# STEEL-CONCRETE CONNECTIONS FOR FLOATING WAVE ENERGY CONVERTERS

**L. Barker Ewart**, *Industrial Doctorate Centre for Offshore Renewable Energy, University of Strathclyde, UK*
**N. Barltrop**, *University of Strathclyde, UK*
**D. Findlay**, *Albatern Ltd, UK,*
**P. R. Thies**, *University of Exeter, UK*
**T. Stratford**, *University of Edinburgh, UK*

## ABSTRACT

In order to make wave power technologies competitive within the overall energy market, there needs to be significant reductions in the levelised cost of energy (LCoE). One area for potential cost reduction is the use of cheaper materials that are suitable for use in the harsh marine environment, such as reinforced concrete, which gives good corrosion and fatigue properties while providing excellent strength and stiffness at low unit cost. Concrete has the potential to be used for a wide range of wave energy device configurations, however in general use has been limited to nearshore fixed bottom wave energy converters. To date, no dynamic floating wave energy devices have successfully utilised reinforced concrete as structural material, mainly due to the uncertainty surrounding the behaviour of critical dynamic connections between concrete sections and other materials. This paper explores the main issues surrounding steel-concrete connections for floating wave energy converters, providing a review of available design options and standards and assessing the applicability of these to WECs. A methodology is proposed for the evaluation of connection options, and a case study of the Squid 12S floating WEC (developed by Albatern) is presented.

## NOMENCLATURE

| | |
|---|---|
| CAPEX | Capital expenditure |
| DNV-OS | Det Norske Veritas, Offshore Standard |
| EC | Eurocode |
| FLS | Fatigue limit state |
| LCoE | Levelised Cost of Energy |
| PTO | Power take off |
| ULS | Ultimate limit state |
| WEC | Wave Energy Converter |

## 1. INTRODUCTION

While a significant amount of research has been carried out into wave energy generation, much of the focus to date has been on the development of the energy capture technology and proof of concept; material selection has therefore been a secondary concern. However, in order to progress towards commercialisation there need to be significant reductions in the LCoE and a potential avenue for this is the use of cheaper materials that are suitable for use in the harsh marine environment. A number of studies and reports (e.g. [1], [2], and [3]), have highlighted the benefits of reinforced concrete as an alternative to the more commonly used steel for marine structures and renewable energy devices, and the material has a long history of use in the marine environment (a history of offshore concrete structures can be found in [4] and [5]). The benefits of concrete include:

- High resistance to corrosion, especially when compared to steel, eliminating the need for additional coatings, and reducing through life maintenance costs;
- Low susceptibility to fatigue failure, which is very important for dynamic structures such as WECs;
- Ideal for volume manufacture of nonstandard shapes;
- Provides good strength and stiffness properties at a low unit cost: the raw material for reinforced concrete is approximately an order of magnitude cheaper per tonne than steel [6] ;
- Concrete is locally produced, and therefore less reliant on global markets when compared to steel.

Despite the economic and technical benefits of concrete, within the marine renewable industry use has mainly been restricted to foundations of offshore wind turbines, and nearshore fixed bottom wave energy converters, such as the Limpet. To date there are no dynamic floating wave energy devices that have managed to make the most of the advantages that reinforced concrete has to offer. The main reason for this is the uncertainty surrounding the behaviour of joints and connections between concrete sections and other materials. This is a particular issue when connections are required between large non-moving parts of the structure (particularly suited for concrete), and articulated power take off systems (generally made from steel or other metallic materials). These joints are usually critical to the overall function of the device, and have to be capable of transferring very large dynamic forces and moments around multiple degrees of freedom, and therefore it is important to ensure that their integrity is maintained throughout the lifetime of the structure.

Although there are a number of existing applications that make use of steel to concrete connections: such as shear connectors in composite bridges; holding down anchors in concrete foundations; and connection of steel topside infrastructure to offshore concrete oil and gas platforms; none of these applications have the same particular design constraints as floating wave energy devices: namely the requirement to transmit dynamic, cyclic loading about multiple axes, in a harsh offshore environment, while ensuring that the connections remain watertight.

This paper investigates some of the issues surrounding concrete connections for floating WECs. The paper provides a review and evaluation of typical connection details (section 2) and standard design codes (section 3); sets out a proposed methodology for the evaluation of connection options (section 4); and provides a case study of the Squid 12S floating WEC (developed by Albatern Ltd) in section 5 and ends with conclusions (section 6).

## 2. OVERVIEW OF STEEL TO CONCRETE CONNECTION METHODS

There are many different methods for connection of steel sections to concrete structures, which can be generally categorised as follows, (each of which is discussed in the following section):

- Cast-in fully composite solutions;
- Cast-in removable solutions;
- Post-installed anchors; and
- Adhesive connections.

### 2.1 CAST IN FULLY COMPOSITE SOLUTIONS

One of the most common uses for mechanical shear connectors is in the design and construction of composite bridge structures, where welded headed shear studs are often used to transfer longitudinal shear between steel support beams and concrete decks. These studs are very easy to install, providing the contractor has access to a specifically designed stud welding machine. Because of the commonality of use of this type of connection their behaviour in shear is well understood, and designs can be carried out in accordance with standard design codes, such as EC4-1-1 [7].

One of the main issues with this type of connection is the amount of slippage that has to occur before the full shear capacity is mobilised, resulting in stress concentrations and crushing of the surrounding concrete (see Figure 1) which results in poor fatigue behaviour if subject to high cyclic loading. In addition, the individual shear capacity is quite low, and therefore many connectors are required to provide a full shear connection, which can be labour intensive. There can also be issues with corrosion if there is water ingress between the concrete and the face plate; this is very difficult to inspect and therefore could result in an unpredicted failure of the connection.

Figure 1: Load transfer from welded shear stud [8]

To overcome the potential fatigue issues with arc welded studs, the bridge designers Leonhardt, Andra and Partners developed the Perfobond shear connector in the 1980s as an alternative for shear connection in composite bridges [8]. The connector itself has a high shear capacity, and the composite shear resistance is developed through concrete compression dowels that form in the holes of the shear connector (see Figure 2). Reinforcing bars can be placed through the holes to improve the overall ductility of the connection and increase the overall shear resistance. Fatigue behaviour is improved, as less slip is required to mobilise the shear connection, resulting in more elastic behaviour than for shear heads.

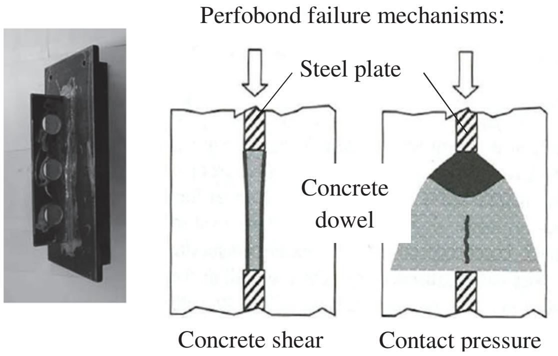



Figure 2: Perfobond shear connectors [8]

The disadvantage of this type of connector is that it more difficult to place the reinforcing bar within the concrete.

## 2.2 CAST IN REMOVABLE SOLUTIONS

The connection solutions discussed above are fully composite solutions, where the connection is cast into the concrete, requiring that the steel is incorporated into the formwork and permanently connected to the concrete structure. However, this may not always be feasible or practical, and there are a wide variety of proprietary cast-in socket and anchor solutions that allow sections to be bolted on after the casting process, such as those developed by Halfen (see Figure 3).

Failure mechanisms of cast-in anchor systems include failure of the steel connector in tension or shear, pull out of the fastener (caused by crushing of the concrete under the fastener head), concrete cone failure in tension, or edge failure in shear (governed by the concrete shear strength). Providing that these different failure modes are addressed, these types of connections are well suited to resisting loading around multiple axis.

The anchor bolts can also be pre-loaded, which improves fatigue resistance in tension as the pre-load reduces the stress fluctuations in the bolt due to cyclic loading. Pre-loading also improves behaviour in shear, as providing the frictional resistance is greater than the applied shear force, this results in a non-slip connection and the shear force is transmitted directly into the concrete, rather than taken by the steel fastener.

An extension of pre-loaded bolts is the use of pre-tensioned reinforcing bar. This is often used in situations where it is advantageous to keep the concrete in compression to reduce the potential for cracking under bending loads. Extending pre-tensioning systems across a joint keeps the joint in compression, and has therefore the same advantages for connection fatigue as pre-loaded bolts.

A disadvantage of this type of connection is that the connectors provide a potential path for water ingress into the concrete leading to durability issues, especially if they are cast all the way through a section. This is possible to overcome through provision of protective coatings for bolt ends, and any problems with corrosion will also be evident during inspections.

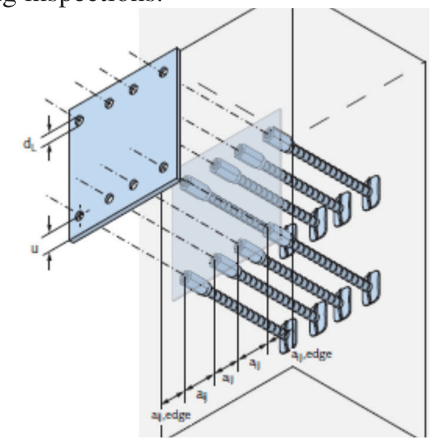


Figure 3: Cast in connections [9]

## 2.3 POST INSTALLED ANCHORS

Post-installed anchors (such as chemically bonded anchors placed in holes drilled in the concrete) are generally used for retrofitting applications, or for in-situ installations where accurate placing of cast in connections is not possible. Cast-in solutions are preferable for precast units as they can be fully integrated and tied into the steel reinforcement.

## 2.3 ADHESIVE CONNECTIONS

Externally bonded plates (either steel or FRP) have been successfully used to upgrade ageing concrete bridges in order to improve bending and shear resistance, and have the potential to replace traditional mechanical shear connections in composite construction [10]. This would overcome some of the issues associated with mechanical shear connection including fatigue and stress concentrations. However, there has been very little investigation to date into the durability of such connections under fatigue loading in the marine environment; this is a very large area of potential research, but as such is outside the scope of this current study.

## 3. AVAILABLE CODES AND STANDARDS

Structural design is carried out in accordance with internationally recognised codes of practice which ensure that the structure will meet a specified target safety level over its design life. However, WECs are novel devices that can fall outside the scope of the available codes and standards. This section provides a brief review of design codes applicable for steel-concrete connections in wave energy applications.

Some of the most commonly used standards within Europe include the Eurocodes, and the DNV Offshore Standards (DNV-OS). The Eurocode suite covers the design of buildings and civil engineering works, but specifically state that they do not cover particular aspects of special types of civil engineering works such as offshore platforms, and therefore may not be entirely applicable to the design of wave energy converters. Eurocode 4 [7] covers composite buildings and bridges constructed from steel and concrete, and as discussed in Section 2 specifically details the design of arc welded shear studs. However, the scope of design for these connectors is limited to the transfer of longitudinal shear in composite beams, and therefore is not directly applicable to connections subject to loads around multiple degrees of freedom.

In addition to the Eurocodes, there is also a European Technical Specification in development (DD CEN/TS 1992-4) [11] which covers the design of many types of fasteners in concrete and includes fasteners subject to tension as well as shear. It therefore has a wider range of application than the design methods for shear studs in EC4; however, the scope of this document is the same as for the Eurocodes, and therefore similarly it is not necessarily directly applicable to offshore structures.

In comparison to the Eurocodes, the DNV-OSs were specifically written for offshore structures, but were developed primarily for the oil and gas industry and therefore deal with large static structures, in direct contrast to most WECs which are highly dynamic structures. They may therefore not always be suitable for design, particularly when it comes to safety philosophy for fatigue loads, as noted by Ambuhl et al. [13] who carried out work to calibrate the fatigue design factors presented in the DNV-OSs for steel connection details, and found that the published factors resulted in lower target levels of reliability than required. In addition to the concerns surrounding the applicability of the documents there are no specific guidelines for the design of concrete fastening systems within the DNV codes, although DNV-OS-C502 [14] does include a brief section on composite design with studs, which follows the same design philosophy as the Eurocodes.

The lack of applicable codes and standards for the design of connections for WECs highlights the issues and uncertainty surrounding this type of detail, and indicates that this is an area where further research would be beneficial in order to determine whether it is possible to exploit the benefits of concrete for the application of floating WECs.

The following section proposes a methodology for screening and evaluation of different connection options in absence of suitable design guidelines and standards.

## 4. PROPOSED METHODS FOR EVALUATION OF CONNECTIONS

While the connection design details for WECs will be heavily dependent on the configuration of the individual device, many of the issues and concerns are similar between devices. Therefore, a generic preliminary evaluation and assessment process has been developed with the following steps:

- Development of high level options, based on potential connection configurations as discussed in Section 2.
- Qualitative assessment of advantages and disadvantages of each option. At this stage, it may be apparent that some connection options are not suitable for a particular application, and

therefore these can be discounted, leading to a reduced short list that can then be assessed in further detail.

- Preliminary quantitative design based on outline design loads. This step should take place early in the design phase, and therefore it is likely that final design loads will not be available. However, this step allows for a comparison between options, to allow preferred options to be identified and taken forwards for further development.
- Preliminary spectral fatigue analysis based on outline fatigue loads. Again, this step allows for a comparison between designs, and gives an indication of whether fatigue is an issue for a particular configuration.
- Following the preliminary design, options can then be evaluated based on the following criteria:
  - Overall weight of steel within the connection which gives an indication of cost;
  - Fatigue resistance;
  - Corrosion potential;
  - Ease of construction; the easier the construction, the cheaper the connection will be;
  - Maintainability; the easier a detail is to inspect and maintain, the cheaper and more reliable it is likely to be.

In this paper, a quantitative evaluation process is recommended, whereby each criterion is given a score of between 1 and 5, where 1 is the most positive, and 5 is the least positive. The different criteria can then be summed together, and the preferred options will be those with the lowest overall scores. In the following section, this methodology has been applied to the Squid 12S floating WEC.

## 5. CASE STUDY- ALBATERN MULTINODE FLOATING WAVE DEVICE

Albatern are currently considering the use of reinforced concrete as a main structural material for the next generation of Squid device (the 12S), but one of the main areas of concern for design is the articulated interface between the concrete node structure and the steel link arm, which provides the connection point for the power take off mechanism.

### 5.1 OPTIONS

An overview of a potential configuration for the 12S Squid unit is shown in Figure 4. Initial techno-economic feasibility studies have shown that concrete is one of the preferred materials for the node structure, whereas the link arm and joints will be manufactured from steel.

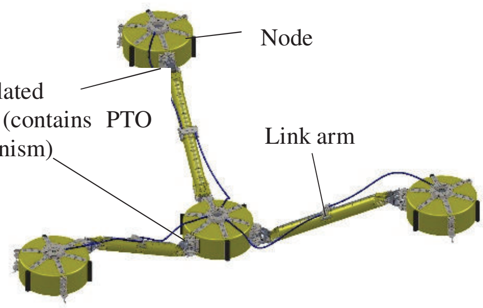



Figure 4: Overview of proposed configuration for 12S Squid

The critical component for structural design of the concrete node in this configuration is the articulated connection between the link arm and the node, which is the point of transfer of the dynamic PTO loads into the main structure, and needs to be robust and remain watertight through the design life. The load components that are transferred through the connections are shown in Figure 5. An overview of the options that are being considered for the connection are shown in Table 1 together with an overview of the advantages and disadvantages of each option (initial qualitative assessment), and the results of the preliminary quantitative design assessment (discussed in Section 5.1).

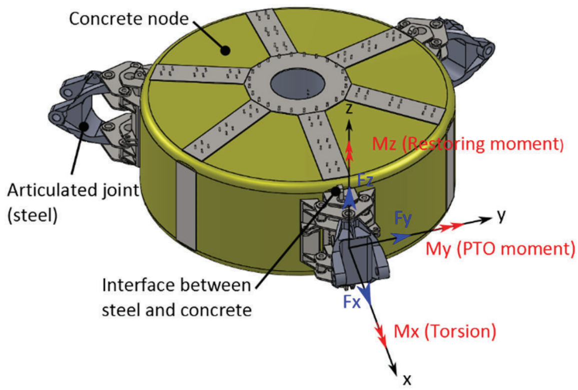
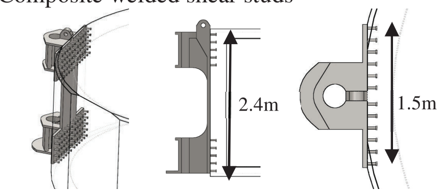
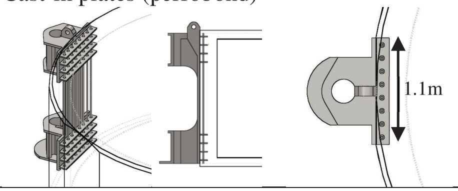
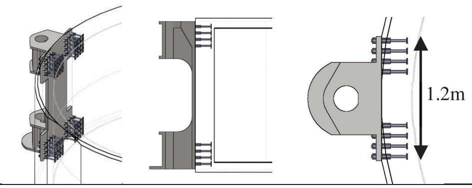
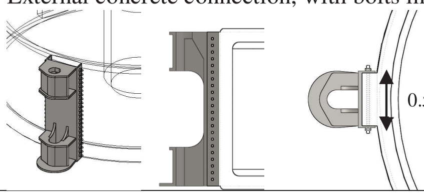
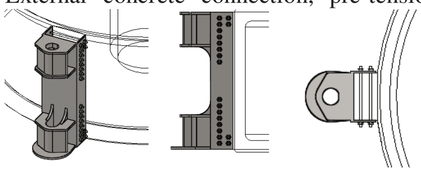



Figure 5: Load actions at connection between link arm and node

**Table 1: Steel – concrete connection option assessment for the Squid 12S device**

| Option development | | Qualitative assessment | | Preliminary quantitative design | |
|---|---|---|---|---|---|
| Option | Sketch | Advantages | Disadvantages | Required ULS design | Fatigue |
| 1 | Composite welded shear studs   | • Fully composite system-concrete and steel act together. Commonly used shear connection<br>• Cheap and quick to install studs (providing there is access to correct machine) | • Not designed to take shear and tension<br>• Poor fatigue detail<br>• Need to incorporate steel section into concrete formwork and can't remove / replace steelwork<br>• Potential corrosion issues if there is water ingress between the plate and the concrete which wouldn't be visible during inspections | 25dia x 150 shear studs, total no. 96.<br><br>Total steel weight: 244kg | 2.4yrs |
| 2 | Cast-in plates (perfobond)   | • Fully composite system – concrete and steel act together<br>• Improved fatigue detail<br>• Suited to taking shear and tension | • Need to incorporate steel section into concrete formwork<br>• Can't remove / replace steelwork<br>• Potential difficulties with placing rebar<br>• Potential pathway for water ingress, increasing the possibility of corrosion of the reinforcement. | 8 no. ribs, 1100x150x20mm dimensions. 8no. 50mm dia holes, with 25mm dia rebar in each<br><br>Total steel weight: 250kg | 18.3yrs |
| 3a | Cast-in anchor sockets   | • Easy to cast in bolts<br>• Steel work is separate from concrete – can be removed / replaced<br>• Provides good resistance to loads around multiple axis<br>• No welding required | • Non-preloaded bolts are poor in fatigue<br>• Bolts may provide a pathway for water into the concrete, increasing the possibility of corrosion of the reinforcement.<br>• May be corrosion issues for bolt heads.<br>• Potential difficulties with rebar placement around bolts. | 64 no. anchors, 240mm total embedment, 25mm diameter<br><br>Total steel weight: 256kg | 0.3yrs |
| 3b | Cast-in anchor sockets with pre-loaded bolts (potentially long bolts to reduce loss of preload) | • As per 3a, but improved fatigue detail due to preload in bolts | • Potential loss of preload through the lifetime of the structure | As 3a, but with preloaded bolts<br>Total steel weight: 256kg | 19.5yrs |
| 4 | External concrete connection, with bolts in shear   | • No water path through into the node<br>• Steel work separate to concrete<br>• Easy to remove and replace steel work – including bolts | • Would need careful consideration of the rebar connection and strength of the concrete attachment 'nib'.<br>• Reduced number of larger bolts, meaning each bolt takes a large amount of shear force – not particularly good for fatigue. | 23 no. M30 bolts, clamping connection on to 500x200mm concrete outstand<br><br>Total steel weight: 291kg | 1.9yrs |
| 5 | External concrete connection, pre-tensioned bars  | • Pre-load improves fatigue detail | • Bars have to have large pretension in order to ensure no slip of bolts in shear.<br>• Potential preload loss through life time.<br>• Careful detailing of rebar connection and concrete attachment 'nib' required.<br>• Bars should not corrode or stress corrosion crack | 20 no. 32mm dia pre-tensioned Macalloy bars<br><br>Total steel weight: 291kg | >20yrs |

## 5.1 PRELIMINARY QUANTITATIVE DESIGN

In order to quantify some of the advantages and disadvantages of different options for the Albatern device, an initial feasibility design had been carried out, based on preliminary design loads from hydrodynamic modelling of the full Squid unit. Although at this stage in the development process it is not possible to carry out a full detailed connection design, this feasibility study allows the different options to be compared on a like for like basis, and can therefore be used as a tool to inform the ongoing design process of this or other WECs.

### 5.1 (a) Ultimate limit state design (ULS)

While it is noted in Section 3 that the available codes and standards are not always directly applicable to wave energy devices, and do not have a large enough scope to cover the wide range of connection options that are available, they do however provide a good starting point for design. Therefore, where code based design methods are available they have been followed for the purpose of this initial study.

The connection configurations shown in Table 1 are based on the requirements for ULS design, looking at the extreme loads developed during the 1 in 100-year storm event. The connection has to transmit torsion ($M_x$), the PTO torque ($M_y$), vertical and horizontal shear ($F_z$ and $F_y$), as well as axial tension and compression ($F_x$) into the concrete. The largest preliminary load actions are $M_x$ and $M_y$ (each >2MN.m), with $M_x = 1.6M_y$. For the purpose of this design study, it has been assumed that the worst case of all forces can act simultaneously. Partial factors have been applied to the loads and material resistances in accordance with recognised design codes or guidelines where available.

Headed shear studs (Option 1) have been designed in accordance with the guidance in BS EN 1994-4-2 [7] and also DNV-OS-C502 [14]. While it is noted that the equations presented in these standards are not directly applicable for connectors loaded in combined tension and shear, the Designers Guide to EC4 [14] provides a formula to check shear connectors for this load case.

The perfobond connector (Option 2) is not covered in any of the standard codes, however there are a number of different empirically derived design equations presented in the literature. For the purpose of this design, the equations proposed by Valente [8] have been used which are considered to result in a conservative design solution.

The bolted connection (Option 3) has been designed in accordance with the principles in DD CEN/TS 1994-4-1 and 2 [11], which deal with the general design of fastenings for use in concrete (Part 1), and headed fasteners in particular (Part 2). Reference is also made to the Halfen Technical documentation [9], which provides guidance on the design of these types of connections.

Bolts and pre-tensioned bars in shear have been checked in accordance with BS EN 1991-1-8 [15], with the shear resistance of the concrete checked in accordance with DNV-OS-C502 [13].

### 5.1 (b) Fatigue limit state design (FLS)

Due to the dynamic nature of floating wave energy devices, fatigue due to the operational loads is often the driving design criteria, rather than ultimate limit states which ensure survival during extreme events. To evaluate the fatigue behaviour of each of the connection options, an assessment of fatigue life has been carried out based on the required ULS.

Fatigue assessment is most commonly carried out in the time domain, with the number of stress cycles that a detail has to endure calculated from the stress time history using the rainflow cycle counting method [16]. However, the level of modelling and analysis that is required for this is not appropriate at this stage in design, and therefore a frequency domain approach has been followed in this case.

Rapid fatigue analysis methods, based in the frequency domain, were developed in the 1980s for the offshore oil industry [18], which allow the expected stress range and number of cycles to be determined for each sea state included in the wave scatter diagram for a particular site.

The current design is based on the North Atlantic Scatter Diagram (NASD), as given in [19]. This spectrum encompasses the worst case sea states encountered throughout the North Atlantic, and therefore gives a conservative spectrum for structural design. The scatter diagram gives the number of occurrences expected for each sea state (defined by significant wave height $H_s$, and peak period $T_p$) in a given year. The process that has been followed for this fatigue analysis is presented below.

- For each action which contributes to fatigue loading, a load transfer function per unit wave amplitude has been determined from the hydrodynamic model of the device. This gives the magnitude of a particular action (for example the torsion moment at the connection Mx), for the full range of wave frequencies.
- For each connection detail, the magnitude of stress that occurs due to a unit load has been calculated, based on linear elastic analysis. This is multiplied by the load transfer function per unit wave amplitude in order to give the frequency domain stress transfer function per unit wave amplitude.
- The stress spectrum for a particular sea state is determined by multiplying the wave spectra for a particular sea state (assumed at this stage to be a Jonswap spectra defined in accordance with [19]) by the square of the stress transfer function.
- The long term stress range is calculated using the properties of the stress spectrum, assuming that the stress range is distributed in accordance with the Dirlik probability density function – this is an empirically derived function suitable for narrow band spectra, which gives better correlation with the time history rainflow counting method than other distributions such as the Rayleigh distribution [18].
- The number of cycles expected at each stress range can then be calculated for each sea state (this has been carried out using Matlab), depending on the expected duration of each sea state based on the NASD. This can then be summed together to give a full stress cycle histogram.
- Fatigue life has been estimated using published S-N curves, and the Palmgren-Minor summation rule for damage to different magnitude stress cycles.

As concrete generally performs better than steel under fatigue loading, this fatigue assessment has only considered the steel components. It is noted however that for a full detailed analysis, the fatigue life of the concrete components would also need to be considered.

S-N curves for different steel details have been taken from [20]. There is no specific S-N curve published for the perfobond connector as a whole, however it is assumed that fatigue failure would be a result of failure of either the weld between the rib and the faceplate, or stress concentrations due to bearing across the rib hole, and therefore each of these details have been checked individually.

The expected fatigue damage of each connection has been determined based on a single year duration; the fatigue life has then been calculated based on the number of years it would take for the damage level to be greater than 1 (no safety factors are included in this value). The fatigue life due to the torsion moment ($M_x$), and PTO induced moment ($M_y$), have been calculated separately and the worst case has been presented in the results section.

5.1(c) Results

Results from the ULS and FLS outline designs are included in columns 5 and 6 of Table 1.

## 5.2 DISCUSSION

Following on from the preliminary qualitative and quantitative assessment presented in Table 1 each option has been assessed on the basis of the criteria set out in Section 4. For each criterion, options have been given a score between 1 and 5, with 1 being the best and 5 being the worst.

The results of this assessment are presented in Table 2, which provides the score and a brief explanation for each option and criterion.

**Table 2: Option assessment**

| Option | Weight | Fatigue | Ease of construction | Corrosion potential | Maintainability | Total |
|---|---|---|---|---|---|---|
| 1 | **1** *Lowest weight overall* | **5** *Very poor* | **4** *Complicated to incorporate steelwork into formwork* | **4** *Any corrosion of shear studs won't be visible* | **5** *Can't remove / replace steelwork* | 19 |
| 2 | **2** *Ribs slightly heavier than studs* | **2** *Much improved, but still less than required* | **4** *Difficulty placing rebar around ribs* | **4** *Any corrosion of ribs won't be visible* | **5** *Can't remove / replace steelwork* | 17 |
| 3a | **3** *Cast in anchors slightly heavier* | **5** *Very poor* | **2** *Anchors are easy to incorporate into formwork.* | **3** *Corrosion potential – but can be inspected* | **2** *Most steelwork parts can be replaced* | 15 |
| 3b | **3** *Cast in anchors slightly heavier* | **2** *Fatigue improved with preload, but still less than required* | **2** *Anchors are easy to incorporate into formwork.* | **3** *Corrosion potential – but can be inspected* | **2** *Most steelwork parts can be replaced* | 12 |
| 4 | **4** *High weight of steel due to additional plates* | **5** *Very poor* | **2** *Slight increased complexity with additional concrete nib* | **3** *Corrosion potential – but can be inspected* | **1** *Easy to replace bolts and connection if required* | 15 |
| 5 | **4** *High weight of steel due to additional plates* | **1** *Fatigue improved with preload* | **2** *Slight increased complexity with additional concrete nib* | **3** *Corrosion potential – but can be inspected* | **1** *Easy to replace bolts and connection if required* | 12 |

Table 2 attempts to quantify the benefits and disadvantages of each option and shows that the preferred options are option 3b (Cast-in anchor sockets with preloaded bolts), and 5 (External concrete connection with pre-tensioned bars). The advantages of these configurations include the good fatigue behaviour provided by pre-tensioned connections, the ease of construction, and the improved inspection and maintainability characteristics, when compared to the other options.

Worst performing options are the composite connections, due to the increased complexity in construction and the lack of ability to inspect and maintain the connections. Option 1 (shear studs) is the least favoured option, due to the very poor fatigue behaviour.

An important point that the quantitative assessment has highlighted is the necessity to consider fatigue in design. Whilst some details performed significantly better than others, none of the calculated fatigue lives are as long as the required design life (which is around 20yrs) and an economic analysis would probably show that a safety factor on fatigue life should be included. This shows that fatigue is the dominant failure mode for the connection design and the presented connection details would have to strengthened to take this into account.

## 6. CONCLUSIONS

This study has looked into the issues surrounding steel-concrete connections for floating wave energy devices and has concluded the following:

- Current design codes do not adequately cover the design of steel-concrete connections for floating wave energy converters. These connections tend to be critical details transferring large dynamic loads from the power take off system into the main structure.The uncertainty surrounding the behaviour needs to be reduced in order to be able to make use of reinforced concrete in the design of these types of structures.
- Fatigue loading is an area of concern, and is very likely to drive design. Details which reduce fatigue loading, such as pre-loaded bolts or pre-tensioned reinforcement bars, are therefore preferable.
- Corrosion of connections needs to be considered carefully; details which allow water ingress should be avoided as this could exacerbate corrosion both of the connection steel work and also internal steel reinforcement within the concrete.
- Connections details which allow for easy inspection and maintenance are preferred, as this allows parts to be replaced in case of greater amounts of degradation or damage than expected during the lifetime of the structure.
- If a suitable system for steel-concrete connections can be identified, this will allow reinforced concrete to be used for the main structural components of floating wave energy converters, helping to minimise the overall CAPEX, and reduce the LCoE for WECs.

The assessments carried out within this study provide a high level overview of the issues, but further work is required in order to gain more knowledge and reduce the uncertainty surrounding the behaviour of these types of details, including dry laboratory tests to investigate behaviour under static and cyclic loads, and ultimately large scale sea trials to get a fuller idea of the behaviour in real sea conditions.

## ACKNOWLEDGEMENTS

This work has been carried out as part of the IDCORE programme, funded by the Energy Technology Institute and RCUK Energy programme (grant no. EP/J500847/1)

## REFERENCES

1. K. SANDVIK, R. EIE, J.-D. ADVOCAAT, A. GODEJORD, K. O.HÆREID, K. HØYLAND AND TOR OLE OLSEN, "Offshore Structures - A new challenge," in *XIV National Conference on Structural Engineering*, 2004.
2. HI-CON A/S, "FLOAT - development of new flexible UHPC," ForskEL, Hjallerup, Denmark, 2012.
3. OCEAN POWER DELIVERY LTD, "Pelamis WEC - Main body structural design and materials selection," DTI, 2003.
4. G. C. HOFF, "Concrete for Offshore structures," in *Concrete Construction Engineering Handbook, 2nd Edition*, E. G. Nawy, Ed., CRC Press, 2008, pp. 13-1 to 13-32.
5. R. P. FERNANDEZ AND M. L. PARDO, "Offshore concrete structures," *Ocean Engineering* , vol. 58, pp. 304-316, 2013.
6. M. F. ASHBY, "Appendix A: Data for Engineering Materials," in *Material Selection in Mechanical Design, 4th Edition*, Oxford, Butterworth-Heinemann, 2011, p. 218.
7. BSI, "BS EN 1994 Eurocode 4: Design of composite steel and concrete structures," 2004.
8. I. VALENTE, "Experimental studies on shear connection systems in steel and lightweight concrete composite bridges," 2007.
9. HALFEN, "Halfen HUC Universal Connection Technical Product Information," 2014.
10. A. SI LARBI, E. FERRIER, B. JURKIEWIEZ AND P. HAMELIn, "Static behaviour of steel concrete beam connected by bonding," *Engineering structures,* vol. 29, pp. 1034-1042, 2007.
11. BSI, "DD CEN/TS 1992 Design of fastenings for use in concrete," 2009.
12. S. AMBÜHL, F. FERRI, J. P. KOFOED AND J. D. SØRENSEN, "Fatigue Reliability and Calibration of Fatigue Design Factors of Wave Energy Converters," *International Journal of Marine Energy,* pp. 17-38, 2015.
13. DNV, "DNV-OS-C502 Offshore Concrete Structures," 2012.
14. R. P. JOHNSON, Designers' Guide to Eurocode 4: Design of composite steel and concete structures, 2nd edition, ICE Publishing, 2011.
15. BSI, BS EN 1993-1-8:2005 Eurocode 3 Design of steel structures. Design of joints.
16. J. SCHIJVE, Fatigue of structures and materials, Springer, 2009.
17. A. HALFPENNY, "A frequency domain approach for fatigue life estimation from finte element analysis," *Key Engineering Materials,* vol. 167, pp. 401-410, 1999.
18. DNV, "DNV-RP-C205 - Environmental Conditions and Environmental Loads," DNV, April 2014.
19. DNV, "DNV-RP-C203 fatigue design of offshore steel structures".