constructionenquirer.com/2015/02/03/shell-plans-to-dismantle-brent-oil-platforms/)

attack (particularly in Canada; Figure 5.15). Design guidance for FRP reinforced concrete includes [11] and [12]. FRP reinforcement can be preformed into different shapes, and supplied as grids and fabrics, not only straight bars.

Figure 5.14 – FRP reinforcement with sand coat for bond. (http://www.b-composites.net/245.html)

Figure 5.15 – FRP reinforcement in a road bridge deck (Hughes Brothers).

As well as reinforcing bars, there are a variety of steel, polymer, and FRP fibres that can be included in the concrete mix [13, 14]. These 'macro-fibres' are typically 40mm. Whilst they cannot replace the need for bar reinforcement, they can provide enhanced tensile strength, impact resistance, durability, and potentially fatigue resistance to the concrete.

5.D.2 TECHNOLOGY TRANSFER

Concrete technology (including both ordinary reinforced and prestressed concrete) is very well established in the construction industry, supported by a large supply network (such as concrete suppliers, formwork systems, post-tensioning systems, specialist pre-cast yards, etc.). The offshore industry has developed pre-stressed high performance concrete for massive durable structures since the 1970s, and these are subject to extreme wave loadings and include floating pontoons and barges.

There have been several suppliers of FRP reinforcement in the marketplace since the 90s. FRP reinforcement is well proven and used in specific markets, particularly in Canada where FRP reinforcement is used in steel-free bridge decks (to avoid de-icing salt damage to bridges). Other applications include marine works, soft-eyes in concrete tunnels, and MRI and radar installations (where electromagnetic transparency is required).

Applications in the wave energy sector can be broadly divided into (a) massive static structures, such as wave columns and (b) buoyant dynamic devices. Current concrete technology from the construction and offshore sectors can be directly transferred to massive static structures, where weight is required. Buoyant dynamic wave energy devices have a different set of design requirements.

- The mechanisms required to generate power mean that the wave energy converters are subject to a very wide range of axial, shear, bending and torsional loads, and must do so in a broad range of positions. The high ratio of variable applied loads to permanent loads are likely to place different demands on the concrete structure to typical construction applications. It will be necessary to examine how structural forms, connection details, and fatigue demands typically found in construction applications can be transferred to wave energy devices, and to check whether they are in the same design space, to allow existing design codes to be applied.
- The allowable wall thickness of the sections depends upon the need for buoyancy, and as the devices are fairly small (compared to e.g. offshore platforms), will need relatively thin wall thicknesses. To provide adequate durability, impact resistance, and to carry bending (requiring two layers of reinforcement), it will likely be necessary to use high-performance concrete, FRP or stainless steel reinforcement, and possibly post-tensioning, and to test their performance.

5.D.3 MATURITY AND RISK

TRL level – 6. Concrete (including ordinary reinforced and prestressed) technology is mature within the construction and offshore industries, but have yet to make impact in the wave energy sector. Developments such as FRP reinforcement and fibre reinforcement are less mature, but are applied in construction applications. Some of these products (such as basalt FRP reinforcement) are progressing through the product development cycle are in some cases at TRL 5 rather than 6.

The principal risks in transferring concrete technology to the wave energy sector are:

1. Ensuring good practice to avoid re-learning the important of (for example) detailing, mix design, quality control, and construction methods.
2. To create concrete structures that can transfer the required loads, and also provide the required durability and fatigue despite limitations on wall section thickness necessary for buoyancy.
3. To create practical connections for wave energy devices to transfer large concentrated loads, and ensure water tightness and durability.
4. New technologies (such as FRP reinforcement) are likely to be necessary to meet (2) and (3) above, but relevant durability and fatigue data that is relevant to the wave energy sector is not available for these materials.

5.D.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

Pelamis Wave Power (PWP) commissioned Arup to conduct a series of studies into the design of their principal structural components. This includes a manufacturing report with a cost breakdown [15] which is a reasonably accurate representation of likely cost outcomes for reinforced concrete WEC structures. They based their costings on the following prices for raw material supply:

Steel Rebar (supply only) - £580 per tonne – 2012 price.

Concrete (supply only) - £105 per m^3

In this study, the supply of raw materials accounted for 22% of the overall construction cost, based on the manufacture of tubes for a single machine. Aspects such as mould fabrication, fixing of reinforcement and concrete placement, logistics costs (cranes) of assembling and loading out, and indirect construction costs are the other major contributors to the overall cost. Most of these costs are heavily influenced by the specifics of a particular design and the quantity to be produced.

It is a reasonable assumption from the figures presented in the referenced report that, when manufactured in volume, a reinforced concrete structure could have a lower CAPEX than a fabricated steel equivalent, perhaps of the order of 20%.

Smaller modular units that can be produced in large volumes should demonstrate substantially greater savings because the volume advantages will be seen more rapidly and craneage costs will reduce along a stepped function.

5.D.5 RECOMMENDATIONS

1. Design studies to examine how concrete technology can be applied to a selection of typical wave energy devices (both massive static structures and dynamic buoyant structures). A range of feasibility options should be examined to evaluate the design space for different concrete technologies, where they can be best applied, and how the compare. The study will examine solutions such as ordinary reinforced concrete, post-tensioned concrete, different reinforcement materials, different concrete mix technology, etc. Different connection details will also be examined as part of this study. This process will establish appropriate concrete technology for typical wave energy device applications, and will also identify where additional work is required to address potential gaps in design guidance.
2. The design studies should lead to projects to design, construct, test, and demonstrate typical concrete wave devices.
3. FRP-reinforced concrete is likely to be beneficial for wave energy devices (due to the combination of corrosion-resistance and reduced concrete cover requirements), but its use will require testing to check the mechanical, durability and cyclic performance of FRP-reinforced structures for wave energy devices.

5.D.6 REFERENCES

1. BSI, “Eurocode 2: Design of concrete structures.” BS EN 19912-1-1:2004+A1:2014. BSI, London, (2014)
2. Beeby A.W., “Concrete in the oceans: cracking and corrosion”, Cement and Concrete Association, (1978).
3. Gjørv O.E., “Durability design of concrete structures in severe environments”, 2nd ed., CRC Press (2014).
4. Matthew S., “Design of durable concrete structures”, FB 70, IHS BRE Press (2014).
5. ACI, “Considerations for design of concrete structures subjected to fatigue loading” 215R-92 (re-approved 1997), American Concrete Institute, Farmington Mills, US (1997).
6. Mindness S., “Developments in the formulation and reinforcement of concrete”, CRC Press (2008).
7. Concrete Society, “Durable post-tensioned concrete structures”, TR72 (2010).
8. DNV, “Offshore concrete structures”, Offshore standard DNV-OS-C502 (2012)
9. fib, “Concrete structures for oil and gas fields in hostile marine environments”, Bulletin 50, Fédération Internationale du Béton, Lausanne, Switzerland (2009).

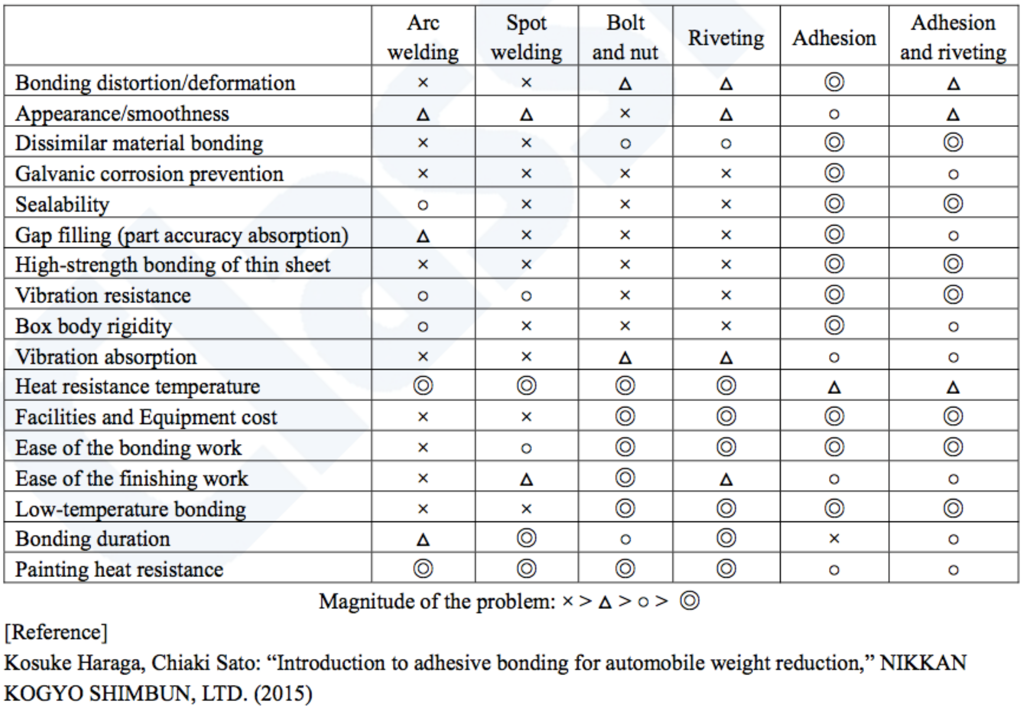
10. Burgoyne C.J., "Rational use of advanced composites in concrete", Proc Inst Civil Engineers, Structures and Buildings, 146, 253-262 (2001).
11. fib, "FRP reinforcement in RC structures", Bulletin 40, Fédération Internationale du Béton, Lausanne, Switzerland (2007).
12. ACI, "Guide for the design and construction of structural concrete reinforced with fiber-reinforced polymer bars", ACI 440.1R-15, American Concrete Institute, Farmington Mills, US (2015).
13. Concrete Society, "Guidance on the use of macro-synthetic fibre reinforced concrete", TR65 (2007).
14. Concrete Society, "Guidance for the design of steel-fibre-reinforced concrete", TR63 (2007).
15. Arup, Pelamis Wave Power Concrete Tube Study Manufacturing Report. 219879-00, October (2012)

5.E ADHESIVE BONDING OF STEELS

5.E.1 TECHNOLOGY – STATE OF THE ART

Mechanical joining is the major method used in the assembly of large marine steel structures with welding predominating. There is increasing interest in the use of structural adhesives, given their successful application in areas like bridge repair, aircraft fabrication, automotive, transportation, rail and heavy equipment assembly.

In the recent Class NK Guidelines for Use of Structural Adhesives [1] problems associated with various attachment techniques are compared. Adhesive bonding offers many benefits.



	Arc welding	Spot welding	Bolt and nut	Riveting	Adhesion	Adhesion and riveting
Bonding distortion/deformation	×	×	△	△	◎	△
Appearance/smoothness	△	△	×	△	○	△
Dissimilar material bonding	×	×	○	○	◎	◎
Galvanic corrosion prevention	×	×	×	×	◎	○
Sealability	○	×	×	×	◎	◎
Gap filling (part accuracy absorption)	△	×	×	×	◎	○
High-strength bonding of thin sheet	×	×	×	×	◎	◎
Vibration resistance	○	○	×	×	◎	◎
Box body rigidity	○	×	×	×	◎	○
Vibration absorption	×	×	△	△	○	○
Heat resistance temperature	◎	◎	◎	◎	△	△
Facilities and Equipment cost	×	×	◎	◎	◎	◎
Ease of the bonding work	×	○	◎	◎	◎	◎
Ease of the finishing work	×	△	◎	△	○	○
Low-temperature bonding	×	×	◎	◎	◎	◎
Bonding duration	△	◎	○	◎	×	○
Painting heat resistance	◎	◎	◎	◎	○	○

Magnitude of the problem: × > △ > ○ > ◎

[Reference]

Kosuke Haraga, Chiaki Sato: "Introduction to adhesive bonding for automobile weight reduction," NIKKAN KOGYO SHIMBUN, LTD. (2015)

Figure 5.16. Problems Associated with Various Joining Techniques are Compared [from Ref 1]

It is clear from the table that adhesive bonding could offer considerable benefits in the fabrication of WEC devices:

- greater design freedom will arise for use of new material combinations
- reduction in access and dimensional restraints imposed by welding equipment
- reduction in cost of fabrication
- elimination of crevice corrosion
- improvements in fatigue resistance because of the better stress distribution in the joints

Despite these advantages, there is no documented case of adhesive use for steel fabrication or assembly in WEC devices.

Shipbuilding

European shipbuilding has been actively seeking new methods to reduce cost and increase competitiveness. During the design, fabrication and modification of ships and offshore structures there are innumerable joining tasks to assemble the structures and install equipment. Welding, bolting and riveting predominate but interest in adhesive bonding is increasing particularly as a new joining method for lightweight assembly [2]. There have been several cooperative research initiatives in the European Union in the last 15 years focused on the use of adhesive bonding in shipbuilding. The most relevant to the subject of this report is BONDSHIP. The Bondship project was a major European initiative to introduce adhesive bonding into shipbuilding for joining lightweight materials. The project ran from 2000 to 2003 and involved a consortium of research organisations, designers, material suppliers, shipbuilders, ship-owners and operators. The major output was a set of guidelines [3, 4] which sum up all the steps necessary to design, build, inspect and repair all types of bonded joints in ships. In the summary of the reports they indicate one of the major issues with adhesive bonding.

- ***Long-term performance****: This document is based on the assumption that the long-term performance of a bonded joint cannot be reliably predicted from the results of accelerated ageing tests. Therefore, requirements to the resistance of the joint are combined with requirements that limit the consequences of failure of the joint and that it must be possible to repair the joint using an approved repair method.*

In addition to the published guidelines, a number of papers were published detailing the actual experience with various parts of the project [5,6,7]. Despite this extensive program, adoption of adhesive bonding for steel structures in shipbuilding has been minimal. A number of other guideline documents have been issued which provide baseline information on the methodologies to be used in assessing adhesives for the marine environment.

Class NK Guidelines for the use of structural adhesives [8]

These guidelines were prepared as a follow up to a previous set of guidelines which allowed structural adhesives to be used as a replacement for secondary bonding with solvent in the construction of fiberglass reinforced plastic ships extending their use to steel or aluminum ships. The applications covered mostly the attachment of fittings and fixtures within the structure and did not extend to major load carrying joints in contact with seawater. The guidelines describe appropriate tests and requirements and recommend safety factors.

DNV Rules

DNV has prepared a set of rules for the classification of High Speed, Light Craft and Naval Surface craft [9] that addresses adhesive bonding. In the section on bonded joints [Part 3, Chpt 4, Section 8] it is stated

> *"The use of bonded joints is subject to the approval of the Society. Bonded joints are not accepted for transfer of the global loads on the hull or on joints the failure of which would compromise the watertight integrity of the vessel."*

In 2012 DNV issued a standard for certification for Type Approval of adhesives [10] covering the pre-selection of adhesives suitable for use in the marine environment. They caution that design of joints shall be evaluated during the approval of classed objects and this evaluation is not included in the Type Approval.

Summary

Despite the many advantages of adhesive bonding, the certification authorities are taking a very cautious approach in the case of ships. There is no history of the use of adhesives on metal joints in direct contact with seawater. All of the applications discussed are above the waterline and mostly focus on the bonding of aluminium and composites. A paper presented by Winkle et al [11] describes the potential for the use of toughened structural adhesives to replace conventional welding in the stiffener/plate connections of thin plated grillage structures. Advantages outlined included elimination of thermal distortion and residual stresses with little cost or weight penalty. The various standards and guidelines provide a complete information package on the design of joints, adhesive selection, the appropriate test programs, the safety factors and the assembly systems. This represents a considerable body of information that can be applied to the fabrication of WEC devices using bonding.

Offshore Applications

In 1997, the HSE published a report by Cowling on adhesive bonding for offshore structures [12]. Among the advantages listed were avoidance of hot working, avoidance of distortions arising from welding, a reduction in corrosion between components, improvements in design leading to weight / cost savings and facilitating alternative types of construction e.g. sandwich structures. Among the limitations listed were uncertainty over long term durability, impact resistance, fire resistance and absence of procedures for quality assurance including inspection, repair and maintenance. Again the applications identified are in the area of attachment of fittings and fixtures.

Research and Technology

There are a number of general publications which describe bonding in a marine environment and review the state of the art in research. We will not summarise them here. A more general review of adhesive bonding in the marine environment is provided in [13], while a comprehensive review of experience, evaluation and testing methods is provided in [14]. Initial strength of structural adhesives is high (typical strengths 20 -40 MPa) and joint strength can be predicted using simulation and modeling programs but subsequent time dependent deterioration can be observed, particularly in a humid environment. Kinloch [15] found that the locus of failure of well-prepared joints was initially cohesive in the adhesive layer but switched to apparent failure between the adhesive and the substrate after environmental ageing. There have been some publications related to durability of steel to steel bonds in a marine environment. Knox et al [16] studied the durability of thick-adherend lap shear joints bonded with a toughened heat curing epoxy adhesive in a preloaded and unloaded state for 12 weeks at 30˚C and 100% RH. They found that the presence of a fillet retarded the degradation of the bonds but the preload was detrimental to the durability performance. Bowditch [17] discusses the durability of adhesive joints in the presence of water and presents some data for epoxy bonded mild steel/mild steel butt joints aged in seawater. In the unstressed state joints showed no loss in strength in 8 years immersion while stressed joints failed in 48 hrs (40 % loading), in 3 years (20% loading). Joints subjected to 10% loading did not fail in 42 months and were found to have increased slightly in strength vs the unstressed controls. In a recent paper [18], Davies et al discuss the prediction of the long term strength of steel epoxy joints in seawater. Aging was carried out in water/salt and seawater at three temperatures. The focus is on the development of a predictive model but concludes that further model development is needed to include the complex mechanisms observed on aged specimen.

It is clear that prediction of durability of structural adhesive bonds in water still presents some challenges and consequently risks. A recent review by Pethrick [19] is recommended for a comprehensive discussion on techniques for analysis of aged joints.

5.E.2 TECHNOLOGY TRANSFER

This section will look at the use of structural adhesives for metal bonding in the transportation industry. We have excluded information on aircraft bonding, despite the fact that adhesives are extensively used, because the substrates bonded are Al and Titanium, the substrate preparation and curing processes are specialized and expensive, and the products have no relevance to the assembly of steel structures. We have also excluded building construction where flexible adhesives are used in glazing and façade attachment applications, generally in conjunction with mechanical fastening. These products are not suitable for structural bonding of metals.

Automotive

A major technology driver in automotive manufacture is lightweighting. Companies are looking to replace steel with lighter materials, e.g. high strength steels, aluminium, magnesium, glass and carbon fiber reinforced composites [20]. Initial approaches will utilize thinner steel, high strength steel and aluminium. These materials require the automotive manufacture to move away from traditional joining to adhesive bonding or combination approaches where adhesive is coupled with conventional fastening, e.g. spot welding or riveting. Automotive bodies utilize galvanised steel and bond with crash resistant adhesives in conjunction with mechanical fastening. This results in an increase in the durability of the joints vs mechanical fastening alone. The data shown in the graph below indicates clearly the benefits to be achieved with hybrid bonding approaches [21].

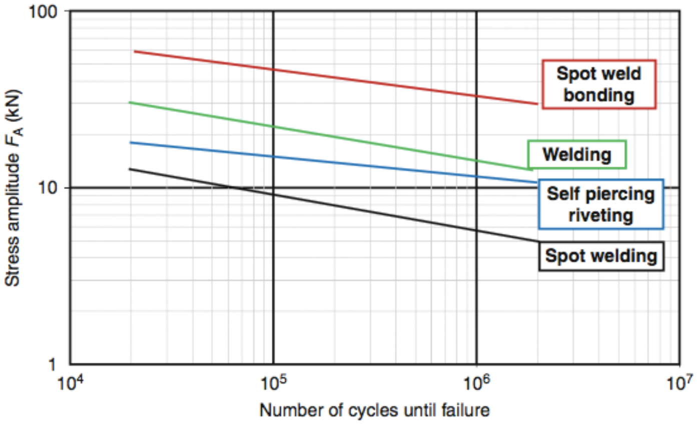


Figure 5.17. Fatigue Strength with Different Joining Methods [from Ref 21]

The adhesive used in the body fabrication are all designed for use with corrosion protected surfaces and are overcoated with paint. In addition, they need the passage through the paint bake oven to cure to full properties. Salt spray testing is routinely used in adhesive qualification testing for automotive applications but there is never a requirement for complete immersion testing. The adoption of a modularized approach to WEC device fabrication would facilitate the adoption of many of the automotive processes, but for larger parts passage through a cure oven is not possible and the adhesives used in automotive applications could only be utilized on small parts.

Transportation and rail

For the convenience of this summary, transportation (trucks, buses, vans) and rail (high speed trains, commuter trains, freight wagons) are grouped. These constructions utilize heavy steel chassis for load bearing and build up the body from lightweight framework and panels. Structural adhesives are being used to assemble frames, panels, booms and cabs made of metal, plastic and composites. Add-on metal parts are typically made from lightweight galvanized steel or aluminium and structural adhesives are used in combination with mechanical fastening. Mechanical fastening is used to fix the parts during assembly while the functional strength is provided by the cure of the structural adhesive. In these cases the fasteners are used sparingly and many times do not require through holes. These adhesives cure at room temperature. Cost savings are obtained by reduction in the overall number of mechanical fixings and associated labour savings. Structural adhesives can fill gaps, seal joints, distribute stresses evenly across the joint area and allow joining of dissimilar materials without the risk of galvanic corrosion. Toughened structural adhesives are available which provide good cold impact, long term fatigue resistance and durability [22]. Similar applications are now routine in bus assembly [23] and in rail car fabrication [24].

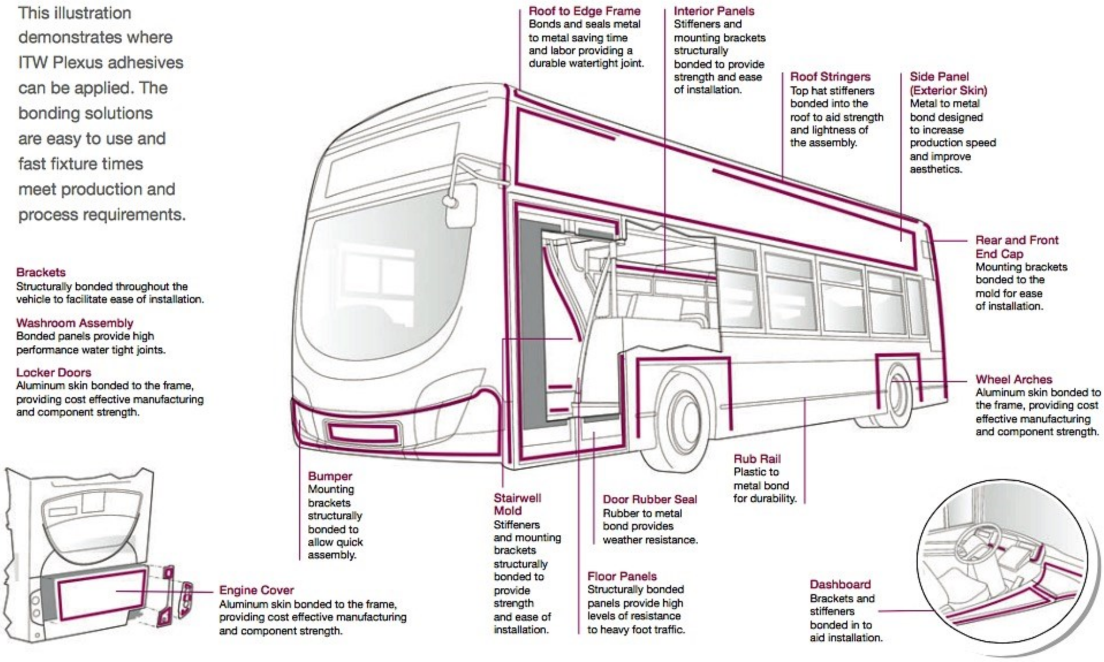


Figure 5.18. Adhesive Bonding in Buses [from Ref 23]

Adhesive products for transportation applications

Acrylic and epoxy adhesives are utilized for structural bonding applications in all these areas. As part of the study, all the major suppliers were contacted and asked for their recommendations as to the ideal products in their range to be considered for structural bonding in WEC devices. Several suppliers provided recommendations and in the case of others I have selected likely products based on the published literature. Table 5.2 below provides a listing of products together with features and comments. A more comprehensive description of the products in available in the individual technical data sheets which are available on the manufacturers websites. The purpose of the table is not to provide a comprehensive list of all available products, but rather to confirm that suitable products are commercially available and should be considered to have a good probability of meeting the mechanical joint strength requirements if tested for WEC devices. Though some data is available for salt spray resistance, the duration of the tests is short and no information for seawater immersion is available with the exception of Araldite 2015. Data for bonds immersed for up to 1 year is provided in [18].

Manufacturer	Product	Type	Features	Salt spray resistance	Comment
Henkel	Loctite AA H8500	2 part Acrylic	Peel and impact strength	80% retention @1000hr	
	Loctite EA 9460	2 part epoxy	Impact and fatigue resistant	63% retention @1000 hr(35 C)	
Ashland	Pliogrip 5500/5600	2 part Epoxy	Toughened E-coat process capable	NA	Also bonds composites
Huntsman	Araldite 2014-1	2 part Epoxy	Good environmental resistance	NA	Confirmed use with seawater
	Araldite 2015	2 part Epoxy	Impact and fatigue resistant	NA	Fatigue data on Aluminium. Confirmed use with seawater. Ref 18.
	Araldite AW4858/HW4858	2 part epoxy	High strength and peel	NA	Ideal for CFRP
Permabond	ET5428	2 part Epoxy	Toughness and high strength	NA	Ideal for composites
Scott Bader	Crestabond M1-30	2 part acrylic	High impact peel and fatigue resistance	93%retention@500hr	DNV GL Approved for maritime applications.
	Crestabond M1-60	2 part acrylic	Excellent impact and fatigue resistance	64%retention @500hr	DNV GL approved for maritime applications. Fatigue data to 10^6 cycles

Table 5.2. List of adhesives for structural bonding

5.E.3 MATURITY AND RISK

Structural adhesive bonding is now a mainstream technology in general manufacturing. In the marine area, structural adhesive bonding is a mainstream technology for bonding composites, plastic and wood – particularly in applications inside the hull and above the waterline [13,14]. In the case of metal bonding, structural adhesives have not been used in situations where there is direct contact with seawater. There are no design rules available. In the assembly of WEC devices use of structural adhesives is at TRL level 6.

This situation is addressed in a publication by Weitzenbock and McGeorge [25]. The paper discusses the dilemma posed by our inability to predict the long term performance of adhesive joints in the marine environment. In the case of shipbuilding, the authors make the following point:
"There is virtually no documentation of the long term performance of bonded joints in a marine environment. Thus there is no correlation possible between the results of predictive tests and data from the real environment. As a consequence we have a classic chicken and egg situation and designers and fabricators, accustomed to the situation existing with traditional steel fabrication, will not take the risk of utilizing structural adhesives".
The authors recommend adopting the principles of risk-based design, i.e. identify hazards, carry out a risk assessment and adopt suitable risk control measures. For risk control measures they suggest the following:

1) Use best practice in material selection, joint design and production technology.
2) Ensure that the design allows detection of damage before ultimate failure. The structure should be designed with sufficient redundancy and reserve strength so that detectable damage in a joint is tolerable.
3) Develop and demonstrate a repair procedure.

They endorse this new approach because it replaces the requirement to document a lifetime at the beginning and replaces this by combining requirements relating to the resistance of the joint with requirements that limit the failure of the joint.

WEC devices represent a special situation. They are unmanned so there is no risk to life in the event of joint failure. At the same time, there is no possibility for inspections and observation of damage. There are many opportunities for bonding in fabrication and this will become a bigger challenge if other materials are used to replace steel. There are uncertainties in the use of metal bonded adhesive joints in direct contact with seawater and caution should be exercised there, but on the dry side of WEC devices there are considerable advantages to replacing welding and mechanical fixing with adhesive bonding [11, 12]. It is certainly appropriate to utilize adhesive bonding on the dry side of any WEC device and there is adequate information already available in the reports and standards above to guide the designer and many new products available from the transportation industry with the possibility of functioning well on the dry side of WEC devices.

5.E.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

Section 5.E.1 of this report shows a comparison chart for adhesive bonding vs metallic joining processes. Adhesive bonding will require a different joint design and more attention to surface preparation and cleanliness prior to bonding. The requirements for all stages of a large part assembly process have been described as an output of the BONDSHIP project [5]. Additional capital costs will be incurred as a result of the purchase of adhesive dispensing equipment and curing/clamping systems. If heat curing is required, capital costs relating to oven provision or contact heating systems will be incurred. All of these costs will be specific to the type of assembly being bonded but the equipment can then be reused for other projects. Typical structural adhesive prices will vary depending on supplier, volumes, packaging and technology. Generally pricing will follow the pattern 2K PU< 2K Acrylic< 2K epoxy< 1 K epoxy< Crash resistant 1K epoxy and average cost of adhesive would be approx. £8/kg. Some 2 K acrylic adhesives are flammable and this will require a flameproof assembly area. Many of the products have a strong odour and this will necessitate provision of adequate ventilation during application and cure.

A number of comparisons have been published of the relative cost of adhesive bonding and other mechanical and thermal joining processes. These all indicate the cost effectiveness of bonding over welding or rivetting when the total part production process is considered, including preparation and re-finishing.

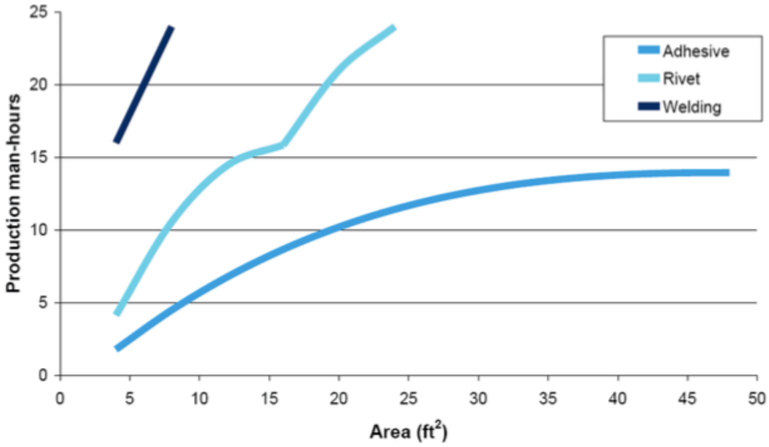
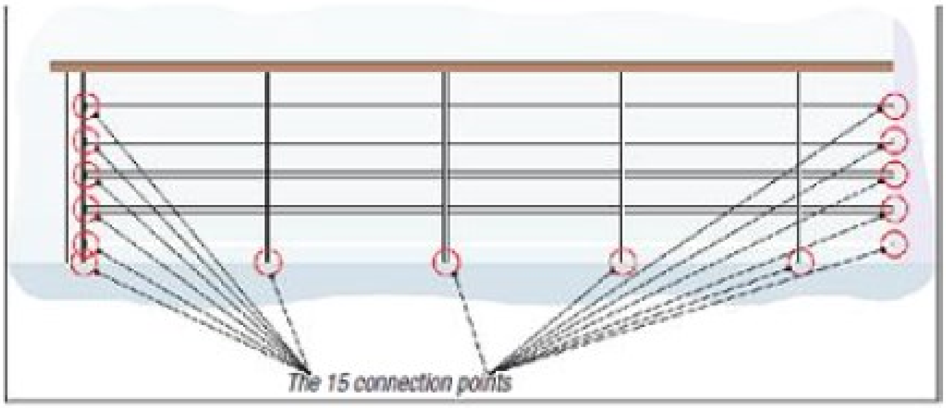
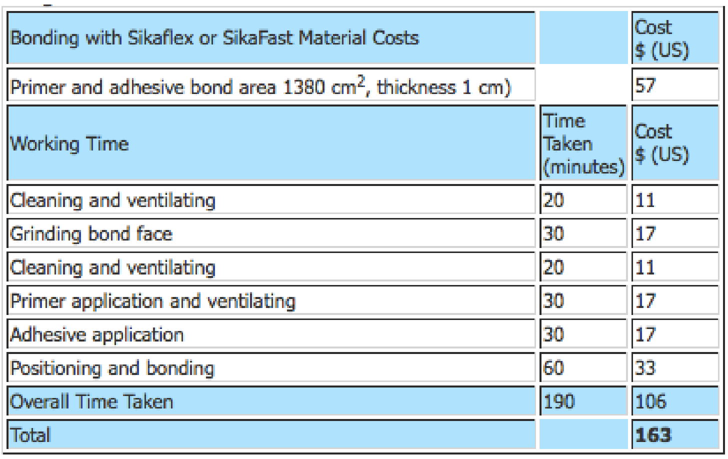


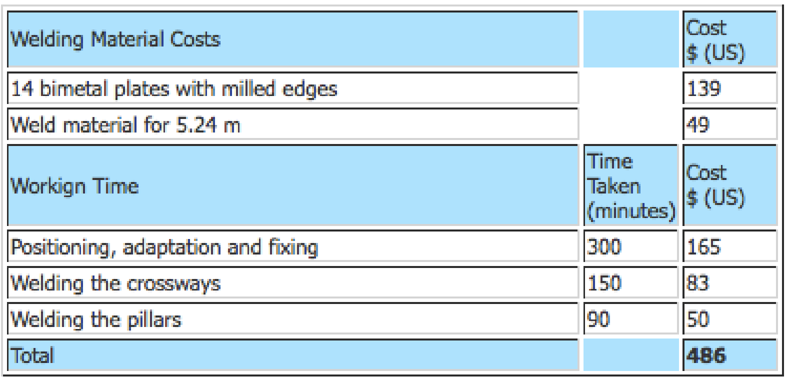
Figure 5.19. Man-hours Vs Assembled Area for Various Fastening Methods [from Ref 27]

A more detailed analysis for the attachment of a tubular aluminium railing section to the steel deck of a ship has been provided by Sika [28].





Bonding with Sikaflex or SikaFast Material Costs		Cost $ (US)
Primer and adhesive bond area 1380 cm^2, thickness 1 cm)		57
Working Time	Time Taken (minutes)	Cost $ (US)
Cleaning and ventilating	20	11
Grinding bond face	30	17
Cleaning and ventilating	20	11
Primer application and ventilating	30	17
Adhesive application	30	17
Positioning and bonding	60	33
Overall Time Taken	190	106
Total		**163**



Welding Material Costs		Cost $ (US)
14 bimetal plates with milled edges		139
Weld material for 5.24 m		49
Workign Time	Time Taken (minutes)	Cost $ (US)
Positioning, adaptation and fixing	300	165
Welding the crossways	150	83
Welding the pillars	90	50
Total		**486**

All amounts are based on a labour cost of $33 per hour

Figure 5.20. Cost Comparison of Attaching a Railing Segment to a Vessel using Adhesive Bonding and Welding [from Ref 28]

It is clear from the information presented that replacement of welding by adhesive bonding can lead to significant savings. If the cost of the bimetallic plates is removed from the analysis above, it is possible to compare the process and material costs for the attachment process. In this case adhesive bonding represents a 50% cost reduction over welding. In data published by Henkel [29] cost comparisons are reported for adhesive bonding and overlap welding. In this data, adhesive bonding represents a 43% cost reduction over welding.

The contribution of welding to the cost of an individual structure is related to the exact design, however in structural steel for maritime use, welding (labour and materials) can represent up to 50%

of the total capital cost. For durability related reasons, bonding should be confined to the dry side of the WEC device, perhaps encompassing half of the total amount of welded joints. If it were possible to change all of these welded joints to adhesive bonding then capital cost savings of up to 10% should be possible on the structural steel of a WEC device.

5.E.5 RECOMMENDATIONS

This landscape study has documented the information available on the use of structural adhesives to bond metals in a variety of industry segments. The literature in this area is vast and only selected examples have been included in this report. WEC devices will operate in a submerged or semi-submerged mode and will be subject to severe fatigue loading. There is very little published information available on the performance of structural adhesives in this environment and whatever studies are available are typically of short duration. As outlined above, there is a possible way forward to address the “chicken and egg“ problem of confirming the performance of structural adhesive for steel bonding on the wet side of WEC devices, however it is necessary to consider the probability of success, the efforts needed to achieve it and the likely timeframe. Having reviewed the information, the following recommendations are made:

Adhesive Bonding of Wet Steels

It is not recommended to carry out any work to support the use of adhesive joints on the wet side of WEC devices. It is the MLS Team’s opinion that it would not be possible to generate sufficient supporting information in a 3 year timescale to qualify adhesives for structural bonding of steel in a submerged/semi-submerged environment.

1. All of the published data show that a deterioration of joint strength of steel occurs in direct contact with water. These tests are of short duration and there is no methodology available to allow prediction of joint durability for long periods (15 to 20 years). There is very little relevant information on fatigue effects in seawater.
2. Bonding of steel is most likely to be carried out at ambient temperature with two part adhesives. This generally limits the glass transition temperature which can be achieved. Adhesives with a low glass transition are more susceptible to moisture diffusion and linked joint deterioration.
3. Substrate preparation and joint cleanliness are very important to ensure durability in a hostile environment. It is difficult to ensure this in the environment in which large structural steel parts are fabricated.
4. Any qualification program undertaken would be specific to the adhesives/substrates/joint configurations chosen. Because all adhesive formulations are unique, it would always be necessary to carry out separate qualification tests for an individual situation.
5. It would be necessary to generate design guidelines for adhesive bonded joints before the technology would be acceptable to designers and fabricators of devices.

Adhesive Bonding of Dry Steels

Adhesive use on the dry side of WEC devices is less problematic. Various guidelines [1,3,4,8,9,10] exist to provide a framework for qualification of products and details of joint design are available in the Bondship documents. Structural adhesive products are available in the transportation industry and are being used in applications similar to those that would apply on the dry side of WEC devices [26]. We would recommend carrying out work to quantify the benefits from the use of adhesives on structural applications on the DRY side of WEC devices, e.g. replacing welded dry side stiffeners with bonded components. There is also a need to study the load resistance, fatigue and impact tolerance of these joints under WEC device conditions.

Given that failure in WEC devices is linked to corrosion fatigue of welded joints, there is information available from automotive assembly to support the superior performance of weld- bonded joints over welded joints in fatigue testing [20]. Use of the weld-bonding technique or other hybrid bonding techniques (rivet-bonding, bolt-bonding) could enhance the corrosion fatigue resistance of steel joints. There is currently no information of this type available [26]. It would be useful to explore the possible use of some of these new constructions in steel/steel joining in the dry side of WEC devices.

5.E.6 REFERENCES

1. Class NK Guidelines for the Use of Structural Adhesives, Annex III pp. 19, (2015).
2. Lightweight construction for advanced shipbuilding- Recent Developments, P Noury, B Hayman, D Mc George and J Weitzenbock, 37th WEGEMT Summer School, ETSIN, Madrid, November 2002.
3. BONDSHIP Guidelines: CODE, DNV Report No. 2004-0134 Revision No 02, (2005).
4. BONDSHIP Guidelines: Recommended Practices, DNV Report No 2004-0193 Revision No 2 , (2005)
5. Lessons learnt from designing and producing adhesively bonded prototyping structures in a shipyard, J Cantrill, A Kapadia and D Pugh, Proc. Instn. Mech. Engrs., Vol 218 Part M, J. Engineering for the Maritime Environment, Special Issue paper, pp. 267- 272.
6. Theory and practice: requirements for adhesive bonding in marine structures , G Wacker, D Brugge, K Fach and W Franzelius, Proc. Instn. Mech. Engrs., Vol 218, Part M, J Engineering for the Maritime Environment, Special Issue paper, pp. 217- 226.
7. Integrity of hybrid steel-to-composite joints for marine application, S W Boyd, J I R Blake, R A Shenoi and A Kapadia, Proc. Instn. Mech. Engrs., Vol 218 Part M, J Engineering for the Maritime Environment, Special Issue paper, pp. 235 – 246.
8. Guidelines for the use of Structural Adhesives, Class NK , 2015
9. DNV Rules for the Classification of High Speed, Light Craft and Naval Surface Craft
10. Adhesives – Standard for Certification No 2.9 Type approval program No.1-501-12, DNV, (2012).
11. What can adhesives offer to shipbuilding, T I Winkel, M J Cowling, S A Hashim and E M Smith, Paper No 6A-1, NSRP Ship Production Symposium, August, 1990.
12. Offshore Technology Report OTO 96030, A review of adhesive bonding for offshore structures, HSE P3384, M J Cowling, 1997.
13. Marine Industry, Peter Davies, in Handbook of Adhesion Technology, L M F da Silva, A Ochsner and R D Adams (Eds), Springer Verlag, 2011, pp. 1237-1262.
14. Adhesives in Marine Engineering, Jan R Weitzenbock, Woodhead Publishing , 2012 Chapter 1, A J Kinloch, in Adhesion 3, KW Allen (Eds), 1979.
15. Durability aspects of adhesively bonded thick adherend lap shear joints, E M Knox and M J Cowling, Int. J. of Adhesion and Adhesives, 20, 2000, pp. 323-331.
16. The durability of adhesive joints in the presence of water, M R Bowditch, Int. J Adhesion and Adhesives, 16, 1996, pp. 73 -79.
17. Prediction of long term strength of adhesively bonded steel/epoxy joints in sea water. M Bordes, P Davies, J-Y Cognard, L Sohier, V Sauvant-Moynot and J Galy, Int J Adhesion and Adhesives, 29, 2009, pp. 595- 608.
18. Design and ageing of adhesives for structural adhesive bonding – A review , R A Pethrick , Proc IMech E Part L. J Materials Design and Applications, 229, 2015, pp. 349 – 379.
19. It's time to reassess materials for automotive lightweighting, Tom Ellringham, in Special Report; Vehicle Lightweighting, Automotive World, February 2016.

20. Automotive Industry , Bernd Burchardt, in Handbook of Adhesion Technology, L M F da Silva, A Ochsner and R D Adams (Eds), Springer Verlag , 2011, pp. 1185 – 1212.
21. Untraditional Use of Adhesives in Structural Metal Bonding, Adhesives and Sealants Industry Magazine, September 2006.
22. Creating bonding solutions for the transportation industry and beyond, ITW Plexus Publication.
23. Rolling stock adhesive selector guide, Huntsman.
24. The designer's dilemma: how to deal with the uncertainty about the long term performance of adhesively bonded joints, J R Weitzenbock and D McGeorge, Proc. Instn. Mech. Engrs, Vol 218, Part M, J. Engineering for the Maritime Environment, Special Issue paper, pp. 273 – 276.
25. Design guide for bonding metals, Henkel North America.
26. Hybrid Adhesive Joints , L F M da Silva, A Pirondi, A Ochsner (Eds), Springer Verlag,
27. Adhesive Bonding Techniques and Applications, C.V. Cagle, 1968
28. www.jamestowndistributors.com/userportal/document.do?docId=975
29. Loctite General Manufacturing Structural Bonding adhesives selector guide .

5.F ARTICULATION USING LAMINATED ELASTOMERIC COMPOSITES

5.F.1 TECHNOLOGY – STATE OF THE ART

Laminated Elastomeric Components (LECs) comprise bonded layers of steel and rubber. LECs exhibit very high compressive load capacity, but allow large displacements in shear. They can be configured in a variety of geometries (plane, cylindrical, conical, spherical) to allow articulation or translation over a limited range. They have the potential in some wave energy applications to eliminate sliding surfaces and therefore provide a truly maintenance free alternative to plane sliding or rolling element bearings. Consequently a significant change in operational expenditure could be realized through the adoption of this technology. It is not yet known how the capital cost will compare to more conventional bearings.

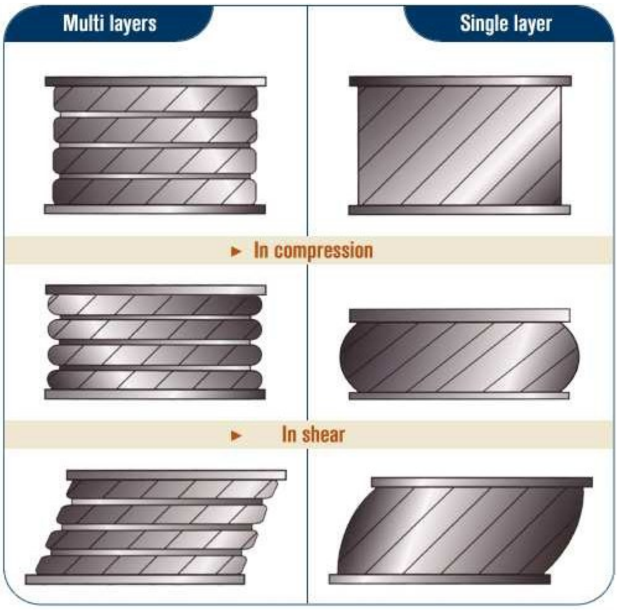


Figure 5.21. Laminated Elastomeric Components

LECs are used extensively within structural engineering for components such as bridge bearings and seismic isolators. They also have several decades of application within the offshore sector, principally in riser and mooring flexible joints.

5.F.2 TECHNOLOGY TRANSFER

The fundamental technology of LECs was developed for bridge bearings in the 1950s and is now ubiquitous within that industry (1). Their design and manufacture has been standardized e.g. (2) and they are available as a commercialized product from a wide range of manufacturers.

In the 1970s, the same fundamental technology was applied to the problem of providing flexibility in the connections of offshore risers (3). The technology is now used in a number of offshore applications such as riser systems and mooring connections. A summary of current applications can be found in (4). At least two suppliers to the oil and gas sector offer these products; Oil States Industries (5) and Techlam (Hutchinson) (6).

Within the wave energy sector, Carnegie Wave Energy have used an offshore flexible joint for the connection of their CETO device. Aquamarine Power have conducted investigations into using LEC technology for hydraulic swivel connectors and within the joining system of a novel mechanical connector (7).

In order to adapt this underlying technology to a WEC application designs would need to be developed to meet the specific operational range, degrees of freedom, ultimate and fatigue loading. Further comprehensive testing is needed at least in the early stages of development, until there is greater confidence in analytical design tools.

5.F.3 MATURITY AND RISK

TRL Level – 6. The underlying technology has been demonstrated in a relevant environment through its use within the offshore sector. However components specific to the operational range and duty cycle of wave energy devices have not yet been developed.

Some of the key risks associated with the use of LECs within a wave power application are outlined below:

Range of motion. Flexible joints in riser systems are typically designed with a range of motion of up to +/- 30 degrees (5). Substantially larger rotation ranges may be required in WEC applications.

Fatigue. Previous studies (8) have shown that the fatigue life of LECs is dominated by the shear strain at the edges of the steel reinforcing plates. These shear strains are influenced by loading in any orientation and it is not trivial to deduce the stress state under multi-axial loading. It is well known that relaxation of elastomers is detrimental to their fatigue life. One of the key challenges for wave energy is therefore to develop a detailed understanding of the loads to which the LEC will be subjected and to overlay this with the specialist knowledge of elastomeric fatigue design.

Capital Cost. Depending on issues such as the required range of motion, fatigue life and geometry (e.g. cylindrical v. spherical), there are likely to be very significant variations in the manufacturing cost of LECs. Can high integrity components be produced at a realistic CAPEX ?

5.F.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

The motivation for investigating the use of LEC components is the potential to eliminate major maintenance activities on the bearing systems of articulated WECs. The replacement of any bearing type will be a costly activity, most likely requiring the WEC to be returned to quayside, and possibly to land. This has two detrimental impacts on LCOE. Firstly there are the O&M costs, including replacement parts, maintenance personnel, vessels and other equipment and facilities (possibly including craneage or dry docks). Secondly, revenue will be reduced because of the lost production during the maintenance period. This can be significantly mitigated by planning bearing replacement for the low production summer months.

To provide meaningful numbers for the scale of this OPEX benefit the maintenance schedules, activities and costs of full scale WECs should be assessed, which is beyond the scope of this landscaping project.

5.F.5 RECOMMENDATIONS

In order to develop the use of laminated elastomeric articulation solutions reference WEC technologies should be selected to which it would be applied. If this is done, designs could be developed, in conjunction with industry experts that allow component life and cost comparisons of LECs versus conventional bearing solutions.

A design and testing program should be developed based on an in depth risk review of the application. At the very least this would be anticipated to include thorough fatigue analysis and fatigue testing.

5.F.6 REFERENCES

1. Wetzk, Volker. Bridge Bearings - a Historical Survey (from the German by Barthold Pelzer). Berlin : s.n.

2. BS-EN 1337-3. Structural Bearings Part 3 - Elastomeric Bearings. 2005 - 07.

3. Co., Murdoch Machine & Engineering. Ocean Floor Riser Connection. US 4076284 A United States, May 5, 1976.

4. Innovative elastomeric components applicable to current and future ocean energy developments. Cordero, J. P. Chaumieau and F. Bilbao : s.n., 2010. ICOE.

5. FlexJoint Brochure. [Online] Oil States Industries. http://oilstates.com/wp-content/uploads/Offshore-FlexJoint-Technology.pdf.

6. Laminated Elastomeric Components. Hutchinson. [Online] http://oil-gas.hutchinsonworldwide.com/technologies/laminated-elastomeric-component.

7. Montague, Richard. Mounting System and Method. US0152621 A1 United States, June 2013.

8. Coveney, V, [ed.]. Elastomers and Components - Service Life Prediction - Progress and Challenges. ISBN: 978-1-84569-100-4.

5.G CONCRETE-STEEL HYBRIDS

5.G.1 TECHNOLOGY – STATE OF THE ART

"Composite (steel / concrete) construction dominates the non-residential multi-story building sector. This has been the case for over twenty years. Its success is due to the strength and stiffness that can be achieved, with minimum use of materials" (1)

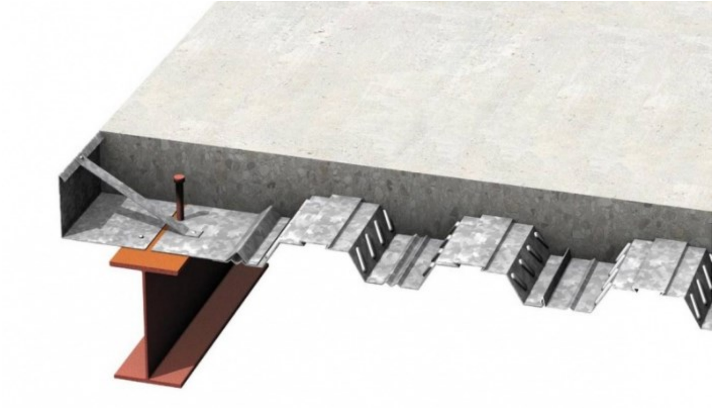


Figure 5.22. Typical steel / concrete hybrid building construction

Typical 'composite construction' details are shown in Fig. 5.22; steel beams connected to a concrete slab by friction-welded shear studs carry predominantly tensile loads, whilst the concrete remains in compression. Similar load sharing takes place in the steel / concrete floor panel. The geometry of the cold-formed steel decking is optimized to provide shear features and a good bond between the concrete and decking.

Whilst this form of construction detail is efficient where the design is dominated by uni-directional loading, it is not immediately apparent as to how it could be applied effectively to the typically reversing loads experienced by WECs It could have limited application in static, shoreline devices.

Composite columns, formed by filling or encasing steel sections in concrete have greater compressive strength than either the steel or concrete sections alone, and the concrete can prevent local buckling of the steel. This technique of preventing steel buckling could be useful for WECs, particularly if it reduces the need for fatigue sensitive fabricated stiffeners. Circular and square concrete-filled steel tubes are used in applications such as high-rise construction and foundations. They can be used with or without internal steel reinforcing bars, using lightweight through to high performance concretes (100MPa), or using fibre-reinforced concretes. Concrete-filled steel tubes are often selected for the ease of construction and the ease with which connections can be made to the external steelwork.

Bi-steel is another product developed by the construction industry that could be applied to WECs (2). This product is a sandwich of two steel plates held a set distance apart by friction stir welded studs. The space between the plates is filled with concrete. Bi-steel panels have very good bending strength for a given weight of steel. They could be applicable to WEC construction for example in the raft like devices were the design is dominated by the bending characteristics of flat panels. There are however significant risks associated with aspects such as their fatigue behaviour and in the joining of panels.

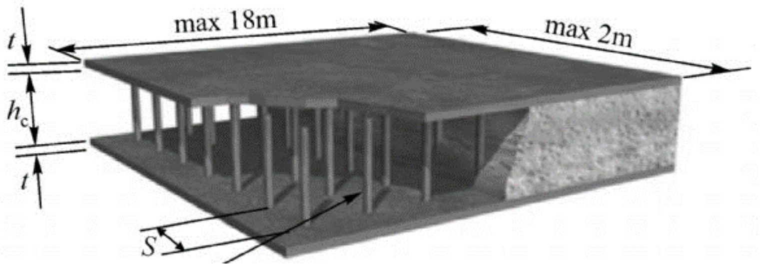


Figure 5.23. Bi-steel panel

5.G.2 TECHNOLOGY TRANSFER

Steel – concrete hybrid structures are used extensively in the construction industry. The most common example, composite slabs and beams, may not be directly relevant to WECs. Other technologies such as buckling restrained steel sections may be of greater applicability.

The design of steel and concrete composite structures is covered by codes (3).

Bi-steel was the subject of a considerable degree of research in the late 1990s by numerous parties and in particular British Steel and the Steel Construction Institute (refer e.g. (4). It still appears on the Tata steel website (5), but appears to be restricted to specialist applications such as blast walls. In order to transfer this technology to the wave energy sector, a number of issues would need to be investigated, including fatigue behaviour when subjected to an extensive number of cycles as well as the techniques of joining panels (and their fatigue resistance).

There is little evidence of steel concrete composites having been widely adopted in the marine environment. One exception being sheet pile walls that are sometimes backed by concrete fill, but in this instance the two components are not really acting as a structural composite.

5.G.3 MATURITY AND RISK

TRL level – 6. Steel – concrete hybrid structures are mature technologies within the construction industry. They have not however made an impact on the offshore construction industry and solutions appropriate to the loading environment of WECs have not been developed.

Some of the key risks associated with the use of steel-concrete hybrids within a wave power application are outlined below:

Suitability for the loading environment. The most common examples of steel –concrete composite construction deal primarily with dead weight loads. The compression and tension zones of the structure are well defined and each material can be utilized to its best advantage. In WEC structures cyclic loads tend to dominate and so there is a risk of either concrete elements failing in tension, or the advantages of the composite construction being completely eroded. Concrete filled columns and bi-steel are less exposed to this risk and for that reason are more likely to find application in WECs than composite floor decking systems.

Corrosion. The concrete-steel interface is very prone to corrosion and may be more difficult to protect with standard techniques (cathodic protection and coatings) than a straightforward steel structure.

Fatigue of shear features. Most of the technologies outlined rely on friction-welded studs to transmit shear forces between the steel and the concrete elements. Fatigue of this connection detail will be a significant concern for WEC structures, and whilst this has been studied in construction (Refer e.g. (6)) and offshore applications, it is not clear how this will translate to WEC structures.

Joining of Bi-steel panels. The maximum size of bi-steel panels will be smaller than most full scale WECs. A reliable fatigue tolerant method of joining panels together is necessary. Also, details of connecting structures made from Bi-steel to other components of the system will not be as straightforward as in a simple plate structure.

Logistics. Steel-concrete hybrids will be significantly heavier than an equivalent steel only design. Depending on the point in the manufacturing process at which the concrete is poured this could add substantially to initial logistic costs as well as creating constraints to maintenance and de-commissioning.

5.G.3 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

The basic costs of standard structural steel sections and concrete are not too onerous. In particular, in Q1 2016 the price of steel has fallen markedly to below half of the peak reached in 2011 and remains highly volatile. Some cost figures are provided below from the MEPS database:

Carbon steel structural sections and beams (assumed onshore construction grade)	499 Eu/tonne (400 £/tonne)	Feb. 2016 (7)
Rebar	340 Eu/tonne (270 £/tonne)	Feb. 2016 (7)
Concrete (supply only, excluding placement and reinforcement)	£105/m^3 (8)	2012

A rough indication of bi-steel panel costs has been provided as follows:

"… basic empty panels using 8mm face plates at 300 ctrs and in the region of 4mx2m work out at between £800 and £1200 per square meter supply only."

The costs associated with joining of components (fabrication and / or welding) will be significant as will the logistic costs (cranes etc.) associated with assembling and transporting a heavier structure. These costs will be specific to the WEC design and the available facilities and cannot be realistically assessed within this landscaping project.

5.G.5 RECOMMENDATIONS

Increasing the fatigue life and reducing the weight of steel in structures by eliminating the need for fabricated stiffeners is perhaps one of the most realistic advances that could be made using steel – concrete hybrid structures. It is recommended that further design studies based on a real WEC application are conducted to assess the cost benefits that could be obtained from this approach. This should focus on products or techniques similar to concrete filled tubes or bi-steel. Composite decking systems are not considered to be appropriate for WEC applications.

5.G.6 REFERENCES

1. Composite Construction. Steel Construction Info. [Online] http://www.steelconstruction.info/Composite_construction.

2. The development and use of British Steel Bi-steel. Bowerman, J.W. Pryer and H.G. 1998, Jornal of Construction Steel, Vol. 46.

3. Eurocode 4: Design of composite steel and concrete structures. EN1994-1-1.

4. Behaviour of double skin composite. Boswell, McKinley and. 2001, Journal of Constructional Steel Research.

5. Physical Perimeter Security and Protective Construction Solutions. Tata steel. [Online] http://www.tatasteeleurope.com/static_files/Downloads/Tata%20Steel%20Projects/Construction%20Tab%203%20DS%20Download%20-%20Physical%20Perimter%20Security%20Brochure.pdf.

6. Resistance of stud shear connectors to fatigue. R.P., Johnson. s.l. : Elsevier, 2000, Constructional Steel Research.

7. EU carbon steel prices. MEPS. [Online] http://www.meps.co.uk/EUprice.htm.

8. Arup, Pelamis Wave Power Concrete Tube Study Manufacturing Report. 219879-00, October (2012)

5.H POLYMER AND COMPOSITE – STEEL HYBRIDS

5.H.1 TECHNOLOGY – STATE OF THE ART

Steel is seen as a key element in most WEC devices and almost all devices included some element of steel. One of the feedback outcomes of the Materials study was that wave energy device designers felt that the structures would ultimately be a mix of materials but that composites or polymers would have significant benefits in weight saving and reduced corrosion. Within the team it was felt that this would be achieved with either a steel backbone and composite panels or steel backbone and polymer buoyancy for example.

The main areas for improvement are seen as:

- Optimisation of joining technologies
- Connections to composites or in composites
- Load bearing in composites and polymers
- Use of composites to increase steel capacity due to buckling or compression

The principal benefits are the following:

- Reduced weight of structures
- Improved fatigue and corrosion resistance
- Reduced installation costs

Currently pultruded elements have been used as structural sections and Strongwell [1] have a catalogue of the structural sections they provide. The issue that arises with the use of pultruded and other composite elements is how to connect them into either a stronger material or in such a way as to prevent a reduction in strength (e.g. by bolting through the materials). Captivating polymer buoyancy has been carried out in the offshore industry usually for the provision of buoyancy for mid water arch and riser tower systems by various companies [2,3]. These are some of the most basic forms of a composite system such as the proposed design below which captivates buoyancy in a steel shell and the fabricated component built using a steel shell and standard mooring buoyancy.

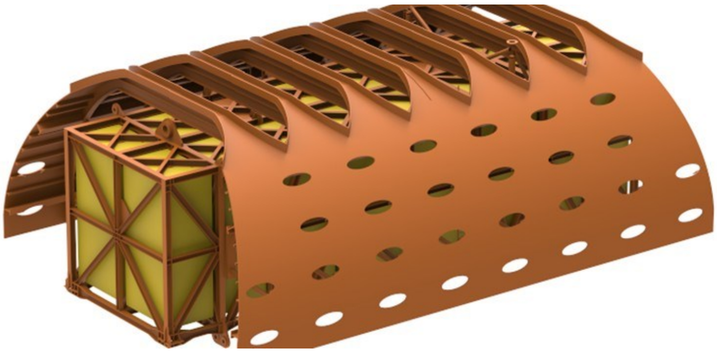


Figure 5.24. Composite Mid-Water Arch

Figure 5.25. Composite Mid-Water Arch from Buoyancy Units

5.H.2 TECHNOLOGY TRANSFER

The processes required to create the proposed improvements mainly focus around the containment or joining of the composite or polymers to the steel backbone.

The main design requirements would be to understand the design limits of the materials assuming that there are the usual tensile, compressive, shear and strain limits.

The main operational requirements would be to understand the effects on the various materials of exposure to the marine environment and any potential degradation from immersion in water and external pressure.

Some composite-to-steel lap joints have been tested and the use of adhesives is becoming ever more widespread, this is dealt with in the section on bonding. TWI have a patented process “Comeld” with a pre-treated surface which has shown some good results.

For mechanical joining clinching and riveting techniques are used. The high production rate techniques that have been studied at TWI include clinching, which uses a special punch and die to form a mechanical interlock between the sheet metals being joined, and self-piercing riveting, in which a semi-tubular rivet is set using a punch and die to flare the rivet within the lower sheet so that no pre-existing hole is required. The advantage of this technique is can be done on pre-painted parts. Self-piercing rivets are a technology that seems promising in relation to the joining of metals and composites the procedure has been used in for example aluminium sheet used for truck cabs [4]. The use of self-piercing rivets in high strength steels has also allowed use of high strength steels without the constraint of welds on fatigue life since no spot welding; even though the number of connections made may be higher the improved fatigue life outweighs this cost [4, 5].

The main area for technology transfer appears to be from the automotive sector where the most cost effective mechanical joining techniques appear to be employed.

5.H.3 MATURITY AND RISK

The maturity of the technology is at a minimum of **TRL Level 5** as it is already being used in other industries such as automotive, however it would need to be proved on thicker materials for use in wave energy devices. The testing of the current equipment and manufacturing procedures in representative materials is probably required to demonstrate the robustness and longevity of the above joining processes. The cost benefits from the use of composite materials would be related to improved design lives and reduced installation and maintenance costs.

5.H.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

Steel Hybrid structures offer several economic benefits including the potential for:

- Reduced corrosion issues and CP requirement
- Lighter weight with reduced installation costs
- Buoyancy can potentially be made more cheaply in polymers and composites than in steel (cost/tonne net buoyancy)
- Complex curved shapes can be moulded fairly easily

Without a specific project study the cost impact can only be estimated, however, the costs for one off components would definitely be higher than steel. Panel manufacture would be more than steel. Production mould costs for panels, for example are in the order of £500/m2, with panel costs of around £600/m2. Only when the component is a complex shape or mass-produced would cost benefits likely arise in relation to similar steel components. In terms of overall project costs, the hybrid structure could reduce costs where weight was important.

Buoyancy units made from polymer for immersion to around 4-5 Bar would be more cost effective than equivalent steel units, as the hydrostatic pressure increases but connection to the units is difficult unless shaped specifically with a steel core. Hence the usual method of support is to encapsulate in a steel framework. This type of composite structure could potentially save 10-20% on costs. In addition the buoyancy does not suffer from corrosion, fatigue or potential collapse issues.

5.H.5 RECOMMENDATIONS

Conduct a detailed study into the feasibility of using high production rate joining techniques to transmit representative loads in a WEC application and a thorough risk assessment of utilizing these methods in the marine environment.

To further investigate the use of polymer and composite to steel hybrids, design studies should be conducted that address how they might be applied to reference WEC technologies and the benefits that may be gained from this approach.

To progress the use of this further it is considered that the best approach would be to work with an existing WEC device company and implement a design and fabrication optimisation strategy based around the application of a hybrid design. This approach might well include the other technologies being proposed within the material review.

5.H.6 REFERENCES

1. Strongwell, http://www.strongwell.com/products/structural-shapes-and-plate/
2. Balmoral, http://www.balmoral-group.com/balmoral-offshore/index.php/products/riser-towers/riser-tower-buoyancy
3. Trelleborg, http://www.trelleborg.com/en/offshore/products/subsea--buoyancy/midwater--arches
4. Self-piercing riveting case study of Volvo FH12 truck cab, TWI Case Study, accessed at http://www.twi-global.com/news-events/case-studies/self-piercing-riveting-case-study-of-volvo-fh12-truck-cab-154/
5. http://www.henrob.com/

5.I STEELS AND WELDING IMPROVEMENTS

5.I.1 TECHNOLOGY – STATE OF THE ART

Steels are and will continue to be indispensable in the design and construction of WEC devices. The base material has a very good ratio of cost to strength. In WEC design, steels main shortcomings have proven to be the cost of fabrication and poor fatigue strength. Whilst any improvement is seen as an "incremental" change rather than a "leap forward" a combination of approaches could generate a substantial improvement in the efficient use and fabrication of WEC devices.

Whilst the steel design codes may be seen as a "finished" article they do not encompass modern testing, modern welding and fabrication techniques and the widespread use of FEA in design of details. All codes feature the ability to encompass new test data and results. Given that wave energy devices and arrays do not carry high pollution risk like other offshore developments the customised approach to design is likely to be more readily accepted by certification agencies.

The main areas for improvement in design relate to fatigue, as wave energy devices are generally seen as low utilisation devices for normal (ULS) design conditions, or can have the ability to be in a different mode during storm conditions. The benefits can be illustrated by, for example, changing from a DNV F1 to an E curve at a stress range of 75MPa gives a factor of improvement on life of 2 for a seawater joint and from F1 to D an improvement of 3. The main opportunity for improvement in fabrication relates to use of optimised weld preparations with reduced volume of welds and hence reduced fabrication costs. It is also considered that improved welding techniques not considered in the original fatigue databases, along with improved NDE could also generate improvements - provided testing approved by certifying bodies is carried out. In summary the main areas of opportunity are seen as follows:

- Optimisation of welding techniques for automatic welding by improved low volume low energy input J-prep using pulsed MIG technique [3] to lead to at least 50% reduction in welding volume and time. The J-prep allows welders to reach and make the root pass without a wide angled V-prep which leads to consequently substantial filler runs and wider weld bead. This type of profile has widespread use in pipeline welding where the speed of production is important. Specialist welding procedures will need to be generated for each of the typical full penetration details expected to be found in the devices for example plate butt welds, circumferential welds and tube to plate welds. The target for this improvement should be a 30% reduction in overall welding costs for a typical wave energy device.

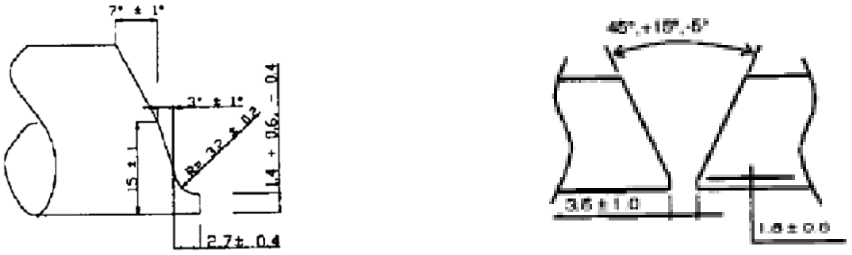


Figure 5.26. Weld types – (left) 7deg - J-Prep; (right) 45deg – Typical Weld Prep

- Detailed joint-specific S-N curves based on resonance testing methods (rapid prototyping) for specific joint details where repeatability is possible. Fatigue design of joints relies upon the designer selecting a corresponding fatigue classification detail which may be overly conservative. Where devices require standard details repeated across a device or devices and using for example revised procedures from above then a detail specific S-N curve could be generated. The design codes [Ref. 4] allow for the generation of joint specific S-N curves and identify what is required to be done to achieve this. Whilst it may not be within the scope of WES to do this work it should be possible to generate the procedures and budgetary costing that would be required to carry out this work to demonstrate the possible benefits which could be achieved with this level of optimisation. This type of approach is being proposed in relation to the tubular structures being used to support offshore wind turbines arrays [5] and would be another efficiency improvement.
- Design improvements such as peening and grinding [1] and introduction of other fabrication improvement such as use of steel castings could also be explained and encapsulated in the proposed new design guidance and procedures. The original British standard [6] has detail on how to account for these procedures and the DNV code [4] also includes these improvements, but there is little guidance on how the improvements can be physically employed within a fabrication specification so the advantage can be accounted for. For example, the improvement in fatigue life for grinding is a factor of 3.5 and for hammer peening is 4, which is significant. The code has some comments regarding workmanship and quality, but doesn’t really deal with the practical reality of how the improvements should be practically achieved. This is another area where new WEC-oriented design guidance, fabrication specifications and associated weld procedures would be a substantial benefit to the sector,

- Improvements to the S-N curves could also be based on improved NDE testing and post-weld removal of shallow defects using selective weld root grinding. This methodology could be developed by testing what defects can be reliably detected, using for example UT inspection and therefore the welds “cleaned up” by grinding in advance of being put into service. Tests carried out on existing structural welds in drilling rigs [2] showed a life extension of 40 years. The life extension strategy included the following measures:

    - mechanical testing of samples extracted from the rig
    - on-site implementation of fatigue life improvement techniques (e.g. weld-toe grinding)
    - calculation of fatigue life for the structure after repairs and modifications

  Implementing these improvements at the start of life should similarly extend fatigue lives for WEC structures giving benefits to the weight of steel required by allowing higher stresses and improving the design life at the same time.

It is proposed that all of the above could be encapsulated in a new Wave Energy Device oriented design guidance notes, fabrication specifications and associated weld procedures. This would require cooperation or technical assistance from bodies such as DNV and TWI and would be the sort of project that a single WEC design company would be unable to achieve but a body like WES is perfectly placed to deliver.

The principal benefits of this approach are the following:

- Reduced weight of structures

- Improved fatigue resistance without extra cost
- Reduced fabrication costs through lower welding volumes

5.I.2 TECHNOLOGY TRANSFER

The processes required to create the proposed improvements currently exist in test houses and specialist welding contractors, however, they would need to be brought together into a focused design team to generate the improvement in costs which are required. Similarly, the facilities exist in universities in Scotland and organisations such as TWI to carry out the testing required to quantify the expected benefits. This work is unlikely to be carried out by a single WEC designer, as the designers and testers would need to work together and a single WEC developer would be unlikely to have the human or financial resources to deliver this approach.

The main challenge would be to recognise common procedures which could then be used across all devices and then devising a detailed weld qualification testing programme and associated test programme to achieve the optimised fabrication procedures and guidelines which would deliver the cost improvements. The initial stage would be to define the scope and cost of such a programme.

5.I.3 MATURITY AND RISK

The maturity of the technology is at a minimum of TRL Level 6 as it is already being used in other industries such as Oil and Gas, aerospace and automotive where optimisation of the design for both operational and fatigue loads is standard practice. Similarly optimising the manufacture for mass production is part of the design process. For fabrication techniques, the technology or techniques exists and has been demonstrated in industry supported by testing from bodies such as TWI. For a WEC developer, particularly the smaller ones, this process is not possible as either there are insufficient skills to either carry out or manage the process in conjunction with insufficient budget. Whilst design optimisation may occur in WECs, the recommendation goes beyond this into optimising the fabrication processes themselves and gaining maximum benefits from modern techniques, supported by sufficient testing to allow improvements to existing design criteria.

5.I.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

Steel is likely to remain a significant component in the fabrication of WEC structures for many of the designers. The current fabrication costs are driven on the design side by the low utilisation of the material for extreme load cases as the design is governed by fatigue, hence overdesigned. Added to this (as confirmed by previous WEC designs such as Pelamis [7]) fabricators will not look at new and innovative fabrication methods, preferring to stick to the long standing already qualified welding and fabrication procedures. It is not surprising as there is little incentive to change, as this would mean extra expense and risk in developing new procedures and methods which may take some time to get correct. Experience has shown that the Fabricators will not produce the reductions and need to be encouraged to make any changes. Whilst benefits are seen in other industries such as heavy plant fabrication by accounting for modern welding and fabrication processes the Wave Energy industry is stuck with the codes and procedures developed mainly for the Oil and Gas and heavy steelwork industries. These industries can accept a high level of conservatism as cost models such as those used in the Wave Energy sector are irrelevant.

The target for cost reduction for fabrication would be to reduce welding costs by 50%, reduce required steel weight by 25% and lead to an overall cost reduction of 25 to 30%. This number was put forward in the telecon of [7] and was felt to be achievable. Based on a current fabrication cost of typical WEC structures of around £4000 per tonne, this would reduce to the region of £2,800 - £3,000 per tonne.

The effect of achieving these reductions would be lower prototype costs and also improved margins for the operators. Further reductions would still be achievable as production volumes increased.

5.I.5 RECOMMENDATIONS

A project is recommended to evaluate the effect of modern testing, welding and fabrication techniques on the design of steel WEC structures. Reduced structural weight and fabrication costs can be achieved by lower welding volumes and improved fatigue resistance, which could be encapsulated in new WEC oriented design guidance, fabrication specifications and associated weld procedures.

To progress the use of this further two inter-related study areas are proposed. One addressing reduction in fabrication cost and the second investigating improvements to allowable fatigue stresses.

A comparative study should be conducted of the fabrication cost of typical WEC structures using conventional and advanced fabrication details.

The second study should evaluate the improvements that can be made to allowable fatigue stresses in typical WEC details through the implementation of a suite of enhancement methods. These may include, weld prep. geometry, reduced heat techniques, grinding / peening and high quality NDE techniques. Fatigue testing would be conducted to verify improvements.

The outcomes of these studies could be encapsulated in new WEC oriented design guidance, fabrication specification and associated weld procedures

The benefit of this approach is that the improvements qualified with one type of device could be implemented across the renewables sector and therefore would have a very high long term value and return on investment.

5.I.6 REFERENCES

1. Peening to enhance fatigue life, TWI study on hammer peening of welds on London bridges shows improvement of 3-4 times in life on treated welds
2. Life extension of offshore rigs/Tubular repair without grinding, TWI studies on toe grinding of welds to extend or enhance fatigue lives
3. Performance claims of MIG/MAG variant checked, TWI study on new welding technique for butt welds using 20mm plate with narrow prep angles showing up to 50% reduction in welding times still meeting the requirements of ISO 15614-1:2004.
4. DNV RP C203 Section 2.14.3, “Qualification of new S-N curves based on fatigue test data”
5. OCAS presentation on improved fatigue life of welded joints, DNV OS F101/105 and RP C203
6. BS7608, Fatigue design and assessment of steel structures. 1993.
7. Telecon between Charles Taylor , ex-Pelamis Structural Manager and Structural Landscaping Group, 7/6/16

5.J ELASTOMERS

5.J.1 TECHNOLOGY – STATE OF THE ART

Elastomers are polymers that generally have a low modulus and a very high elastic strain range. They are often referred to as rubbers. Thermoset elastomers are formed through a vulcanization process that creates cross links between the polymer chains. This process was discovered in 1839 by Charles Goodyear, who transformed gum from the rubber tree (gum elastic) into an elastic solid that is now known as natural rubber.

Since the 1920s a large range of thermoset elastomers (a.k.a. synthetic rubbers) have been developed each with their own set of tailored mechanical and chemical properties. Well known examples of these include Chloroprene (Neoprene), Butyl Rubber and Nitrile rubber. There are many more.

A further class of elastomers, thermoplastic elastomers, have been in use since the 1960s (1). Thermoplastic elastomers differ from thermosets in the nature of their crosslinking bonds. They have distinct manufacturing benefits in comparison to thermosets, requiring little or no compounding and being suitable for production processes such as injection moulding. They are also recyclable.

There are a number of texts that provide a great deal of information on both the chemistry and physical properties of a wide range of elastomers. Refer for example to (2).

Natural Rubber

Despite the extensive developments in elastomer technology, natural rubber compounds (3) remain a leading candidate material for WEC concepts that require highly distensible structures. Natural rubber itself exhibits high tensile strength, resistance to tearing and abrasion and high resilience. Two of its major shortcomings; poor high temperature properties and attack from petroleum based chemicals are probably not a major concern for WEC applications.

Natural rubber is subject to degradation due to ozone and UV attack and it has poor fatigue properties. These issues can be addressed to an extent through the blending of natural rubbers with synthetic thermoset elastomers and the incorporation of fillers such as carbon black. These compounding techniques can produce materials with radically different properties to the base natural rubber.

Rubber / Fabric Composites

As is evident from the examples of technology transfer presented in section5.J.2, the majority of relevant applications of elastomers do not purely use the elastomeric compound; they use composite materials in which the elastomer is bonded to a fabric layer. Various thread materials are used depending on requirements such as the tensile strength. They range from nylons and aramids to Kevlar's and in some instances woven steel wires.

5.J.2 TECHNOLOGY TRANSFER

Automotive Tyres

It is estimated that 70% of global natural rubber production is used in tyres (4). Modern tyres are a complex fabric, steel, and elastomeric composite that are engineered to meet a demanding set of technical and commercial requirements. They share a number of parallels with the requirements of wave energy such as durability under complex loading scenarios, a high number of fatigue cycles and high resilience (low rolling resistance).

A variety of rubber compounds are used in a modern tyre that have been engineered to meet the specific requirements of each component. For example treads typically consist of blends of natural rubber and other elastomers compounded with fillers and vulcanizing chemicals whilst liners are made from butyl rubber which retains the compressed air inside the tyre.

Wave Energy Converters may benefit from a similar approach whereby established basic elastomer technologies are compounded to produce rubber blends that are tailored to the specific demands of the application.

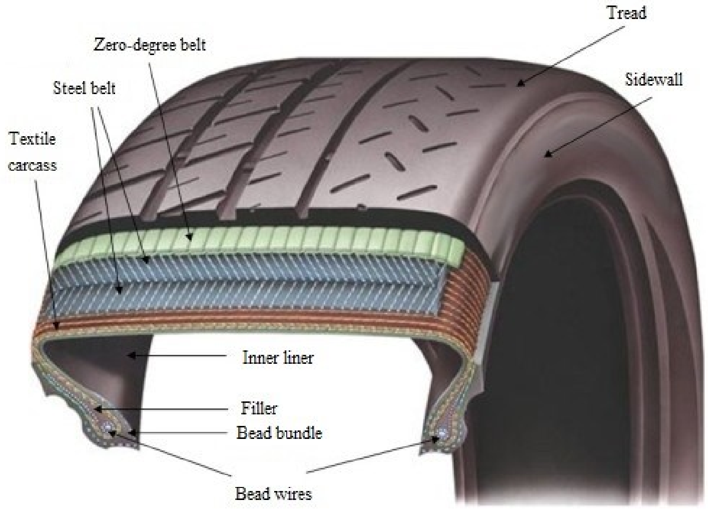


Figure 5.27. Typical Tyre Construction

Marine Applications

Rubber fenders use the large elastic strain range of natural or synthetic rubbers to absorb the impact energy of ships as they moor alongside quaysides. They operate for extended periods of time in the atmospheric, submerged and splash zones whilst subjected to large loads and deformations. They do not experience the same degree of fatigue loading as a WEC structure. The design of fenders is covered by codes (5) and fendering products are widely available from a range of manufacturers.

'Yokohama' fenders are large inflatable rubber fenders used for 'ship to ship' and 'ship to dock' transfer operations. They are manufactured from rubber reinforced with fabrics and are encapsulated within a net structure. Their material, performance, and dimensions are covered by standards (6).

Figure 5.28. Yokohama Fenders

Rigid Hull Inflatable Boats (RHIBs) are another example of elastomeric structures tailored for the marine environment. The elastomers commonly used are Hypalon, Poly vinyl chloride and Polyurethane. These are bonded to a high strength fabric. RHIB tubes are widely available, and companies exist who develop specialist products (e.g. for defence applications) based on similar basic technology (7)

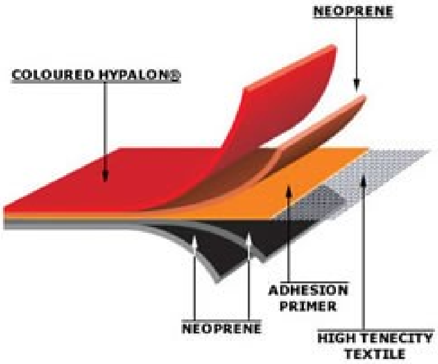


Figure 5.29. Typical Fabric Make Up for RHIB tubes

Within the wave energy sector the Anaconda device (SeaEnergy (8)) is a large rubber tube which captures energy from the waves as a 'bulge wave' travels down its length. The Anaconda has reached a stage of tank testing and full scale design.

AWS have developed the AWS-III, a multi-absorber floating WEC which uses rubber diaphragms which cover air-filled cells as the primary power absorption mechanism (9). AWS have completed model testing at up to 1:10 scale and have built a half scale 'cassette' (power absorption) module. They have encountered fatigue problems with the design of the flexible diaphragms and anticipate that these will be challenging to resolve. AWS have also proposed the 'Electric Eel' (10), a development of the Anaconda concept that incorporates electro active polymer or hose pump power take off components distributed along the length of the device.

5.J.3 MATURITY AND RISK

TRL Level – 6. Elastomeric technologies that are suitable for WEC applications are well proven in the marine environment with examples of products that have been in use for a number of decades. Nevertheless some questions remain over ageing and fatigue effects. Actual full scale WEC structures have not yet been constructed in rubber and it is possible that variants of existing rubber / fabric composites and /or compounding mixes will be required to meet the specific duty cycle of WECs.

Some of the key risks associated with the use of elastomers within a wave power application are outlined below:

Fatigue. Poorly designed elastomeric components can fail very rapidly in fatigue whilst well designed items can exhibit long service lives, as evidenced by some of the examples in section 0. The analysis of fatigue cracking in elastomers is a complex and specialist subject (11). Practical engineering design codes comparable to the S-N approach employed in metal structures do not currently exist and this inhibits the ability of designers to develop realistic fatigue tolerant structures in elastomeric materials. There is also evidence that rubbers may have a greater susceptibility to fatigue when immersed in seawater than in the more widely studied in-air condition. (12)

Environmental effects. Elastomer properties are adversely affected by weathering effects including ozone and UV degradation. Seawater can also accelerate the leaching of constituents of the rubber compound. WECs, particularly those that operate in the splash zone, must contend with all of these effects and the elastomer selection and life prediction must take them into account.

Multiaxial / complex stress conditions. In an elastomer even apparently simple loading conditions can lead to relatively complex stress conditions. For example, a rubber block compressed between two plates will bulge out sideways creating areas of shear and tension that are prone to cracking. WEC structures will typically be subjected to widely varying multiaxial loads. The computational complexity involved in ensuring adequate ultimate limit state and fatigue limit state designs will be high.

5.J.4 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

The design of WEC structures based on the use of elastomeric materials will be radically different to those that have previously been manufactured at scale. As indicated in the above there is a wide range of both elastomer and reinforcement types each with their own technical and commercial variations. It is therefore not realistic within this landscaping study to quantify the improvement to overall structural costs that could be provided by elastomeric materials.

Some indications can however be derived from the costs of products manufactured using similar materials. This is more informative than the raw material costs (of elastomers and reinforcement) as the product cost integrates the relative quantities of the different components as well as the cost of the subsequent manufacturing processes.

Car tyres can provide an indication of the cost per kilogram of a volume manufactured rubber / fabric composite product. A budget tyre (155/70 R13) may weigh in the region of 6.5kg (13), and have a sales price, of £25 or below (14). This equates to a selling price per kg of £3.85.

A further cost indication has been obtained for Yokohama fenders. A 3.3m dia x 6.5m long fender weighing 1870 kg retails for $27,500 (£18,750) or around £10 per kg. It should be noted that because of the critical environmental and safety implications of the Yokohama fenders (e.g. avoidance of significant damage to oil tankers at sea) there are likely to be significant approval and warranty costs associated with these components.

These costs per kg are similar to, or somewhat higher than those for fabricated steel. However it seems plausible that inflated structures could be significantly lighter than a steel equivalent and this would result in an overall step change in costs.

Additionally, transportation and installation costs could be dramatically altered with lighter, flexible structures that could be assembled / inflated close to or on site.

5.J.5 RECOMMENDATIONS

Elastomers, or elastomer / fabric composites, have the potential to enable a radically different type of WEC structure compared to those that have been trialed at full scale to date. The basic materials technologies are mature although their behaviour is complex and variants of existing compounds and composite make ups may be necessary to meet the specific requirements of WECs

One practical measure that would be of benefit to the development community would be the compilation of a set of guidelines to assist designers in the early concept development stages. This should include a pragmatic rather than a strongly academic approach to fatigue design. Such guidelines would promote the uptake of elastomers by engineers and improve the quality of concepts and communication with the elastomer specialists whose expertise will be required as projects develop.

5.J.6 REFERENCES

1. Handbook of Thermoplastic Elastomers. s.l. : Elsevier, 2014.

2. Burak Erman, James E. Mark, C. Michael Roland. The Science and Technolgy of Rubber. s.l. : Elsevier, 2013.

3. Thomas, Sabu. Natural Rubber Materials. s.l. : Royal Society of Chemistry, 2014.

4. Mir Hamid Reza Ghoreishy, Mohammad Alimardani. Natural Rubber Materials. Chp. 24 - Application in tyre engineering and other fields. s.l. : RSC Publishing, 2014.

5. BS 6349-4 - Maritime works. Code of practice for design of fendering and mooring systems. s.l. : BSI, 2014.

6. ISO 17357 - Floating Pneumatic Rubber Fenders. 2014.

7. Avon Engineered Fabrications. [Online] http://www.avon-rubber.com/Our-Businesses/aef.htm.

8. Anaconda. Seaenergy. [Online] http://www.checkmateukseaenergy.com/anaconda/.

9. Grey, S. Technology Description and Status AWS-III, Wave Energy Scotland Knowledge Capture Project AWS Project 15-007, 2016.

10. Hall, A. et al, Technology Description and Status Electric Eel, Wave Energy Scotland Knowledge Capture Project AWS Project 15-007, 2016.

11. A literature Survey on fatigue analysis approaches for rubber. Mars W.V., Fatemi A. 24, s.l. : Elsevier, 2001, International Journal of Fatigue.

12. Fatigue behaviour of natural rubber in marine environment: comparison between air and seawater. Pierre-Yves Le Gac, Mael Arhant, Peter Davies, Alan Muhr. 2015, Materials and Design.

13. How much does a car tyre weigh. Openeo. [Online] http://www.oponeo.co.uk/tyre-article/how-much-does-a-tyre-weigh.

14. Mytyres. [Online] http://www.mytyres.co.uk/cgi-bin/rshop.pl?cart_id=37904270.110.25637&dsco=110&ranzahl=4&rsmFahrzeugart=ALL&search_tool=standard&suchen=Show+tyres&x_tyre_for=&s_p_=&ist_hybris_orig=&m_s=&tyre_for=&with_bootstrap_flag=1&sowigan=&Breite=155&Quer=70&Felge=13&.

5.K DIELECTRIC ELASTOMER GENERATORS

5.K.1 TECHNOLOGY – STATE OF THE ART

Dielectric Elastomers (DEs) are highly deformable rubber-like solids, which are mechanically incompressible and electrically non-conductive. The sequential stacking of multiple DE sheets separated by compliant electrode layers yields a deformable capacitive transducer (hereafter referred to as Dielectric Elastomer Transducer, or DET in short) that is capable of converting electricity into mechanical energy and vice-versa [1]. Typical materials used as DEs are natural rubbers, silicone elastomers, nitrile rubbers and polyacrylate elastomers (both in unfilled and filled form). Typical materials used for compliant electrodes are silicone compounds filled with conductive particles such as carbon black, carbon nanotubes, copper or silver [2].

DETs can be used as solid-state actuators, sensors and generators in any kind of machine featuring mechanical members with reciprocating motion [1]. DETs have been largely developed as actuators and are known as “artificial” muscle, under the generic title of Electro Polymer Artificial Muscle (EPAM), which was developed in the early 2000s [3]. In generator mode, DETs operate via the variable capacitance electrostatic generation principle, thereby increasing the voltage of the charges that lie on the electrodes as the DET capacitance decreases.

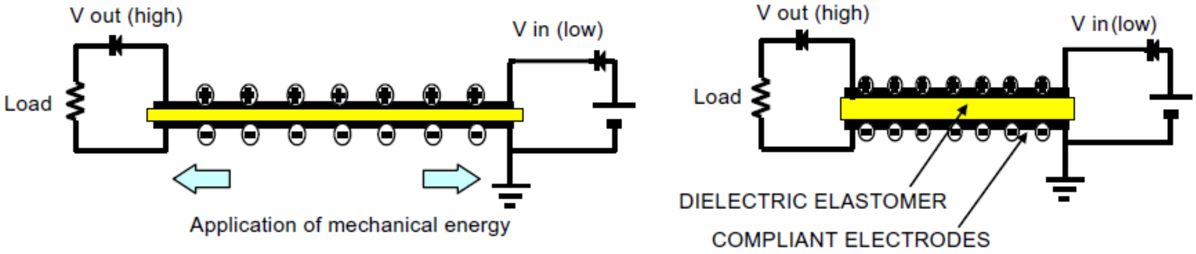


Figure 5.28. Operating principle of a Dielectric Elastomer Generator [from Ref 3]

There are several ways in which a DET can be used to produce electrical energy from the mechanical work used to stretch and contract it. Assume a constant voltage cycle. Application of mechanical energy to stretch the material causes reduction in thickness and expansion of the surface area (see Fig. 5.28, left). At this moment, a voltage may be placed upon the polymer (i.e. positive charges are placed on one side and negative charges on the other side). When the stretching forces are removed, the elastic recovery force of the DET acts to restore the original thickness and to decrease the surface area (see Fig. 5.28, right). The increase in thickness upon relaxation acts to push the opposite charges apart from each other, effectively raising the voltage applied to the DET. Even though the capacitance of the DET reduces upon relaxation, there is a net increase in the energy stored on the DET compared to that put on by the original application. This increase can be harvested as electrical energy.

The amount of energy that a given mass of DET can generate is determined by its maximum strain and dielectric breakdown strength. Using polymer materials such as acrylic and silicone elastomers, energy densities more than an order of magnitude greater than those of piezoelectric or electromagnetic materials have been produced [5, 6, 7].

Due to the low mass density of DE materials (nearly 1000 kg/m^3), values for the energy density of DETs (namely, the amount of energy converted in a cycle per kilogram of transducer) typically range between 0.1 and 2 kJ/kg, which, for generators operating at low frequencies (for instance, at less than 1 Hz), compare very well (and sometimes are even better, especially as the operating frequency is smaller) with that of traditional electric machines. Beside good energy density, other advantageous properties of DETs that could make them the optimal choice for the development of machines that generate electricity from low-frequency reciprocating motions are [2]:

- good electromechanical conversion efficiency (usually in the range 60-90%);
- suitability of operation at low frequencies seen in wavepower, c. 1 Hz
- moderate or low cost (100 €/kg for small batches and less than 10 €/kg for large batches);
- solid-state monolithic embodiment with no sliding parts and very low internal friction;
- easy manufacturability, assembling and recyclability;
- good chemical resistance to corrosive environments;
- silent operation and no need of lubrication.

The potential application of DEGs to harvesting of wave energy has been identified as early as 2001 [1]. In August 2007, SRI International and HYPER DRIVE Corp. completed an EPAM-based generator prototype designed to provide on-board power to a navigation buoy and carried out a test of its practical use in the Tampa Bay near St. Petersburg, Florida, USA [8].

S3 Standing Wave Tube Electro Active Polymer WEC

In 2008, French company SBM developed and tested a DET-based Wave Energy Converter called the S3 (S3 Standing Wave Tube Electro Active Polymer WEC), in a wave-tank [9]. Floating under the ocean surface, the S3 amplifies pressure waves similarly to a Ruben's tube. In the S3 system, Electro Active Polymer (EAP) generators are distributed along an elastomeric tube over several wave lengths, they convert wave induced deformations directly into electricity.

The S3 is ostensibly an electrically-charged flexible tube closed at both ends and filled with slightly pressurised seawater (Figure 5.28, Ref. 10). This electro-active rubber snake is then suspended just below the surface of the water, where the wave energy is at its most powerful, to induce local changes in the tube's diameter and absorb the energy. The tube structure and PTO are merged by using EAP generator rings embedded along the body of the WEC to convert ocean wave energy directly into electricity without any moving mechanical parts. In 2010 at a test basin in Sophia-Antipolis, France, the WEC produced electricity for the first time directly from waves with the use of submerged EAP. According to SBM [9] "SBM Offshore investigating the feasibility of deploying a scale prototype in 2017 and is inviting industry partners to help turn the concept into commercial reality".

POLYWEC Project

The POLYWEC project is funded by the European Union under Framework 7 (Energy – Future and Emerging Technologies) and runs from 2012-2016 [11]. The main goal of the project is to introduce a radical change in the traditional architecture of WECs by using converters characterized by deformable lightweight and low-cost polymeric elements. The full title of the project is "New mechanisms and concepts for exploiting electroactive Polymers for Wave Energy Conversion". The project consortium is co-ordinated by the PERCRO SEES Centre (Security Environment Energy and Safety Centre) of Scuola Superiore Sant'Anna (Pisa, IT).

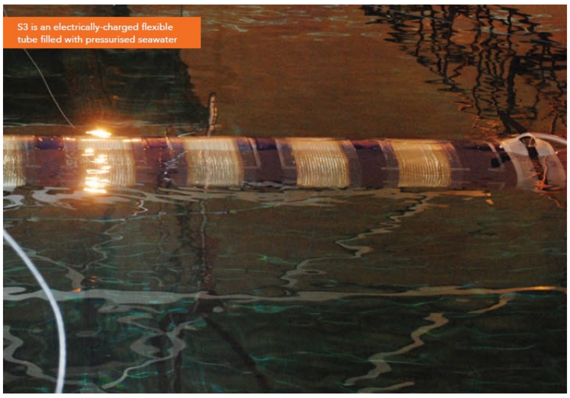
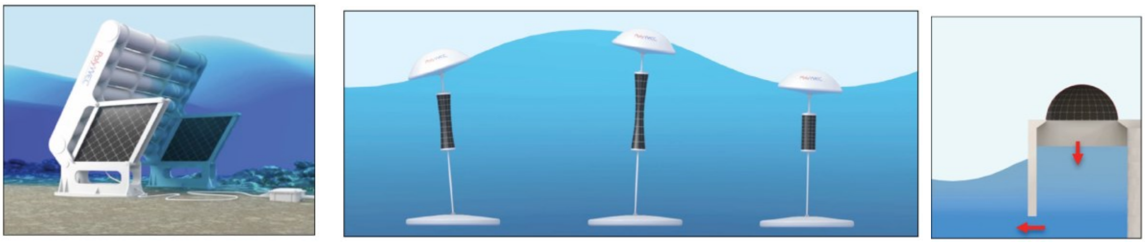


Figure 5.29. Tank testing of S3 DE generator from SBM Offshore [from Ref. 9]

The PolyWEC project has been focussed on: the definition and analysis of feasible architectures for the implementation of WECs Dielectric Elastomer Generators (DEGs); the development of theoretical models able to predict their performances; the conduction of a campaign of material tests for existing DE materials that can be eligible for the purpose of this application; the development of prototypes of first generation devices and the consequent experimental tests on dedicated test-benches and the implementation of tests in wave-tank of the conceived concepts.

Three concepts of DET-based WECs developed in the project are the polymeric wave-surge (Poly-Surge), the polymeric buoy (Poly-Buoy) and the polymeric oscillating water column (Poly-OWC) systems. The concepts are shown in Figure 5.30 (from Ref. 2). The Poly-Surge concept consists of a buoyant flap hinged at the sea bottom and exploits the surging motion of waves. In traditional systems (such as the Oyster device by Aquamarine Power) the wave induced oscillatory motion of the flap is used to pump water to the coast via hydraulic pistons and high-pressure flow lines. At the coast, the high pressure water is then converted into electricity via a turbo-generator. Replacement of the hydraulic power take-off system (and of the turbo-generator) with lozenge DETs [12] could enable local conversion of wave energy into electricity without requiring any mechanical or hydraulic transmission. Besides simplifying the system and reducing part count, this replacement could improve system efficiency, simplify installation and reduce the noise pollution emitted at the coast by the turbo-generator. Due to physical constraints in the oscillatory motion of the flap, Poly-Surge systems are likely to be not resonant in the working frequency range, and should be designed to maximize wave excitation force and to move at speeds that are adequate to limit vortex losses at the edges [12].



(a) (b) (c)

Figure 5.30. Three WEC concepts from the POLYWEC EU Project [2]: (a) Poly-Surge – Oscillating Flap with a lozenge DET; (b) Poly-Buoy – Oscillating Buoy with a cylindrical DET, and (c) Poly-OWC – Oscillating Water Column with inflating circular diaphragm DET

A second WEC architecture that could be suited for wave energy harvesting via DETs is the oscillating buoy (Poly-Buoy, see Figure 5.30b). An oscillating buoy WEC consists of a floating body, either submerged or semi-submerged, that moves under the action of sea waves with respect to an appropriate number of submerged and nearly fixed reaction points. During these oscillations, the distances between points of the buoy and those of reaction vary. These reciprocating changes in length can be used by power take-off systems with linear motions to extract energy from waves. As alternative to the traditional hydraulic rams or linear electrical generators, cylindrical DETs can be used for this purpose. Depending on the size of the device, the considered DET can be placed either inside the buoy, close to the reaction points (in particular on the seabed or inside the reaction body) or along the line connecting the reaction points and the buoy. For standard buoy shapes and aspect ratios, Poly-Buoys are likely to be designed so as to be resonant in the working frequency range, which makes their performances very sensitive to the intrinsic passive stiffness of the DET [13].

Oscillating Water Column (OWC) wave energy converters are based on the reciprocating motion of a column of water enclosed in a chamber (tube or duct) that has at least one submerged opening. In traditional OWC concepts, the movement of the oscillating water column induces a pressure variation inside a closed air chamber; such a pressure variation is used to drive a turbo-generator, which converts the stored pneumatic power into usable electricity. In OWCs, replacement of the turbo generator by an inflating diaphragm DET could significantly simplify overall system architecture and installation, improve overall energetic efficiency and climate adaptability, and reduce operating noise. For standard chamber shapes and aspect ratios, Poly-OWCs (Figure 5.30c) are likely to be designed so as to be resonant in the working frequency range, which makes their performances very sensitive to the intrinsic passive stiffness of the DET. Thanks to the presence of an air pocket, the dynamic response of a given Poly-OWC can be tuned to the prevalent frequency content of the incoming waves by simply acting on steady-state chamber pressurization [14].

EPOSIL Project

"Silicone-Based Electroactive Polymers for Energy Generation (EPoSil)" is a joint research project in which a consortium of four industrial companies and two universities under the direction of Robert Bosch GmbH is working to develop wave power generators [15, 16]. The German Federal Ministry for Education and Research (BMBF) is supporting the project with a budget of almost 2 million €, as part of the program "Intelligent Materials for Innovative Products".

The core components of the wave energy converter are thin elastomer layers made out of silicone. Elastic electrodes are deposited on the upper and on the lower surface of the silicone films. The thickness of these films are in the range of 20-50 µm and they must be manufactured between tight tolerances in order to avoid an electrical break-through of the layers. Through the movement of the waves, mechanical power is transmitted to the converter.

Wacker Chemicals AG [16] is providing the silicone, which is a major component of the electroactive polymer, which converts mechanical into electric energy. Manufactured using a patent-pending process that obviates the need for solvents, these continuous films are made from addition-curing silicone rubber compounds and are commercially available in thicknesses less than 100 microns – they can even be obtained in thicknesses as low as 20 microns. The manufacturing process yields homogeneous, flawless films that are characterized by their extremely uniform thickness, which varies by no more than 5 percent across the entire width and length of the film web.

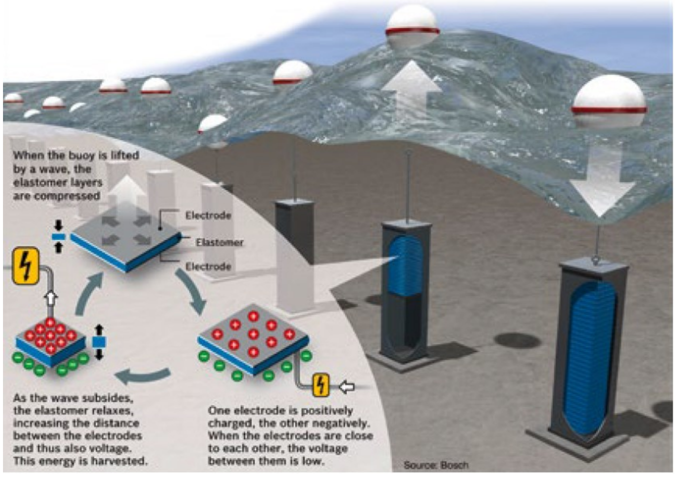


Figure 5.31. Energy generation with dielectric elastomer current transformers. EPoSil Project (from Ref. 15)

Silicone elastomers are rubber-elastic materials consisting of inorganic polysiloxanes that crosslink irreversibly to yield a three-dimensional network. Silicone elastomers have a property profile that makes them indispensable in many industrial applications: extraordinary heat resistance, low temperature flexibility, chemical inertness and biocompatibility. These materials have a strongly hydrophobic, i.e. water-repellent, surface, are selectively permeable to gases, and are very good electrical insulators. A typical characteristic is their high resistance to a large number of physical and chemical influences, which is why, unlike organic rubber compounds, they do not age. Thus, their chemical, physical and technical properties remain virtually constant over the temperature range of roughly -45 to +200 degrees Celsius.

5.K.2 TECHNOLOGY TRANSFER

Dielectric Elastomer Transducer (DET) technology is still in its infancy as part of the overall Electroactive Polymers sector. The most important applications are likely to be the artificial muscle area in biomedical and robotics sectors, but this could be as much as 10 years in the future. There is not sufficient maturity level in the EAP technology sector to transfer into the development of DETs for wave energy converters. Furthermore [17] makes the point that “No dielectric elastomer has been designed specifically for generators. An elastomer optimized for actuators may not be optimal for generators”.

5.K.3 MATURITY AND RISK

The **TRL level of DET wave energy converters is between 2 and 3** (TRL 2 – technology concept formulated; TRL 3 – experimental proof of concept).

The principal technical risks are as follows:

- The main risks are associated with scale-up. The largest DEG WEC device is still only approx. 25cm in diameter, generating less than 1.0W [18]. This will have to be scaled up by a factor of approx. 50, to a 25.0m diameter membrane of unknown thickness, to generate approx. 300KW.
- A general concept for control and energy harvesting will have to be developed – this does not currently exist and the risk is that it will not be possible to adequately control such large DEG converters, while achieving necessary generation efficiencies and availabilities.

- The manufacturing challenges with making 25.0-50.0m diameter DET membranes will have to be overcome. The risk is that it will not be possible to manufacture such large membranes of either elastomers or the electrode layers [19] to sufficient tolerances of thickness etc. to withstand the long fatigue lifetimes of the materials.
- Materials challenges – the risk is that the available DEG materials, based on acrylic or silicone elastomers, when scaled up to diameters of 10s of metres, will not be able to withstand the high forces, tens of millions of fatigue cycles and repeated electrical charging/discharging in an immersed marine environment, without suffering mechanical and electrical failures.
- A lack of testing standards for DETs and DEGs means that basic building blocks for technology development are not available – this work is only starting for DETs [20] and the risk is that the absence of standards will delay the development of wave energy converters based on these materials.

5.K.3 COST DRIVERS AND POSSIBLE ECONOMIC BENEFITS

Due to the maturity level of the technology (TRL 2-3) and the fact that there are no comparable large scale structures made from DEGs, it is impossible to discuss cost drivers at this stage of the developments. Possible economic benefits to WECs are therefore also impossible to estimate at this stage.

5.K.4 RECOMMENDATIONS

As compared to traditional WECs with hydraulic or electromagnetic power take-off system, Dielectric Elastomer Transducer (DET)-based WECs offer the following potential features: reduced capital costs; easy installation and maintenance; good shock and corrosion resistance; good energy conversion efficiency; good climate adaptability; reduced noise during operation.

As of today, DET technology is however not yet ready to deliver fully-functional WEC systems that are capable to operate in real ocean conditions for sufficiently long periods of time.

In this perspective, critical materials and process issues that need to be addressed are:

- Assessing the long-term fatigue, ageing, degradation and reliability of the employed materials;
- Standardisation of the testing protocols needed to assess these materials and devices
- Conceiving better dielectric elastomers and conductive electrodes with improved electromechanical transduction properties and reduced dissipative effects;
- Investigating the manufacturing and assembly issues associated with full-scale deployment of these types of WECs.

5.K.5 REFERENCES

1. R. Pelrine et al., “Dielectric elastomers: Generator mode fundamentals and applications”, In SPIE’s 8th Annual International Symposium on Smart Structures and Materials (pp. 148-156). International Society for Optics and Photonics (2001)
2. M. Fontana and R. Vertechy, “Wave energy converters based on dielectric elastomer generators: Status and perspectives”, EAI Speciale II-2015 Ocean energy: Ongoing research in Italy, accessed from http://www.enea.it/it/pubblicazioni/pdf-eai/speciale-ocean-energy/specialeeai-ocean-energy.pdf
3. US Patent No. 8183739 B2, “Electroactive polymer actuated devices” (2005), SRI International.
4. S. Chiba et al, “Consistent ocean wave energy harvesting using electroactive polymer (dielectric elastomer) artificial muscle generators”, Applied Energy, Vol. 104, pp. 497–502 (2013).

5. S. Chiba et al, “New opportunities in electric generation using electroactive polymer artificial muscle (EPAM)”. Journal of the Japanese Institute of Energy, Vol. 86, pp. 743–7 (2007).
6. R. Kornbluh and R. Pelrine “High-performance acrylic and silicone elastomers”, Chapter 4 in *Dielectric elastomers as electromechanical transducers: Fundamentals, materials, devices, models and applications of an emerging electroactive polymer technology*. Eds. Carpi, F., De Rossi, D., Kornbluh, R., Pelrine, R.E. and Sommer-Larsen, P., Elsevier (2008).
7. Soo Jin Adrian Koh et al, “Dielectric elastomer generators: How much energy can be converted?”, IEEE/ASME Transactions on Mechatronics, Vol. 16, No. 1, February (2011).
8. Chiba S, Kornbluh R, Pelrine R, Waki M. Innovative power generation for energy harvesting using electroactive polymer artificial muscles. In: Proceedings of SPIE, vol. 6927. San Diego, CA, USA; p. 692715-1–9 (2008).
9. P. Jean et al, “Standing wave tube electro active polymer wave energy converter”, Proceedings of SPIE - The International Society for Optical Engineering 8340:6- · March 2012, doi: 10.1117/12.934222.
10. SBM Offshore, “Sea power sees SBM surf towards new wave energy demonstrator”, Currents Magazine, Issue 11, October 2015, accessed at http://www.sbmoffshore.com/wp-content/uploads/2015/10/Currents11_OCT_15_17-low-res.pdf
11. European Union Seventh Framework Programme [FP7/2007–2013] under grant agreement n° 309139. Project POLYWEC, “New mechanisms and concepts for exploiting electroactive polymers for wave energy conversion”, www.polywec.org
12. G. Moretti et al, “Modeling of an oscillating wave surge converter with dielectric elastomer power take-off”, Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2014), San Francisco, California, USA (2014).
13. G. Moretti et al, “Modeling of a heaving buoy wave energy converter with stacked dielectric elastomer generator”, Proceedings of the ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS 2014), Newport, Rhode Island, USA.
14. R. Vertechy et al., “In-Tank Tests of a Dielectric Elastomer Generator for Wave Energy Harvesting”, Proc. SPIE 9056, Electroactive Polymer Actuators and Devices (EAPAD) 2014, 90561G (March 8, 2014); doi:10.1117/12.2045046.
15. “Silicone foils harvest electricity from wave power”, PCIM Europe, Community Dialog, Issue 01-February (2015), also http://www.bosch-presse.de/presseforum/details.htm?txtID=6363&locale=en
16. Wacker Chemie AG, “Electricity from the ocean waves”, accessed from http://www.wacker.com/cms/en/wacker_group/innovations/innovations_2014/strom_aus_der_meereswelle/meereswelle_1.jsp
17. S. Koh et al, “Dielectric Elastomer Generators: How much energy can be converted?”, IEEE/ASME Transactions on Mechatronics Vol. 16, No. 1, February (2011).
18. M. Fontana, “POLYWEC - General presentation of activities, Nov. 2015”, Private Communication, April 2016.
19. S. Rosset and H.R. Shea, “Flexible and stretchable electrodes for dielectric elastomer actuators”, Applied Physics A, Volume 110, Issue 2, pp 281-30 (2013).
20. Carpi, F, et al, “Standards for dielectric elastomer transducers”, Smart Materials and Structures, Vol. 24, No. 10 (2015).

6 SUMMARY OF FINDINGS

6.1 KEY MATERIALS AND PROCESS AREAS

Following detailed consideration, the 11 Technology Areas described in Section 5 were down-selected to 8, based on the Material Landscaping Study Team's assessment of the potential impact the technology solution could have on the wave energy sector, combined with the possibility of achieving this impact in a 3-year timeframe.

In some cases (3 out of 11), it was felt that enough progress could not be made in a 3-year timeframe to actually produce results that would benefit the WEC sector.

Table 6.1 lists the recommended areas, in each case proposing possible 3-Year project milestones.

HYBRID STRUCTURES INCORPORATING ROTATIONALLY MOULDED POLYMERS, FIBRE REINFORCED COMPOSITES AND / OR STEEL

Rotational moulding of polymers has many advantages over other manufacturing processes, in production of large, hollow, lightweight, corrosion-resistant and inexpensive marine floating structures. However, the mechanical properties of commonly-used polymers for rotational moulding are not high enough for consideration for heavily-loaded WEC structures with current technologies. The critical issue that needs to be addressed is the incorporation of fibre-reinforced composites or metals into the rotational moulding process.

WEC structures can also be re-designed to take advantage of reorientation of load paths through steel skeleton structures, leaving floating structures less heavily loaded. To further investigate the use of polymer and composite to steel hybrids, a detailed study is recommended into the feasibility of using high production rate joining techniques to transmit representative loads in a WEC application and a thorough risk assessment of utilizing these methods in the marine environment.

A reduction in CAPEX of 50% is potentially achievable if the fibre-reinforced rotational moulding technology is properly developed and used in hollow floating WEC structures. Some OPEX savings could also result from lower maintenance costs.

For hybrid composite-steel construction generally, CAPEX reductions of 10-20% can be expected. Composite panels are higher cost than steel, however composites have advantages of lower weight and less corrosion issues.

TENSILE STRUCTURES

An initial step into the use of tensile structures would be to perform an assessment that looks across the range of WEC concepts and identifies the feasibility of incorporating tensile structures into their designs. One output from this study should be an 'applicability factor'. i.e. what percentage of the existing concepts could benefit from these techniques. Another potential output is the development of a new and disruptive WEC concept.

Depending on the outcomes of the initial feasibility study it may be appropriate to progress to further design and costing studies of tensile systems for appropriate reference WEC technologies.

A reduction in CAPEX in the range of 10 to 30% is possible, depending on designs, if this novel technology is properly developed and used to tether and take off power from floating WEC structures. Some OPEX savings could also result from lower maintenance costs due to simpler PTOs.

STEELS AND WELDING IMPROVEMENTS

Two inter-related study areas are proposed. One addressing reduction in fabrication cost and the second investigating improvements to allowable fatigue stresses.

A comparative study should be conducted of the fabrication cost of typical WEC structures using conventional and advanced fabrication details.

The second study should evaluate the improvements that can be made to allowable fatigue stresses in typical WEC details through the implementation of a suite of enhancement methods. These may include, weld prep. geometry, reduced heat techniques, grinding / peening and high quality NDE techniques. Fatigue testing would be conducted to verify improvements.

The outcomes of these studies could be encapsulated in new WEC oriented design guidance, fabrication specifications and associated weld procedures.

A reduction in CAPEX in the range of 25-30% is possible if advanced welding techniques and steel fatigue design procedures appropriate to WECs are developed.

ELASTOMERS

Elastomers, or elastomer / fabric composites, have the potential to enable a radically different type of WEC structure compared to those that have been trialed at full scale to date. The basic materials technologies are mature, although their behaviour is complex and variants of existing compounds and composite make ups may be necessary to meet the specific requirements of WECs.

One practical measure that would be of benefit to the development community would be the compilation of a set of guidelines to assist designers in the early concept development stages. This should include a pragmatic rather than a strongly academic approach to fatigue design. Such guidelines would promote the uptake of elastomers by engineers and improve the quality of concepts and communication with the elastomer specialists whose expertise will be required as projects develop.

Elastomer / fabric composites enable radically different WEC structures with a step change in manufacturing CAPEX and logistics costs.

CONCRETE STRUCTURES

Design studies are recommended to examine how concrete technology can be applied to a selection of typical wave energy devices (both massive static structures and dynamic buoyant structures). The study should examine solutions such as ordinary reinforced concrete, post-tensioned concrete, different reinforcement materials, different concrete mix technology, etc. Different connection details should also be examined as part of this study. The design studies should lead to projects to design, construct, test, and demonstrate typical concrete wave devices.

FRP-reinforced concrete is likely to be beneficial for wave energy devices (due to the combination of corrosion-resistance and reduced concrete cover requirements), but its use will require testing to check the mechanical, durability and cyclic performance of FRP-reinforced structures for wave energy devices.

Concrete structures have low basic raw material costs and should show significant CAPEX savings, particularly where modular designs enable volume production of smaller units that do not attract onerous logistical costs.

ADHESIVE BONDING OF COMPOSITES

If composites are to be used with maximum benefit in WEC devices, it is necessary to establish a suitable joining technology. Adhesive bonding offers the best possibility. A project is recommended to establish the capability of adhesives to join composites to composites and composites to metals in a WEC device environment. Suitable materials could be selected based on the composites to be bonded and the device environmental conditions, temperature, humidity, stress/strain, fatigue, sunlight exposure/salt. The study should focus on the wet side (in direct contact with sea water), the dry side (within the sealed area of the device) and the splash zone (the breaking wave area).

A reduction in CAPEX in the range of 10 to 20% is possible if this technology is properly developed and used in WEC structures. Some OPEX savings could also result from lower maintenance costs.

ADHESIVE BONDING OF DRY STEELS

A project is recommended to quantify the benefits from the use of adhesives on steel/steel structural applications on the dry side of WEC devices, e.g. replacing welded dry-side stiffeners with bonded components. There is also a need to study the load resistance, fatigue and impact tolerance of these joints under WEC device conditions. Given that failure in WEC devices is linked to corrosion fatigue of welded joints, there is information available from automotive assembly to support the superior performance of weld- bonded joints over welded joints in fatigue testing. Use of the weld-bonding technique or other hybrid bonding techniques (rivet-bonding, bolt-bonding) could enhance the corrosion fatigue resistance of steel joints.

A reduction in CAPEX in the range of up to 10% is possible if this technology is properly developed and used on the dry side of WEC structures. Some OPEX savings could also result from lower maintenance costs.

ARTICULATION WITH LAMINATED ELASTOMERIC COMPOSITES

In order to develop the use of laminated elastomeric articulation solutions, reference WEC technologies should be selected to which they would be applied. Designs should be developed, in conjunction with industry experts that allow component life and cost comparisons of LECs versus conventional bearing solutions. A design and testing program should be developed based on an in depth risk review of the application. At the very least this would be anticipated to include thorough fatigue analysis and fatigue testing.

LECs offer the potential for a genuine step change in OPEX. Estimating the CAPEX costs of this technology is extremely difficult and will vary from device to device.

6.2 OTHER RECOMMENDATIONS

INDUSTRY BEST PRACTICE

Several of the subject areas discussed within the materials landscaping project fall into the category of low risk and low impact. Design information and/or subject matter specialist experts exist that could allow these technologies to be readily applied in the wave energy sector without further research and development. There is considerable benefit in ensuring awareness of these ‘industry best practices’ and in providing ready access to comprehensive and marine specific design information.

EDUCATION AND CONSULTANCY SERVICES

Most wave energy development companies are small organisations with a limited technical resource who are attempting to cover an exceptionally diverse range of subjects. The industry could benefit from good quality, industry-specific educational or consultancy resources, covering the range of relevant structural materials that would allow small companies to rapidly acquire sufficient knowledge to make well informed material choices in their designs.

Subject	Recommendations	Gaps	Project Milestones	Successful Outcomes
A. Rotationally Moulded Polymer and Composite Hybrids and H. Polymer and Composite - Steel Hybrids	Methods need to be developed for incorporation of pre-consolidated composites or steels into the rotomoulding process, or by post-moulding reinforcement using welding or tape-placement of composites. Assessment of joining techniques, metal to polymer and metal to composite, including adhesive bonding, rivetting, bolting and clinching	Techniques for reinforcement of rotationally-moulded polymer components, joining techniques for metals to polymers and metals to composites	**Year 1.** Demonstrate reinforcement and joining feasibililties. **Year 2.** Design and costing study of WEC concept using new technologies. **Year 3.** Manufacturing and tank testing of prototypes	Cost-effective way of manufacturing lightweight, heavily loaded floating structures. Hybrid design and costing techniques using steel, polymer and composites
C. Tensile Structures	Feasibility studies assessing the range of application across the WEC concept space. Potential identification of new disruptive WEC concept. Design and costing studies on reference WEC technologies with cargo-net manufacturer.	Case-specific application of cargo-net loading	**Year 1.** Design cargo net, flotation and PTO concepts. **Year 2.** Manufacturing and tank testing of prototypes. **Year 3.** Optimise and scale up device concepts	Cost-effective way of loading point absorber devices. New WEC concept.
I. Steels and Welding Improvements	Comparative fabrication cost study. Fatigue enhancement study. New WEC specific design guidance, fabrication specifications and welding procedures.	Quantification of cost savings available	**Year 1.** Study to quantify possible cost savings; procedure development and acceptance testing. **Year 2.** Revised fabrication and testing specification; Dissemination of study results and design guidelines.	>25% Cost savings for steel fabrication
J. Elastomers	Compile practical guidelines to promote uptake by designers in the early concept development phase.	Design database for elastomeric/fabric materials and joints in seawater	**Year 1.** Design guidelines for WEC developers. **Year 2.** Joining and fatigue studies and tests. **Year 3.** Development of novel elastomeric WEC concepts	Validated design methods for elastomers and fabric-reinforced elastomers in WEC devices. Novel elastomeric WEC concepts.
D. Concrete Structures	Investigate device-specific concrete designs leading to how new reinforcement materials (FRP) would be developed. Fatigue and durability issues in seawater, connection issues	Design and costing database for WEC devices in concrete	**Year 1.** Fatigue studies in seawater. Investigation of new reinforcements. **Year 2.** Study of connection issues. **Year 3.** Concrete design and costing guidelines for WEC developers	Durable concrete for WEC applications
B. Adhesive Bonding of Composites	Adhesive bonding of composites is well understood. No experience exists on WEC devices. A program should be carried out to establish the correct joint features to guarantee survivability in WEC devices, The program should examine joint performance in all three zones and under cyclic load and seawater exposure.	Design and costing database for adhesive bonds in composites, in seawater and in splash zone	**Year 1.** Fatigue and impact testing of adhesive joining solutions for immersed composites. **Year 2.** Fatigue testing of composite adhesive joints in splash zone. **Year 3.** Design and costing guidelines for WEC developers	Durable composite adhesive joints and validated design and costing techniques

E(i). Adhesive Bonding of Dry Steels	Steel to steel adhesive joints on the dry side of WECs should be possible since all required materials exist. Hybrid joints worth investigating.	Design and costing database for steel adhesive joints in WEC devices	**Year 1.** Redesign and manufacture WEC-like stiffened steel structure with bonded stiffeners. **Year 2.** Fatigue and impact testing of bonded design. **Year 3.** Design and costing guidelines for WEC developers	Durable steel adhesive joints and validated design and costing techniques
F. Articulation with Laminated Elastomeric Composites	Design and test of a reference WEC joint	Designs suitable for the operational range, degrees of freedom and fatigue loading of WECS	**Year 1.** Design of LEC joint for WEC devices. **Year 2.** Fatigue and immersion testing of LEC joints. **Year 3.** Design and costing guidelines for WEC developers	Zero-maintenance articulated joints
E(ii). Adhesive Bonding of Wet Steels	Uncertainty relating to survivability of steel to steel bonds in seawater will not be resolved in 3 years.	Design and costing database for steel-to-steel adhesive bonds in seawater	Not recommended at this time	Durable steel adhesive joints and validated design and costing techniques
G. Concrete – Steel Hybrids	Design of a steel / concrete hybrid structure resistant to buckling without fabricated stiffeners.	Design and costing database for hybrid steel/concrete structures	Not recommended at this time	Reduction of fabricated steel weight & overall cost
K. Dielectric Elastomers Generators	Long-term electromechanical fatigue and ageing of DEG materials in seawater needed. Better elastomer and conductive layer materials and manufacturing processes are needed, which are suitable for scaling up to full-scale devices	Design and costing database for DEG materials	Not recommended at this time	Ability to scale up DEG designs

Table 6.1. Ranking of Recommended Technology Areas

APPENDIX 1. INDUSTRY QUESTIONNAIRE

Introduction

The University of Edinburgh have been commissioned by Wave Energy Scotland (WES) to conduct a landscaping study investigating the materials, coatings and production processes available, or potentially available, for wave energy device structural design.

As part of that project, the University of Edinburgh team, intend to engage with technology developers to elucidate their priorities in terms of materials knowledge gaps, technology transfer and research and development activities.

Your assistance in participating in a telephone interview on this subject would be greatly appreciated. The questions that follow are provided as a guide and catalyst for that discussion.

Discussion Points

Q1. What materials technology have you used or have considered using in the principal structural component(s) of your WEC technology? What have been the drivers to those decisions?

Q2 What are the principal challenges that the materials employed in the structural components have to overcome?

Q3 What limitations do the materials, coatings and manufacturing processes that you have investigated present to the objective of achieving commercially viable wave power?

Q4 Do the materials technologies that you have investigated have any desirable or undesirable impacts on the performance of your technology?

Q5 Do the materials technologies that you have investigated have any desirable or undesirable impacts on the reliability or maintainability of your technology?

Q6 What concerns do you have that the materials technologies that you have investigated could affect device survivability?

Q7 Are there knowledge gaps with regards to existing materials within the industry that prevent them from being utilized to their full potential? For example are appropriate standards available and do they reflect the latest technology developments?

Q8 What materials technologies could be transferred from other industrial sectors that would improve the prospects for commercially viable wave power? What if any research and development activity is needed to allow these technologies to be utilised?

Q9 What are the highest priority materials problems that the industry needs to address in order to progress?

APPENDIX 2. ENVIRONMENTAL REQUIREMENTS

Introduction and Purpose

This document has been prepared as part of a materials 'landscaping' project, commissioned by Wave Energy Scotland (WES) and delivered by the University of Edinburgh (UoE). The purpose of this document is to provide a consistent and concise reference of typical environmental conditions to which WEC materials are exposed. It will be used in the assessment of the suitability of different materials technologies to the Wave Energy sector.

This document is not intended to be an exhaustive definition of all environmental requirements that may be applicable to a specific wave energy technology. Neither is the structural loading imposed by wind and waves included here; these subjects are discussed in a related document entitled "Typical Structural Loads".

Typical Environmental Requirements

Note: Most design codes do not give specific values for the environmental parameters that they cover. Rather, they direct the designer to establish values appropriate to the specific site or geographical region for which they are designing. E.g. Ref. 2 Section 1.3.1.4. Values given in the table below are engineering estimates that are expected to be suitable for a wide global geographical coverage, but they may not be an exhaustive definition of all extreme temperatures.

Requirement Title	Description	Reference
Seawater - min. temperature	The minimum seawater temperature to which the structure may be exposed shall be taken as -2 degrees Centigrade	Ref. 5 Fig. 1
Seawater - max. temperature	The maximum seawater temperature to which the structure may be exposed shall be taken as 34 degrees Centigrade	Ref. 5 Fig. 1
Seawater composition	The chemical composition of seawater shall be taken as being in accordance with the ASTM standard for artificial seawater. This has a salinity of approximately 35g/L	Ref. 4
Seawater - dissolved oxygen	The seawater in contact with the WEC structure is likely to be highly oxygenated due to surface mixing by the action of waves.	
Air – min. temperature	The minimum air temperature to which the structure may be exposed shall be taken as -20 degrees Centigrade	Estimated value
Air – max. temperature	The maximum air temperature to which the structure may be exposed shall be taken as +40 degrees Centigrade	Estimated value
Marine growth	Plant, animal and bacteria life causes marine growth on the structure. Marine growth is typically denser than water (s.g. 1.05-1.3) and increases the drag resistance of surfaces.	Ref. 3 Sec. 4.8.5
Sediments	Entrained sediments can produce sandblasting effects on the structure.	Ref. 3 Sec 4.8.6
Sunlight	Materials in the air and in shallow water will be exposed to the effects of ultraviolet radiation	

Icing	Floating structures may be subject to the build up of ice on exposed elements of the structure.	
Storage and transportation	During storage and transportation structures that are submerged in normal operation may be located on quaysides or transported on vessels where they will be subject to salt spray and UV effects.	

References

1 – “Guidelines for Design Basis of Marine Energy Conversion Systems” – EMEC 2009*

2 – DNV-RP-C205 – Environmental Conditions and Environmental Loads

3 – DNVGL-ST-0164 – Tidal Turbines

4 – ASTM D1141-98 - Standard Practice for the Preparation of Substitute Ocean Water

5 – Donlon et al – “The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system” (http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html)

APPENDIX 3. TYPICAL STRUCTURAL LOADS

Introduction and Purpose

This document has been prepared as part of a materials 'landscaping' project, commissioned by Wave Energy Scotland (WES) and delivered by the University of Edinburgh (UoE). The purpose of this document is to provide indicative loading scenarios that are likely to influence the material selection and design of Wave Energy Converter (WEC) structures. . It will be used in the assessment of the suitability of different materials technologies to the Wave Energy sector.

All WECs react to the wave climate in a unique manner and the driving load cases will vary from device to device and probably also from site to site. This document is not intended as an accurate definition of the loads on WEC structures, but rather as an indication of the most significant loading mechanisms and their orders of magnitude.

Typical Structural Loads

The load categorizations presented below follow the same philosophy as those presented in Ref. 3

Permanent loads

Permanent Mass

Load Description: Loads arising from the support or the acceleration of the mass of the permanent WEC structure and / or permanent ballast.

Typical Load Effect(s):

i. Bending moments on floating structures when they are out of the water. E.g. in the trough of a wave.

ii. Internal pressure on ballast tanks arising from device accelerations

iii. Concentrated lifting point loads and bending moments during device load out

Typical Magnitudes: 10-1000 tonnes. **Reference value**: 1000 Te/MW

Notes: e.g. Pelamis P2 (750kW) – 1300 Te. - Ref [5}

Hydrostatic forces

Load Description: Submerged devices or the submerged portion of floating devices are subject to loads arising from the differential between external and internal pressures

Typical Load Effect(s): Collapse of structures

Typical Magnitudes: 10m depth of water / 1 bar

Notes: e.g. Aquamarine Power Oyster installed in approx. 12m water depth – Ref [6]

Variable Functional Loads

Power Take Off (PTO) reaction (normal operation / fatigue)

Load Description: Many PTO systems consist of a primary actuated component such as a hydraulic cylinder, linear actuator or rotary generator that applies a force or torque to the primary structure. Frequently the force or torque is applied in a bi-directional manner; reversing direction every wave cycle.

Typical Load Effect(s): Point loading on the structure. Fatigue.

Typical Magnitudes: 200 Te / MW (400 Te / MW load range). 10^8 load cycles in 20 year life.

Notes on typical values:

Power = Force x velocity. In steady state conditions a linear velocity of 0.5 m/s is approximately equated to 200 Te/MW

10^8 load cycles in 20 year is equivalent to an average period of 6.3 seconds

Environmental Loads

The following sections can only attempt to indicate the order of magnitude of wave forces on WEC structures. For more information, refer, for example to Reference 2.

Hydrodynamic Loads (normal operation)

Load Description: In normal operating conditions waves impose hydrodynamic pressures onto the WEC structure that may be reacted by the PTO and / or result in acceleration of the structure and surrounding water mass. In many classes of WEC these forces are correlated with the PTO reaction. For example Oscillating Wave Surge Converters attract surge forces (as well as other load components) that cause the WEC to rotate and this rotation is reacted by the PTO.

Typical Load Effect(s): Distributed pressures on the outer skin of the WEC that must be transmitted to the PTO reaction point(s). Fatigue

Typical Magnitudes: 0.5 bar. 10^8 load cycles in 20 year life

Notes: based on the author's experience of research conducted at Aquamarine Power

Variable Hydrostatic Forces (normal operation)

Load Description: As waves pass over a submerged structure, or as a floating structure moves vertically relative to the sea surface, the hydrostatic load component will vary. Some WEC classes use this pressure differential to drive the PTO.

Typical Load Effect(s):

i. Force transmitted to the PTO.
ii. Variation in hydrostatic stresses leading to fatigue

Typical Magnitudes: 0.3 bar. 10^8 load cycles in 20 year life.

Notes: 0.3 bar is equivalent to a wave amplitude of 3m

Hydrodynamic Loads (wave slam)

Load Description: Waves breaking against or on top of a structure can cause wave slamming phenomena with very high transient forces and pressures.

Typical Load Effect(s): Very high, transient loads on localized areas of the structure

Typical Magnitudes: 10bar

Notes: based on the authors experience of research conducted at Aquamarine Power

Wind and current loads

Loads due to wind and currents are typically small in comparison to the wave forces and are not the predominant drivers to the design. Currents can however combine with wave motions to create a greater combined loading effect.

Other significant load effects

Other effects that can have a significant impact on design include:

- Snatch loads in moorings
- End stops within the PTO or articulating structural elements
- Capping or selective operation of the PTO reaction force.
- Increased drag arising from bio-fouling

Accidental

Collision with debris

Load Description: Collision with floating or semi submerged debris such as a tree or shipping container.
Typical Load Effect(s): Puncture of structural boundary. Local weakening

Combination Loads

The worst case structural loading on a WEC is typically some combination of the Permanent Loads, Variable Functional Loads and Environmental Loads described above. Combination loads are beyond the scope of this brief summary.

References

1 – Guidelines for Design Basis of Marine Energy Conversion Systems – EMEC 2009*

2 – DNV-RP-C205 – Environmental Conditions and Environmental Loads

3 – DNVGL-ST-0164 – Tidal Turbines

4 – API-RP-2A – Planning, Designing and Constructing Fixed Offshore Platforms

5 - Yemm et al 2011 - Philosophical Transactions of the Royal Society – “Pelamis: experience from concept to connection” (http://rsta.royalsocietypublishing.org/content/roypta/370/1959/365.full.pdf)

6 - Cameron et al 2010- “Design of the Next Generation of Oyster Wave Energy Converter” (http://pure.qub.ac.uk/portal/en/publications/design-of-the-next-generation-of-the-oyster-wave-energy-converter(44e9cbde-84c9-4a8b-b190-1854284b9772).html)

* It is intended that these guidelines will be replaced by IEC62600-2 which is currently in DRAFT format.

APPENDIX 4. HIGH LEVEL TECHNOLOGY SUMMARIES

CONSTRUCTION COST

1.1 Steel

Potential Solution

1. Automated Welding

Automation of welding leads to substantial savings in the cost of fabrication. The use of semi-automatic processes substantially improves production rates and reduces costs by up to 60%. Tubular welded joints are difficult to automate, whereas beam and plate welds are easier to automate. A detailed review of the weldability of the structures proposed could offer substantial savings. This could be carried out by experts and in conjunction with fabricators.

Ref: Discussion with fabricators Averon Engineering, Fabrication Spec EEMUA 158

2. Design for Fabrication

Technical review of all connections within the structure to minimise use of full penetration welds and to introduce loading in shear, where fillet welds are suitable, could substantially reduce costs. Similarly, standard size welds which match consumable sizes could make the majority of welds single rather than multi-pass solutions. The approach has to be more automated rather than one-off with use of a mix of welded fabrication, steel and iron castings considered from outset. It was clear from the interviews that previous fabrication experience was not common amongst WEC personnel.

Ref: Discussion with fabricators, WEC Materials landscape interviews

3. Adhesive Bonding

Adhesive bonding offers many advantages over traditional mechanical assembly or weld joining, e.g. even distribution of stress, avoidance of weld related stress and corrosion , ease of assembly – particularly for closed sections and ability to join dissimilar materials without risk of galvanic corrosion. Issues remain concerning the durability of adhesive bonds in areas in direct contact with seawater. Adhesives will absorb water in humid environments leading to a change in properties and it is essential to quantify the changes so as to design durable structures. Adhesive use for metal bonding in WEC devices will be limited to areas which are not in direct contact with seawater. Nevertheless adhesives would bring considerable benefits in design and ease of fabrication with potential to reduce overall costs.

Ref: M Bordes et. al., "Prediction of long term strength of adhesively bonded steel/epoxy joints in sea water", International Journal of Adhesion and Adhesives, 2009, Vol 29, pg 595 – 608.

4. Rivetting / Spot Welding

Spot welding (most commonly resistance spot welding) and the similar process of projection welding are extensively used in the automotive industry for the rapid and automated joining of sheet metal parts. Perhaps because of the field in which it has been developed (automotive) the technology available is restricted to joining thin plates of up to about 3mm thickness.

Riveting remains in use in the aerospace sector which can, at least in part, be attributed to the difficulty of welding high strength grades of aluminium as well as compatibility with part composite construction. They can be used in combination with adhesives to resist peel forces.

Both techniques may have some limited application in WEC technology in lightly loaded situations.

Refs: Spot Welding in Science & Technology of Welding & Joining – June 2008
http://www.assemblymag.com/articles/90348-aerospace-fastening-in-the-21st-century

http://www.robot-welding.com/spot_welding.htm
5. Ductile Iron
Spheroidal Graphite Iron offers opportunity for cost reduction for repeated details. Detailing would be different than a fabricated section and connection would have to be through load pin or bolted details. SGI has a lower casting temperature than steel, allowing more complex shapes, superior surface finish and lower casting cost. Potential research to develop some criteria for fatigue assessment would be a useful addition for the industry.
Ref: Discussion with MJ Allen Castings/BS EN 1563
6. Steel Casting
Weldable steel castings are widely available and can be incorporated into larger fabricated structures. They enable the use of complex geometries with reduced stress concentration factors. In fatigue sensitive structures they allow the use of better S-N curves, by moving fatigue critical weld details out of the most highly stressed areas
Refs: DNVGL-OS-B101 & DNVGL-RP-0005 Section 2.4.7
7. High Strength Steel
High strength steel in the oil & gas sector is mainly used for mechanical connectors used to connect pipe sections together offshore. More general use in a marine environment is restricted by increased welding and potential hydrogen embrittlement issues. For WEC devices dimensioned primarily by fatigue, the application of high strength steel appears limited.
Ref: Experience of component design in Offshore O&G
8. Low Spec. Steel
Potential use for ballast to enable use of gravity based rather than piled and grouted solutions, current rates for scrap mooring chain are as low as £250/tonne and steel at £30/tonne. Given the current steel price of £700/tonne, it is difficult to see where low spec. steel fits in the picture other than for ballast.
Ref: Discussion with industry and users
9. New Welding Methods
The science and application of welding technology is continuously developing and new welding techniques can potentially reduce fabrication time and cost whilst improving fatigue performance. The status of technologies such as Friction Stir Welding, Electron Beam Welding and Laser Welding should be reviewed. Friction stir welding is heavily promoted for joining of large panels used in ship-building but is only possible in aluminium, and not possible in steel due to high temperatures to get to melting point. Electron Beam Welding – Used particularly in the aerospace industry for welding of turbine blades, also pressure vessels provides a very low heat input and hence a narrow HAZ. Laser Welding is not mainstream and not likely to be of interest.
Refs: Welding Institute various publications P. F. Mendez - Synthesis and generalisation of welding fundamentals to design new welding technologies: status, challenges and a promising approach

CONSTRUCTION COST

1.2 Concrete

Potential Solution

10. Post-Tensioned Concrete

Post-tensioning concrete potentially has substantial benefits for marine structures, including improved durability, improved fatigue resistance, and the potential for slimmer section sizes (useful in weight critical applications). Although there is a cost penalty compared to reinforced concrete, it is widely used in bridges, increasingly used in buildings (in combination with increased concrete grades), as well as in offshore structures. There is certainly potential to use post-tensioned concrete with wave energy devices, but a need to examine generic details such as anchorage details.

Ref: Concrete Society TR72 (2001) "Durable post-tensioned concrete structures", The Concrete Society, Camberley, UK, www.concrete.org.uk

11. Concrete - Durable Connections

Wave energy devices will need things to be bolted to them, or access ports within them. For example, pad connections can be made in reinforced concrete in which bolts are set in the concrete, and adhesively bonded connections are used in some civil engineering applications. The connections, however, are a particular concern for durability and water-tightness, particularly because the proportion of imposed cyclic load to permanent load is greater than in typical civil engineering applications of concrete. Establishing good generic connection details will be common to all wave energy devices.

Ref(s):

12. Concrete Reinforcement Materials

Stainless steel reinforcement is widely available, but more expensive than normal carbon steel reinforcement. FRP (typically glass FRP, sometimes boron FRP, occasionally carbon FRP in prestress applications) is also now widely available, and is already in use in marine applications. Both stainless steel and FRP reinforcement offer potentially improved durability to normal carbon steel reinforcement, with knock-on benefits in terms of using less concrete cover and hence less mass. FRP reinforcement can have particular benefits through being electromagnetically transparent. These alternative reinforcement materials have substantial potential benefits, but it is not currently obvious whether all of them are suitable (particular in terms of economics) for wave energy devices.

Ref(s): Concrete Society TR 51 (1998) "Guidance on the use of stainless steel reinforcement"

fib (2007), Bulletin no.40 "FRP reinforcement in RC structures", FIB (Fédération internationale du béton), Switzerland.

13. Low Cost Concrete

Where weight is not critical, normal reinforced concrete could be used to form massive components (e.g. anchorage blocks). This is low-technology, and well established, although detailing is important to ensure durability.

Ref(s):

14. High Performance Concrete

How can wave energy devices exploit concrete materials? From a durability perspective, the correct concrete mix (plasticiser, cement content, etc) and correct detailing is vital, but this practice is well established for marine structures. Several modern concrete technologies could potentially be exploited, such as synthetic fibre reinforcement (which provides impact resistance, and potential durability benefits through the prevention of shrinkage cracks). Very high strength concretes (e.g. 100MPa concrete mixes), and ultrahigh performance concrete (with ductility and strength benefits) could allow very thin concrete sections to be used especially when used with carbon fibre prestress, but are these economic? Can foamed concrete or lightweight concrete be used to reduce mass (possibly only in selected parts of the construction)?

Ref(s):

15. Sustainable Concretes

The concrete industry produces around 5% of worldwide man-made CO2 emissions, which is potentially in conflict with the advantages of wave energy devices. Whilst GGBS and PFA cement replacements can be used to reduce the use of ordinary portland cements, GGBS and PFA are increasingly difficult to source due to the closure of coal-fired power stations and the steel industry; another potential contradiction with wave energy devices. Geopolymer concrete replacements are an emerging technology, but come with challenges of their own. It is likely that the sustainable use of concrete for wave energy devices should instead focus on ensuring durable structures with long service lives, ensuring repairability (and potentially adapted for new devices in the future), and minimising the volume of concrete used (e.g. using post-tensioning) to minimise carbon footprint. However, such a study must be balanced against the benefits of the wave energy device.

Ref: MPA, The Concrete Centre (2014) "Concrete industry sustainability performance report - 7th report: 2013 performance data"

16. Repairability of Concrete Devices

Can concrete wave energy devices be effectively repaired, or will they be written-off by damage (such as broken connections, impact damage, corrosion or spalling of the concrete)? Which concrete repair methods can be used to marine structures (surface protection systems, repair mortars, structural bonding, reinforcement protection, cathodic protection, mechanical anchorages...)

Ref: Concrete Society TR69 (2009) “Repair of concrete structures with reference to BS EN 1504"

Concrete Society TR55 (2013) “Design guidance for strengthening concrete structures using fibre composite structures"

17. Novel Concrete Production Techniques

There are a wealth of concrete production methods in use, which tie in with the materials that are used. Formwork solutions such as inflatable forms, or fabric formwork allow complex 3D shapes to be developed. Permanent formwork (e.g. FRP sections) that is left in place after casting can act compositely and efficiently, as well as bringing durability benefits. Slip forming, spun concrete, and precast fabrication could all potentially be beneficial. The benefits of many of these methods will depend upon the scale of production, so whilst they might not be viable initially, they will become increasingly economic with a greater number of units being produced, and are likely to become increasingly economic as the size of the units increase. Such a study should also examine potential the requirements for construction sites.

Ref(s):

CONSTRUCTION COST

1.3 Composites

Potential Solution

18. Pultrusion

The pultrusion process for production of continuous shapes in fibre-reinforced polymers is the most cost-effective means of producing composite structures with high percentages of axial fibres. Profiles such as planks, tubes and beams can be produced in epoxy, polyester and vinyl ester matrices with glass, carbon and other fibres such as basalt. The downside of the process is that the shapes made are prismatic, i.e. cannot vary in dimensions along the length, and that pultrusions are limited in section to approx. 1.0m width, or equivalent box or tubular section. Pultrusions are a potentially low-cost alternative to structural steel for WECs that can benefit from lighter structural mass, however there are important technical challenges to be overcome in joining, particularly in mechanical fastening and adhesive bonding.

Ref(s): http://www.exelcomposites.com/en-us/english/composites/manufacturingtechnologies/pultrusion.aspx

19. Filament winding

Filament winding is a mature method of production of large fibre-reinforced composite structures such as tanks, pressure-vessels and pipes. Continuous glass or other fibres can be wound around at a winding angle, or tape-laid along the axis of a rotating mandrel to form a relatively low-cost composite structure. Mandrels can be collapsible, or can be left in situ, depending on the application. Challenges for WECs include the application of point loads into the structure through mooring and other connection loads and the design of hatches and access points etc.

Ref(s): http://www.netcomposites.com/guide-tools/guide/manufacturing/filament-winding/

20. Thermoset Resin Infusion

Infusion of thermoset resins such as epoxy, polyester and vinylester is being used for large composite structures such as wind turbine blade, yachts, marine masts and bridge structures. Large structures (up to 80m in length in the case of wind turbine blade halves) are infused using a heated tool on one side, and a vacuum bag on the other, a process known as Vacuum Assisted Resin Transfer Moulding (VARTM) and a host of other related processes and acronyms. Large-scale resin infusion technology is mature, but developments in new one-shot processing techniques are being developed to reduce cost and avoid using adhesive bonding to join large structures, such as wind and tidal turbine blades..

Refs: "Wind turbine blade production – new products keep pace as scale increases", Reinforced Plastics January/February 2012

T. Flanagan et. al. "Smart Affordable Composite Blades for Tidal Energy", Proceedings of EWTEC 2015 – 11th European Wave and Tidal Energy Conference, Nantes, France, September 2015.

21. Adhesive Bonding

Fatigue of adhesive joints will be a critical factor in the selection of materials for construction of WEC devices especially in designs combining metals and composites or polymers. Though there are concerns about the seawater resistance of adhesively bonded metals, because of the possibility of interfacial failures, there is less concern about joints to polymers or composites. In the case of these assemblies the integrity of the joint under repeated fatigue loads, when exposed to seawater or splash zone environment, will be a critical factor. Information is available on the performance of composite adhesive joints under cyclic loading, but very little is available about cyclic loading of composite/composite or composite/metal joints exposed to seawater.

Refs: A Bernasconi et. al., "Local stress analysis of the Fatigue Behavior of Adhesively Bonded Thick Composite Laminates", The Journal of Adhesion , 2010, 86, pp. 480- 500 http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/K026925/1

22. Mechanical Joints

For thermoset matrix composites, only adhesive bonding and mechanical fastening can be utilized. Inherently, adhesive bonding is preferable to mechanical fastening because of the continuous connection, whereas in drilling holes for bolts or rivets, fibre or other reinforcements are cut, and large stress concentrations occur at each discrete fastener hole. However, in many structures, such as in the aerospace industry, it is necessary to employ mechanical fasteners in order to remove components or to have access to the interior of the structure. Challenges still remain in understanding long-term behaviour of composite bolted joints when immersed in seawater, however.

Refs: "Composite Materials Handbook-MIL 17: Materials Usage, Design", Volume 3, US Dept. of Defense
Thoppul et. al., "Mechanics of mechanically fastened joints in polymer-matrix composite structures - A review", Composites Science and Technology 69(3-4):301-329

23. Composite Repairs

Composites are used in a wide range of applications in aerospace, marine, automotive, surface transport and sports equipment markets. Damage to composite components is not always visible to the naked eye and the extent of damage is best determined for structural components by suitable Non Destructive Test (NDT) methods. Repairs vary from cosmetic, to small repairs, to serious structural repairs, involving fibre breakage and delaminations. Challenges for repair of composites in ocean energy include the development of underwater composites repair strategies.

Refs: https://www.sme.org/uploadedFiles/Events/Webinars/dorworth_presentation.pdf
J. Graham-Jones and J. Summerscales (Eds), "Marine Applications of Advanced Fibre-Reinforced Composites", Woodhead Publishing, 2016.

24. Thermoplastic Monomer Infusion

Thermoplastic composites are generally less susceptible to seawater ingress than thermoset composites, and can possess advantageous properties in terms of improved toughness, damage and fatigue resistance. Despite these advantages, thermoplastic composites (TPCs) are not widely used for structural applications due to their high melt temperatures, melt viscosities (which require expensive tooling and production costs) and hence poor fibre infiltration. Certain TPCs can now be produced from a precursor in-situ mainly Nylon-6, Nylon-12 and cyclic PBT matrices. As monomer precursors have a much lower melt viscosity and melt temperature, reactive processing allows for much better infiltration of fibres and requires less energy to process. Nylon-6 precursors are the most developed systems but are hygroscopic, absorbing up to 5% weight when immersed in water, adversely affecting mechanical properties. Thermoplastic monomer infusion for composite wave energy structures is challenged by the absence of a commercially-available material system that has low water absorption properties.

Ref(s): K. van Rijswijk, "Thermoplastic Composite Wind Turbine Blades," Aerospace Engineering, Delft University of Technology, 2007
G. Marsh, "Could thermoplastics be the answer for utility-scale wind turbine blades?," *Reinfroced Plastics,* vol. 54, no. 1, pp. 31-35, 2010.

25. Polymer/Composite Hybrids

The production of large, cost-effective hollow polymer structures for marine applications is available using the rotational moulding process. Floats, buoys and tanks for marine applications can be rotationally moulded at very large sizes, as the process does not involve pressure, but rather is a form of internal coating process of light-walled heated metal tooling. Materials such as polyethylene and polypropylene are inexpensive, can be readily rotomoulded and perform well in the marine environment, but do not have the necessary mechanical properties (stiffness, strength, creep and fatigue resistance) to resist the large loads involved in WECs. The challenge for the use of large polymer structures in wave energy would be the development of localised, hybrid polymer/composite reinforcement around loading points, while maintaining the cost-effectiveness of the rotomoulding process.

Refs: http://www.rotationalmoulding.com/products/boats
http://www.floatex.com/aquaculture/polyethylene-stanchions-for-acquaculture-cages.html
http://www.jfcmarine.com/marine-aids-navigation/

CONSTRUCTION COST

1.4 Modular Build

Potential Solution

26. Modular Building

Methods of modular construction of WECs, perhaps using steel, concrete or lightweight polymers and composites could greatly reduce the installation and logistics costs of large-scale WECs. Ideally, structural sections would be transported globally in shipping containers and then assembled near to the wave farm site.

Ref:

CONSTRUCTION COST

1.5 Fatigue

Potential Solution

27. Improved S-N Curves for Steel

Based on proposed R&D JIP this suggestion is that modern fabrication processes and improvements in quality of consumables and equipment could yield better fatigue curves than those in current use which were based substantially on test data from 1980-90s. There is also the possibility of a joint-specific SN curve allowing designer to work above currently allowed stress ranges. Also the inclusion of weld improvements such as grinding and hammer peening are seen as having substantial benefits but which are not allowably claimed within design codes. Included within this scope should be a discussion related to the safety factors (DFF) currently used i.e. 3 for fatigue and whether this is realistic for an unmanned non-polluting system.

Ref: OCAS presentation on improved fatigue life of welded joints, DNV OS F101/105 and DNVGL-RP-0005

28. Optimised Welding Techniques (incl. prep)

J-Prep full penetration welds used on SCRs could reduce costs through lower weld volumes improved techniques (e.g. PGMAW process) to produce higher quality welds with lower flaw likelihood and better HAZ properties while using lower heat inputs. This could be done in conjunction with testing proposed in 27 to verify the improvements.

Refs: Previous project experience on FLAGS Hot Tap welding and BP Thunder Horse SCRs fabrication and welding procedures

29. Composites

The long-term fatigue performance of glass, carbon and other fibre-reinforced polymeric composites is poorly understood, with variables such as fibre-matrix interface bonding, matrix plasticisation due to water absorption, and the effect of mean and compressive loading, as well as several bars of water pressure on composite fatigue curves being still under investigation. Tidal energy blade design using immersed composite fatigue curves has shown important effects on blade design life, and WEC composite structural design will probably show similar effects.

Refs: C.R. Kennedy, **“**Fatigue of Glass Fibre Composites in Marine Renewable Energy”, PhD Dissertation, National University of Ireland, Galway 2013.

P. Davies and Y. Rajapakse (Eds), “Durability of Composites in a Marine Environment”, Springer Publishers, Solid Mechanics and its Applications, Vol. 208, 2014.

30. Polymers and Elastomers

Polymers are widely used in marine environments due to their excellent properties and good weathering resistance. Despite this extensive use, their long term behaviour in such an aggressive environment is still not well known. Accelerated ageing tests are carried out and many polymers and elastomers exhibit increases in stiffness and strength reductions due to changes in the polymer structure. Specifically-developed thermoplastic elastomers for marine applications have excellent resistance to fatigue. However, many elastomers have been characterised in compressive fatigue rather than tensile, and the fatigue properties of elastomeric membranes is not well known.

Refs: http://www.dupont.com/products-and-services/plastics-polymers-resins/thermoplastics/brands/hytrel-thermoplastic-elastomer.html

P.Y. Legac et al., “Ageing mechanism and mechanical degradation behaviour of polychloroprene rubber in a marine environment: Comparison of accelerated ageing and long term exposure”, Polymer Degradation and Stability, Volume 97, Issue 3, March 2012, Pages 288-296

31. Composite Adhesive Joints

See 1.3 (21) above.

Ref(s):

CONSTRUCTION COST

1.6 Submersible Buoyancy

Potential Solution

32. Cargo-Net Loading

The principle here is that rather than have a defined load attachment point, which in low strength materials or composites is difficult and a stress hot spot, that the buoyancy unit is encapsulated in a net with a bridle that could provide a more distributed load to the units, similar to the loading on balloon systems. This applicability is also system dependent but could offer a substantial low cost solution to the attachment of buoyancy units to systems.

Ref: WES brainstorming session

33. Rotational Moulding of Plastics plus Reinforcements

See 1.3 (25) above

Ref: WES brainstorming session

34. Foam sandwich construction

Polyurethane syntactic foams are a convenient source of buoyancy materials for marine applications. Foam filling (sandwiching a foam between two layers of polymer skin) has a broad range of applications where it is used to add buoyancy and strength to assemblies and prevent corrosion by filling void space. There will certainly be a role for foam filling technology in the construction of WEC devices especially when combined with other construction methods e.g. sandwich structures.

Ref: WES brainstorming session

CONSTRUCTION COST
1.7 Load Shedding
Potential Solution
35. Elastomers
The strain range of elastomers is very high (several 100%) making them suitable for structures that substantially change shape under extreme loads. This property could be used to design devices that passively change their hydrodynamics (load shed) in storm conditions, but are stiff enough to capture the energy under normal operating conditions
Ref(s):
36. Shape Memory Alloys
New shape memory polymers have been developed which can be deformed to high strain at room temperature. This deformation introduces crystallization of the polymer, locking in the new shape, but on gently heating the strain is released and the original shape recovered. These types of polymers could probably be used as load shedding devices which would permit deformation of elements of the WEC device under severe load but allow it to recover by application of mild heating e.g. from resistive heating . This is a new technology and it is unlikely that it will be available commercially for some time.
Ref: Y. Meng et. Al. "Body Temperature Triggered Shape Memory Polymers with High Elastic Energy Storage Capacity", Journal of Polymer Science –Polymer Physics, 2016, published on line March 2016.

ARTICULATION SYSTEMS
2.1 Articulation
Potential Solution
37. Verification of the wear characteristics of polymer plain bearings
Solid polymer bearings based on self-lubricating plastics or composite materials are the preferred choice for many WEC articulation systems because of their low wear and corrosion resistance whilst maintaining fairly high load carrying capacity. A wide range of proprietary materials exist, but an up to date independent review and assessment of their technical characteristics (particularly wear rates in representative environments) is not known to exist. Without this verified information, WEC designers struggle to make informed decisions on bearing selection and critically are unable to accurately predict the bearing maintenance requirements.
Ref(s): J.K. Lancaster; dry bearings: a survey of materials and factors affecting their performance. Journal of Tribology Dec. 1973
38. Cost effective methods of applying counter-face materials to plain bearing shafts
The counter-face to a polymer plain bearing must be of appropriate smoothness and hardness and be corrosion resistant. These properties can be provided by higher grade corrosion resistant alloys (CRAs), but these are not affordable when applied to large, heavily loaded bearings. More cost effective solutions such as welded overlays (cladding) or heat shrunk sleeves are required.
Ref(s): http://www.twi-global.com/capabilities/materials-and-corrosion-management/surface-engineering-and-advanced-coatings/cladding/

39. Composite hinge shafts

An alternative to the use of corrosion resistant alloys in hinge shafts is to replace the metal shaft with high strength composites or to cover a plain steel shaft with a composite sleeve. This practice is not common in other industries and the technical constraints to implementing such a solution are not known (by the landscaping team).

Ref(s): http://www.avanco.de/products/drive-shafts/ship-propeller-shafts.html

40. Laminated Elastomers (LECs)

Laminated elastomeric components similar to those used in bridge bearings comprise bonded layers of steel and rubber. Because of the incompressible nature of rubber, they exhibit very high compressive load capability, but allow large displacements in shear and they can be configured to allow articulation or translation over a limited range. They have the potential in some applications to eliminate sliding surfaces and the consequent maintenance requirement

Ref(s): Chaumieau and Cordero; Innovative elastomeric components applicable to current and future ocean energy development ICOE 2010

41. Composite or Engineered Polymer Springs

For limited articulation ranges it may be feasible to use flexible composite components or engineered polymers to provide an adequate range of motion. These could benefit from a base material with adequate strength and good fatigue properties that is not affected by corrosion. Heavily loaded flexing GRP elements are used for example in leaf springs for trucks.

Ref(s): http://www.ifc-composite.com/index.php?id=9
http://www.technologyfromideas.com/go/technologies_for_sale/wave_protector

42. Rolling Element Bearings

Rolling element bearings have generally not been preferred in WEC applications because classic hydrodynamic lubrication theory would suggest that in reciprocating systems they will suffer from issues such as false brinelling. However, whilst in high speed machines, small defects in a bearing rapidly lead to un-acceptable dynamic behaviour, this is less of a concern in slow moving wave energy converters. At least one WEC developer has experienced a longer operating life and more predictable wear from the use of rolling element bearings as opposed to plain bearings.

Ref:
http://www.schaeffler.de/content.schaeffler.de/en/products_services/inafagproducts/rotativ_products/spherical_roller_bearings/spherical_roller_bearings.jsp

ENVIRONMENT

3.1 Corrosion Protection; 3.5 Transported Sediments

Potential Solution

43. Cathodic protection / IC Systems

All WEC devices fabricated from steel will be subject to marine corrosion unless protected. In submerged areas, cathodic protection is one effective prevention strategy. The technology relating to cathodic protection is mature, well understood and relevant guidelines are available. To date, there have not been any examples of Impressed Current systems used in WEC devices, though use is now increasing in Wind

turbine towers, particularly for internal corrosion protection. Additional research in this area is not necessary.
Ref: Recommended Practice DNV – RP-B401 Cathodic Protection design
44. Coatings
Only a limited number of WEC devices have been deployed and experience on site is typically of short duration. Devices fabricated from steel or other metals must be protected from corrosion by suitable coatings and systems which are matched to the severity of effects in the submerged and splash zones. These problems have already been faced with offshore wind turbine towers. Suitable products are available from all suppliers and guidelines and standards are in place, which are now backed up by experience. No additional work is required in this area.
Ref(s): K. Muhlberg "Corrosion Protection of Offshore Wind Turbines", Journal of Protective Coatings and Linings , 2010 , March , pp 20 – 32
45. CP Design Tools
Recently some very attractive simulation tools have become available for assessing the risk of corrosion and the effectiveness of surface protection systems (Beasy Corrosion Manager, Elsyca CORROSIONMASTER software). These tools would be very beneficial in the design of WEC devices, particularly where different materials are combined. In some versions, direct import of CAD models is possible from component level to full assembly and the software identifies corrosion hotspots and predicts corrosion rates. Availability of this capability to WEC device designers would be beneficial. These systems are now commercial, so no additional technology development is required.
Ref(s): R.A Adey et al. "Computer simulation as an Aid to Corrosion Control and Reduction", Paper 0001660 presented at CORROSION 2012, March 11-15 - Salt Lake City, Utah, USA.
46. Emerging Corrosion Protection Techniques
Corrosion protection is a very active area of research and there are many technologies being developed to address limitations in the area. Improvements in the performance of current coating systems are being addressed by the addition of fibers to provide better fatigue resistance. For cost reduction, two coat systems are under investigation based on silyl hybrid or polyaspartic technology. Work is also ongoing on anti-corrosion additives and self-healing polymer systems which provide protection to the metal in the event of coating damage. Systems with carbon nanotube additives or zinc activators are under test which have the potential to increase survivability of coating. The current material suppliers are aware of these technology developments and will be willing to introduce them into products if the promised performance is achieved. It would be useful to maintain a monitoring activity on developments in the coating area and ensure that up to date information is available on best technology for new WEC device designs.
Ref(s): A. Mukherjee, "Innovation in Anti –Corrosion Technologies for Offshore Structures", Tech Vision Report, Frost and Sullivan, Published Dec 2015.
47. Erosion Protection Coatings for Composites
Erosion of composite tidal turbine blades has been recently observed, and is thought to be caused by a combination of sediment and cavitation erosion. The understanding is very preliminary, but WECs are also likely to be affected. Marine and river applications of polymeric composites are often protected from this type of erosion by the inclusion of super-tough polymer coatings such as UHMWPE. This area will have to be further investigated and understood if polymer composites are to last 20 years + in WECs.
Refs: Sharifi et al. "Tribological challenges of scaling up tidal turbine blades", 11th European Wave and Tidal Energy Conference (EWTEC2015), Nantes, France. http://www.compositesworld.com/articles/composites-upgrade-marine-infrastructure

ENVIRONMENT
Biofouling, Effects on 3.2 Performance; 3.3 Loads; 3.4 Reliability & Maintainability
Potential Solution
48. Biocidic Release Coatings
Biofouling is a major concern for maritime transport because of the resulting effect on operational costs, this is the main driver for coating development. WEC devices are also subject to fouling, but unlike ships, they are fixed at anchor. Conventional biocide releasing coatings rely on the movement of the vessel to provide a self-polishing action and thus release biocide continuously. These coatings eventually become depleted and must be renewed in dry dock. Since WEC devices are fixed, biocide releasing coatings may not be ideal because of their potential to create environmental damage in the location and because the need to renew the coating will require removal of the device to shore for cleaning. A more detailed study should be carried out to identify the ideal antifouling coating for use on WECs.
Ref(s): C. Hellio et al (eds) “Advances in Marine Antifouling Coatings and Technologies”. Woodhead Publishing, CRC Press, 2009.
49. Foul Release Coatings
Foul release coatings rely on the fact that their ultra-smooth surface and low adhesion prevents fouling settling and in the event that fouling does settle, it is easily dislodged by the applied shear e.g. from moving seawater during sailing. This type of coating is free from biocide and this could be an advantage over biocide releasing coatings for WEC devices. However it is not proven that this technology is effective over the long term on WECs, particularly since the water velocity may not be sufficient to dislodge foul. A more detailed study should be carried out to identify the ideal antifouling coating for use on WECs.
Ref(s): International Paint Intersleek brochure. http://www.international-marine.com/literature/brochure%20-%20intersleekbrochure.pdf
50. Ecospeed
Ecospeed is a patented system of underwater hull protection which combines a glass platelet filled vinyl ester resin based coating and regular in-water cleaning to keep a ship hull operating at maximum performance. The coating is applied once and lasts for the lifetime of a vessel. No additional coating of the bare metal is needed. The coating is hard wearing and with regular in-water cleaning to remove foul it becomes smooth, increasing the resistance to foul deposition. The coating is completely non-toxic and is not harmful to the environment in any way. This material should certainly be investigated as a potential corrosion protection/ foul resistant coating for WEC devices.
Ref(s): Hydrex’s Ecospeed provides fouling control on underwater ship hulls. Subsea World News, Dec 23 2011.
51. Ultrasonic Cleaning (UT)
There is some evidence concerning the beneficial effects of ultrasound as a deterrence for foul-settling and systems are available for attachment to pleasure vessels to reduce fouling at moorings. A recent review concludes that the technology is still at an early stage and there is no certainty of its efficacy. The area should be kept under review, especially given the possible effects of ultrasonic emissions on marine life in the vicinity of the WEC device.
Ref(s): M. Legg et al. “Acoustic methods for biofouling control – A review” Ocean Engineering , July , 2015
52. Mechanical Cleaning
Given the inevitability of fouling and the limited effective lifetime of the available antifouling coatings, a number of in-water mechanical cleaning systems have been designed for foul removal. Systems utilize ROV equipped with brushes, hydraulically powered units which can capture the effluent and treat it or

thermal shock treatment utilizing hot water. In the case of hull cleaning, capture of effluent to avoid the risk of spreading invasive species is a key requirement. This could be abandoned in the case of WEC device cleaning because of their fixed location. These technologies should be considered as part of a program to identify the best biofouling system for use on WEC devices.

Ref(s): P. Hagan e al. "Status of Vessel Biofouling Regulations and Compliance Technologies – 2014" MERC Economic Discussion Paper 14-HF-01, November 18th, 2014.

ENVIRONMENT

3.6 UV Degradation

Potential Solution

53. Polyurethane Top Coats

Marine coating systems generally consist of three layers, a primer for the metal surface, a thick epoxy layer to provide adhesion and water resistance and a polyurethane top coat, to provide weathering resistance. Polyurethanes are characterised by excellent gloss retention and abrasion resistance. They are more chemically stable than epoxy systems when exposed to sunlight. A wide range of coating formulations are available from suppliers, many of them specially designed for long term exposure in a marine environment. No additional work would be required in this area.

Ref: http://www.pcimag.com/articles/88254-2-component-polyurethane-topcoats

54. Elastomer & Polymer Formulations

Polymers and elastomers are normally stabilised against environmental degradation, however the marine environment introduces additional issues. A considerable body of information is available on the degradation of polymers in marine environment and there is long term experience with several polymer types in the offshore oil and gas exploration industry. It is important that any polymer for use on a WEC device is fully evaluated and adequate stabilisation regimes to guarantee the required lifetime. This is a topic best left in the hands of an experienced material supplier. No additional work is needed in this area.

Refs: Pathways for degradation of plastic polymers floating in the marine environment, Matthew MacLeod et al , Environ. Sci. Processes. Impacts , 2015, 17,1513
Aging mechanism and mechanical degradation behaviour of polychloroprene rubber in a marine environment : Comparison of accelerated aging and long term exposure , P.Y Le Gac et al , Polymer Degradation and Stability , 2012, Vol 97, pp. 288 – 296

PERFORMANCE

4.1 Device Mass

Potential Solution

55. Concretes

See 1.2

Ref(s):

56. High Density and Pumped Ballast

A number of classes of device require additional ballast to achieve optimum hydrodynamic performance. Water, sand or concrete are often used, but higher density minerals are available if required. These

materials can be added to concrete to increases its density, or pumped into and out of ballast compartments, which may have operational benefits.
Ref: http://www.lkabminerals.com/en/Products/MagnaDense/
57. Composite Materials
See 1.3
Ref(s):

PERFORMANCE
4.2 Complex Shapes
Potential Solution
58. Concrete Domes
See 1.2
Ref(s):
59. Inflatable Bags
Flexible inflatable structures have a number of potential applications including being a cost effective means of providing buoyancy and being a potential means of load shedding. They are naturally pre-disposed to forming axisymmetric structures and are used extensively in the marine environment in applications such as Rigid Hull Inflatable Boats (RHIBs) and lift bag technology. They are typically manufactured from high strength polyester cloth coated with PVC.
Ref: http://www.offshore-technology.com/contractors/lifting/jwa/ http://hotribs.com/02articles/059-tube-materials/inflatable-boat-tube-materials.asp
60. Composite Materials
See 1.3
Ref(s):

NOVEL WEC CONCEPTS
Potential Solution
61. Dielectric Elastomers
Dielectric Elastomers (DEs) have been proposed for WECs. DEs are highly compliant incompressible polymeric materials that are electrically non-conductive and can be employed to conceive electro-mechanical transducers. The most well-known dielectric materials are silicone, acrylic and natural rubbers. DE transducers are made by one or multiple layers of dielectric material coated by compliant electrodes. Most materials are filled with conductive fillers like carbon-black in order to achieve dielectric properties. Manufacturing challenges exist in scaling up of the production processes for these materials, particularly in processing of large-dimension thin membranes (for MW-scale WECs) with highly-filled elastomers.
Refs: G. Moretti et al. "Modeling of a Heaving Buoy Wave Energy Converter with Stacked Dielectric Elastomer Generator", Proceedings of the ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS2014, September 8-10, 2014, Newport, Rhode Island, USA

APPENDIX 5 – PRELIMINARY DOWN SELECTION TABLES

Solution	**CONSTRUCTION COST**				
No.	**1.1a Steel**				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
1	Automated Welding	High	Medium	Yes	Cost-savings possible
2	Design for Fabrication	Medium	High	Yes	Are skilled people available ?
3	Adhesive Bonding	Low	High	Yes	For moderate loads only
4	Rivetting / Spot Welding	High	Medium	Yes	Some applications (light loads)
5	Ductile Iron	Medium	Medium	Yes	Used in Wind Energy - no fatigue data available
6	Steel Casting	High	Medium	No	Already available
7	High Strength Steel	High	Low	No	Limited use
8	Low Spec. Steel	High	Medium	No	Can we get it ? From where ?
9	New Welding Methods	High	Medium	Yes	Friction stir, electron beam and laser-welding

Table 1. Potential M & P Solutions for Construction Cost (Steel)

Solution No.	**CONSTRUCTION COST**				
	1.2 Concrete				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
10	Post-Tensioned Concrete	High	High	Yes	Better fatigue, durability, used in bridges & offshore
11	Concrete - Durable Connections	Medium	High	Yes	Concrete will need bolted connections and access ports
12	Concrete Reinforcement Materials	Medium	Medium	Yes	Glass, boron, basalt fibre reinforced plastic rebar
13	Low Cost Concrete	High	Low	No	Could be used for massive anchorage blocks
14	High Performance Concrete	Medium	Medium	No	Expensive
15	Sustainable Concretes	Medium	Medium	No	Geopolymers and other low-carbon concretes, costs ?
16	Repairability of Concrete Devices	Medium	Low	No	Which marine concrete techniques to use ?
17	Novel Production Techniques	Medium	High	Yes	Inflatable formwork, fabric forms etc.

Table 2. Potential M & P Solutions for Construction Cost (Concrete)

Solution No.	CONSTRUCTION COST				
	1.3 Composites				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
18	Pultrusion	Medium	Medium	No	High CAPEX needed to develop larger pultrusion machines
19	Filament winding	High	Medium	No	Available in large sizes
20	Thermoset Resin Infusion	High	Medium	No	Available
21	Adhesive Bonding	Medium	High	Yes	Effect of prolonged seawater immersion
22	Mechanical Joints	Medium	High	Yes	Point load application / effect of seawater immersion
23	Composite Repairs	Medium	Medium	No	Too early to be developing WEC composite repairs
24	Thermoplastic Monomer Infusion	Low	High	No	Too much basic research needed
25	Polymer/Composite Hybrids	Low	High	Yes	Reinforced float structures

Table 3. Potential M & P Solutions for Construction Cost (Composites)

Solution No.	CONSTRUCTION COST				
	1.4 Modular Build				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
26	Modular Building	Low	High	Yes	Methods of constructing large structures in modules for shipping to site for assembly

Table 4. Potential M & P Solutions for Construction Cost (Modular Build)

Solution No.	CONSTRUCTION COST				
	1.5 Fatigue				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
27	Improved SN Curves for steel	Medium	High	Yes	Review of design codes, especially for welded joints
28	Optimised welding techniques (incl. prep)	Medium	Medium	Yes	Application specific
29	Composites	Low	High	Yes	Effect of seawater immersion
30	Polymers and Elastomers	Low	High	Yes	Effect of seawater immersion and creep
31	Composite Adhesive Joints	Low	High	Yes	Effect of seawater immersion

Table 5. Potential M & P Solutions for Construction Cost (Fatigue)

Solution No.	CONSTRUCTION COST				
	1.6 Submersible Buoyancy				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
32	Cargo-Net Loading	Low	High	Yes	Why aren't people doing it ?
33	Rotational moulding of plastics plus reinforcements	Medium	High	Yes	Needs development
34	Foam sandwich construction	High	Medium	Yes	In combination with other technologies

Table 6. Potential M & P Solutions for Construction Cost (Submersible Buoyancy)

Solution No.	CONSTRUCTION COST				
	1.7 Load Shedding				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
35	Elastomers	Medium	Medium	Yes	Design and characterisation needed
36	Shape Memory Alloys	Low	Low	No	Too exotic

Table 7. Potential M & P Solutions for Construction Cost (Load Shedding)

Solution	ARTICULATION SYSTEMS				
No.	2.1 Articulation				
	Potential Solution	Maturity	Impact	Yes/No	Comments
37	Improved Verified Wear Data	Medium	Medium	Yes	Polymer plain bearings
38	Counterface Materials	Medium	Low	No	Technology is available
39	Composite Hinge Shafts	Medium	Medium	Yes	Not used in other applications
40	Laminated Elastomers (LECs)	Medium	Medium	Yes	Limited range of motions
41	Composite Springs	Medium	Medium	Yes	Limited range of motions
42	Rolling Element Bearings	Medium	High	Yes	More suitable to slow-moving WEC devices

Table 8. Potential M & P Solutions for Articulation Systems

Solution	ENVIRONMENT				
No.	3.1 Corrosion Protection				
	3.5 Transported Sediments				
	Potential Solution	Maturity	Impact	Yes/No	Comments
43	Cathodic protection / IC Systems	High	High	No	Available
44	Coatings	High	High	No	Available
45	CP Design Tools	Medium	Medium	No	Available
46	Emerging Corrosion Protection Techniques	Low	Medium	No	Recommend monitoring
47	Erosion Protection Coatings for Composites	Medium	Medium	Yes	Some available for wind turbine blade leading edges

Table 9. Potential M & P Solutions for Environment (Corrosion Protection)

Solution	**ENVIRONMENT**				
No.	**Biofouling, Effects on**				
	3.2 Performance				
	3.3 Loads				
	3.4 Reliability & Maintainability				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
48	Biocidic Release Coatings	High	Medium	Yes	Study to optimise for WECs
49	Foul Release Coatings	High	Medium	Yes	Study to optimise for WECs
50	Ecospeed	Low	Medium	Yes	Study to optimise for WECs
51	Ultrasonic Cleaning (UT)	Low	Medium	Yes	Study to optimise for WECs
52	Mechanical Cleaning	Medium	Medium	Yes	Study to optimise for WECs

Table 10. Potential M & P Solutions for Environment (Biofouling)

Solution	**ENVIRONMENT**				
No.	**3.6 UV Degradation**				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
53	Polyurethane Top Coats	High	Low	No	Available
54	Elastomer & Polymer Formulations	High	High	No	Available

Table 11. Potential M & P Solutions for Environment (UV Degradation)

Solution	**PERFORMANCE**				
No.	**4.1 Device Mass**				
	Potential Solution	**Maturity**	**Impact**	**Yes/No**	**Comments**
55	Concretes	Medium	High	Yes	See 1.2
56	Pumped Ballast	Medium	Medium	No	Available
57	Composite Materials (see 1.3)	Medium	High	Yes	See 1.3

Table 12. Potential M & P Solutions for Performance (Device Mass)

Solution	PERFORMANCE				
No.	4.2 Complex Shapes				
	Potential Solution	Maturity	Impact	Yes/No	Comments
58	Concrete Domes	Medium	High	Yes	See 1.2
59	Inflatable Bags	Medium	Medium	Yes	See 1.2
60	Composite Materials	Medium	High	Yes	See 1.3

Table 13. Potential M & P Solutions for Performance (Complex Shapes)

Solution	OTHER				
No.	Novel WEC Concepts				
	Potential Solution	Maturity	Impact	Yes/No	Comments
61	Dielectric Elastomers	Low	High	Yes	Improved manufacturing and processing needed

Table 14. Potential M & P Solutions for Novel WEC Concepts

APPENDIX 6 – EVALUATION MATRIX

Reference Number	Technology Solution	Initial Weighted Score (out of 60)	Initial Risk Assessment (1 = Low Risk, 10 = High Risk)	Initial Impact Assessment (1 = Low Impact, 10 = High Impact)
33	Rotational moulding of plastics plus reinforcements	42.5	5.0	8.5
25	Polymer/Composite Hybrids	43.0	6.5	8.0
61	Dielectric Elastomers	32.5	10.0	8.0
31	Composite Adhesive Joints - Fatigue	45.5	4.0	7.5
32	Cargo-Net Loading	53.0	2.0	7.3
12	Concrete Reinforcement Materials	39.0	3.5	7.0
21	Adhesive Bonding	40.0	4.8	6.8
17	Novel Production Techniques	35.5	3.5	6.5
59	Inflatable Bags	42.0	4.0	6.5
3	Adhesive Bonding	42.3	5.3	6.3
11	Concrete - Durable Connections	39.0	5.5	6.0
29	Composites - Fatigue	43.0	3.7	6.0
40	Laminated Elastomers (LECs)	37.0	5.0	6.0
58	Concrete Domes	30.0	3.0	6.0
62	Hybrid Steel/Polymer/Composite	45.3	4.0	5.5
63	Hybrid Steel/Concrete	46.8	2.5	5.3
27	Improved S-N Curves for steel	42.7	3.3	5.0
28	Optimised welding techniques (incl. prep) - Fatigue	51.0	1.0	5.0
9	New Welding Methods	41.0	5.3	4.7
4	Rivetting / Spot Welding	39.7	3.0	4.3
30	Polymers and Elastomers - Fatigue	43.3	3.0	4.3
37	Improved Verified Wear Data	42.0	2.5	4.0
47	Erosion Protection Coatings for Composites	45.5	3.0	4.0
5	Ductile Iron	40.3	2.7	3.7
35	Elastomers	37.3	4.0	3.5
41	Composite Springs	35.5	4.0	3.5
50	Ecospeed	40.0	2.5	3.5
51	Ultrasonic Cleaning (UT)	30.5	6.5	3.5
22	Mechanical Joints	39.7	3.7	3.0
23	Composite Repairs	39.7	3.7	3.0
34	Foam sandwich construction	40.7	2.3	3.0
39	Composite Hinge Shafts	37.5	3.5	3.0
42	Rolling Element Bearings	38.0	3.0	3.0

10	Post-Tensioned Concrete	37.5	1.5	2.5
48	Biocidic Release Coatings	33.0	2.5	2.5
49	Foul Release Coatings	29.5	2.5	2.5
52	Mechanical Cleaning	42.0	2.5	2.0