Concrete as a Technology Enabler (CREATE)

Structural Materials and Manufacturing Processes

Stage 2 Public Report

Arup

This project has been supported by Wave Energy Scotland.

1. Project Introduction

This document summarises the work completed during Stage 2 of the Wave Energy Scotland (WES) Concrete as a Technology Enabler (CREATE) project.

The CREATE project aims to confirm that reinforced concrete technology can make a step-change in the LCoE for WECs. Reinforced concrete has a lower unit cost and superior durability compared to steel in the offshore environment. It is also a well understood material and can take advantage of a mature supply chain. The CREATE project is WEC technology agnostic and WEC devices have been chosen where the core benefits of concrete could be realised.

During CREATE Stage 1 (2017-2018), the potential benefit of traditional concrete technology was demonstrated for four WEC devices, highlighting the versatility of the material in the sector. Low mass is not a requirement for power absorption for many device types and in these cases structural concrete can offer a more efficient solution for part or all of the prime mover structure by using the weight of the structure directly, rather than requiring additional ballast. Of these four devices, The Carnegie Clean Energy (CCE) CETO 6 submerged pressure differential device was chosen as an example WEC geometry for more detailed investigation into the potential benefits of concrete. This comprised pre-FEED level design, external manufacturing assessment and cost and risk assessment for a CETO 6 device with a concrete BA. The assessment enabled potential cost reduction to be accurately quantified and key risks identified.

A key outcome of the Stage 1 work concerned the opportunity for precast construction of concrete WECs. Concrete sections can be cast ‘in-situ’ whereby formwork is erected, and the concrete poured onto a mesh of reinforcement where it sets. Precast concrete is an alternative construction method where components are produced using traditional concrete and reinforcement material with reusable formwork (or moulds) in a controlled environment. Precast components are then assembled on site and additional concrete is used to form connections. In the context of WECs, precast construction has the potential of saving cost for serial production despite increased effort for fabrication set up. CREATE Stage 1 considered in-situ concrete WEC designs, and Stage 2 aimed to demonstrate that precast concrete is a technically viable, and cost effective, solution for WEC applications.

To achieve this aim, Stage 2 comprised design development work, targeting key technical risks for concrete devices identified at Stage 1. Key areas of interest included:

- Technical viability of precast concrete construction for WEC devices.
- Areas of high localised loading, e.g. tether and mooring point connections.

A precast design for the CETO 6 WEC was developed to a FEED level and full scale physical and numerical testing undertaken to demonstrate the performance of a critical precast connection. A manufacturing plan for serial production of the device in Scotland was also developed, with input from the material supply chain. This enabled detailed cost assessment, including independent estimation from a major contractor. Concrete offers superior durability performance relative to steel and a detailed operations and maintenance (O&M) assessment was undertaken to quantify this affect. CREATE Stage 2 demonstrated that the use of precast concrete is predicted to reduce the LCoE by 12% compared to a steel alternative. If a 50-year design life for the concrete structure is exploited, the LCoE reduction is predicted to increase to 18%.

The project team brought together leading expertise in WEC loads and performance analysis, concrete and offshore design and concrete construction methods. The project partners are summarised in Table 1. The project is WEC technology agnostic, but the majority of the work assessing key technical risks was undertaken using the CCE CETO 6 device as an example WEC device, with CCE providing realistic geometries and design constraints against which the material was tested.

Table 1. CREATE Stage 2 project team

Project Partner	Role
ARUP	Structural design, manufacturing assessment, lifecycle assessment, cost assessment and overall project management.
cruz atcheson CONSULTING ENGINEERS	Detailed loads and performance analysis, and OPEX assessment.[1]
mpa The Concrete Centre, bam	Independent manufacturing review, engagement with contractors and the material supply chain.
Carnegie clean energy, mocean energy	Leading WEC developers to provide example geometries and realistic design requirements.
DOOSAN, PLEAN PRECAST	Manufacturing and testing of prototype precast connection.

[1] Cruz Atcheson has now been acquired by K2Management.

2. *Description of Project Technology*

The project is technology agnostic, both in terms of the concrete material technology and WEC type. The primary advantages of reinforced concrete over steel include a low unit cost, access to an extensive supply chain and increased durability. Unlike steel structures, the design of offshore concrete structures is typically driven by strength and serviceability (e.g. corrosion protection and water-tightness) requirements, rather than fatigue. Consequently, a minimum design life of 50 years is readily attainable for concrete structures and further cost savings can be realised when this design life is utilised. Steel structures are typically designed for a 25-year life under corrosion and fatigue.

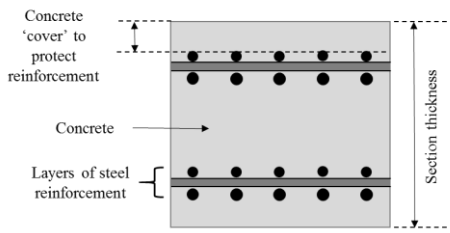
The specific concrete construction methods considered for CREATE Stage 2 are described in Table 2. These construction methods are well-understood in offshore applications, which helps control costs and reduce construction risks.

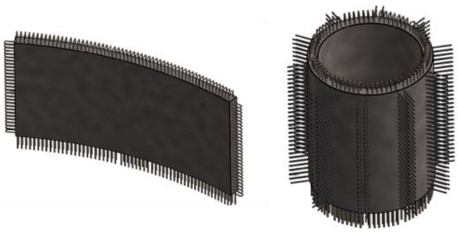
In WEC construction, the use of reinforced concrete construction methods represents an understood approach applied in a novel application. The work in CREATE Stage 1 was predominantly based on in-situ concrete construction. CREATE Stage 2 has explored the technical viability and possible use of precast concrete, for which the potential benefits are summarised in Table 2.

Precast connections are established technology in the construction industry, however there is limited track record of their use considering the requirements present in a WEC context. Specifically, concrete WECs must combine high loading in the offshore environment with thin structural sections necessary to achieve mass targets. WECs also require significant point loads to be locally transferred into concrete structures at tether connection points.

Demonstration of the technical viability of the material to address these specific requirements formed the focus of the CREATE Stage 2 project.

Table 2. Concrete materials and construction methods considered

<table>
<tr><th>Material and Construction Method</th><th>Description</th></tr>
<tr><td>Traditional reinforced concrete with in-situ construction

</td><td>Concrete's primary constituents are aggregate, cement and water. The aggregate comprises crushed rock, which is bound by cement to form concrete. Concrete is combined with carbon steel bars which provide tensile strength to complement the materials intrinsic high compressive strength. The steel is contained a set distance from the surface of the concrete (the 'cover') which protects the encased steel from corrosion and hence improves durability.

Concrete sections can be cast 'in-situ', whereby formwork is erected and the concrete poured onto a mesh of reinforcement where it sets. Due to the simplicity of this construction technique, concrete gives access to an extensive and mature supply chain.</td></tr>
<tr><td>Traditional reinforced concrete with precast construction
</td><td>Precast concrete is a construction method where components are produced using traditional concrete and reinforcement material but using a reusable formwork (or mould) in a controlled environment. Precast components are then assembled on site and additional concrete is used to form connections.

In the context of WECs, precast construction has the advantage of allowing production of a large number of similar components without having to repeatedly erect or dismantle formwork, which saves cost for serial production. It has the additional advantage of enabling better weight control due to higher precision moulds, particularly important in this context.</td></tr>
<tr><td>Post-tensioning
</td><td>Post-tensioning involves stressing additional steel cables within the concrete to generate a permanent state of compression. For durability purposes, post-tensioning strands are typically grouted once stressed when used offshore.

Post-tensioning is predominantly used to control concrete cracks, an important consideration for WECs to ensure durability and water-tightness.</td></tr>
</table>

3. *Viability of Precast Concrete for Wave Energy Converter devices*

CREATE Stage 2 aimed to demonstrate precast concrete is a technically viable and cost-effective solution for concrete WECs. To fulfil this overarching aim, the following 3-step assessment approach was taken.

STEP 1: Conduct a review of precast connection designs and assess their applicability to WECs. Identify the preferred connection design for WECs.

STEP 2: Develop a precast concrete design for the CETO 6 WEC, to demonstrate the technical viability of the chosen precast connection solution(s).

STEP 3: Carry out physical testing of a precast concrete connection, to demonstrate the buildability of the precast connection identified during STEP 1, and to demonstrate water-tightness performance of precast connections under cyclic loading.

Confirmation of precast connection options for WEC devices

The assessment of precast connections comprised a literature review of existing precast design guides, technical publications and project experience from a range of civil engineering applications. Three different precast joints were found to be applicable to WECs, from a review of five configurations. Criteria for assessment of suitability are summarised below.

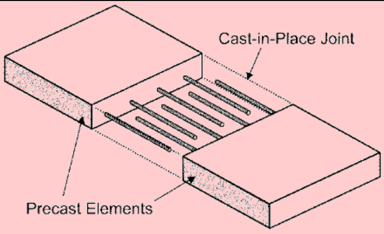
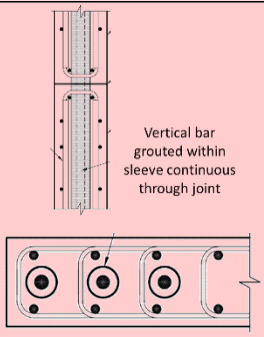
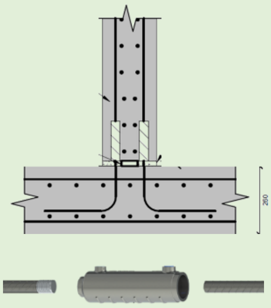
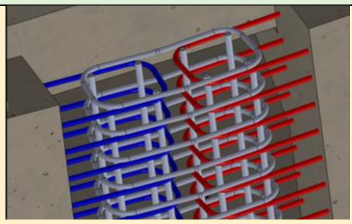
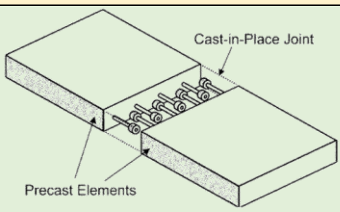
Criteria 1	A full-strength joint in tension and bending. High loading in the offshore environment necessitates this, which is likely to be applicable to the majority of concrete WECs.
Criteria 2	Compatibility with thin structural sections to achieve mass targets. This is likely to be applicable to the majority of concrete WECs.
Criteria 3	Water-tightness for connections on external connections. This is applicable to all concrete WECs.
Criteria 4	Maturity of technology.
Criteria 5	Speed of construction and assembly during serial production.

The advantages and disadvantages of the precast joint types considered are summarised in Table 3, based on design guidance and technical publications. Two joints were considered particularly advantageous for WEC devices and were used during precast WEC design development in Stage 2:

- High-tolerance couplers (Table 3, Option 3) are particularly suited to forming horizontal joints between vertically stacked elements, when water tightness is not a requirement. Units can be supported using local shims/packing to achieve the desired level. The in-situ joint width can be as little as 20mm for these joints. For joints where water tightness is not a strict criterion (e.g. for internal wall joints), this solution is considered appropriate.
- Interleaved T-headed bar connections (Table 3, Option 5) are an existing technology that can transfer the full tension and bending strength in a relatively narrow width connection joint. This feature makes them particularly suited to external joints in WEC devices, which are commonly subjected to high bending forces. T-headed reinforcement is established technology in the construction industry, but it is only in the last 5-10 years that T-headed reinforcement has been developed as a solution for connecting precast panels.

Interleaved U-bar joints (Table 3, Option 4) were also considered a viable option, and are advantageous from a buildability perspective. However, a U-bar joint can struggle to achieve a full-strength connection when the joint is subjected to bending, and thus thickened sections may be required in the joint vicinity to meet the WEC performance requirements. Any thickening of the joint would be to the expense of the overall BA mass and the volume of in-situ concrete.

Table 3: Summary evaluation of different precast joint types. Relevant criteria shown as [Cx]. Suitability for WECs highlighted with green (most suitable) to red (least suitable).

Option		Advantages	Disadvantages
1/ Conventional lap		Develop the full tensile and bending strength [C1] Controls crack widths [C3] Well-established [C4]	Large joint width [C2] Large volumes of in-situ concrete and substantial in-situ temporary works [C5]
2/ Grouted-well voids		Well-established [C4]	Requires large cover and structural sections [C2] Restricted movement on site due to sleeve alignment [C5]
3/ High-tolerance couplers		Well-established [C4]	Restricted movement on site due to coupler alignment and requires tight construction tolerance [C5] Difficult to achieve long-term water tightness[1] [C3]
4/ Interleaved U-bars		Common in bridge deck construction [C4] Narrow joint width required [C2]	Can achieve full tensile capacity, but limited bending capacity [C1]
5/ Interleaved T-headed bars		Narrow joint width required [C2] Can achieve full tensile and bending capacity [C1]	Less well established in the industry compared to other options [C4]

[1] Considered suitable for internal walls where short-term water tightness is sufficient.

Confirmation of precast connection performance under cyclic loading

A key technical risk identified during CREATE Stage 1 was the water tightness performance of joints between precast concrete elements. Design guidance on water tightness assumes predominantly static loading and may not adequately cover the cyclic loading present for WEC devices.

In addition, the Interleaved T-headed bar connections (Table 3, Option 5) identified as the preferred option for external joints on WEC devices is an innovative solution, and there is a limited track record of fabrication, bending performance and water tightness performance for this connection type.

To mitigate these risks, physical and numerical testing was undertaken on a full-scale model of an Interleaved T-headed bar connection. The test geometry is shown in Figure 1, and is based on a critical joint connection identified for the CETO 6 BA design, between the base slab and outer walls. This represents the joint experiencing the most significant loads and hydrostatic pressure at the serviceability limit state.

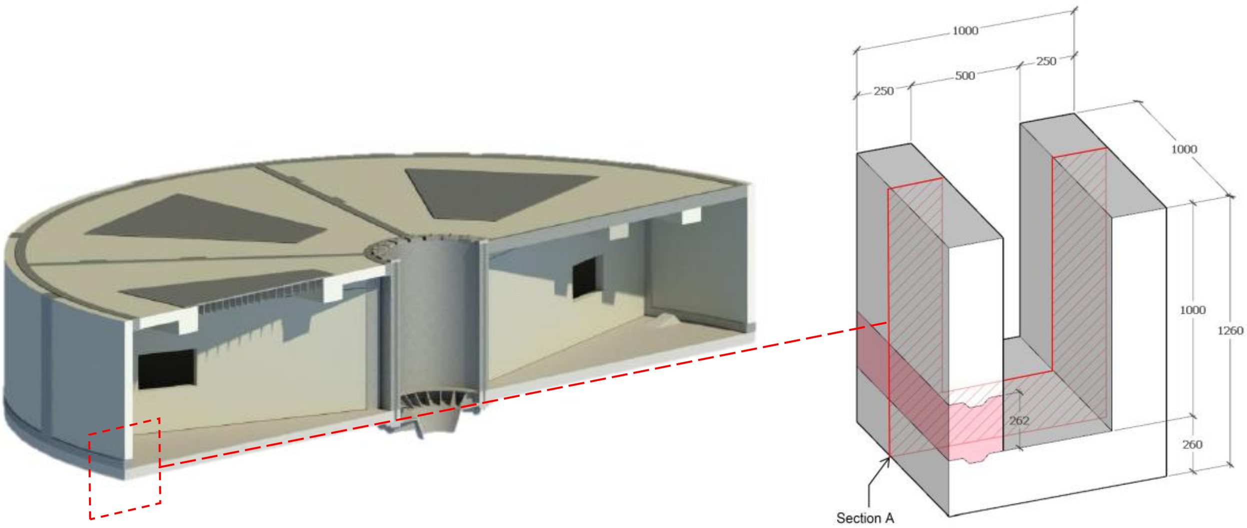


Figure 1: Left image - critical precast connection identified on concrete CETO 6 BA design. Right image - Test specimen design based on this joint to demonstrate the water-tightness performance of the precast connection.

Testing was undertaken 10,000 load cycles of 60MNm applied to the connection using hydraulic actuators (Figure 2). This represents serviceability limit state loading. The physical test results were benchmarked against detailed Nonlinear Finite Element Analysis of the U-shaped specimen.

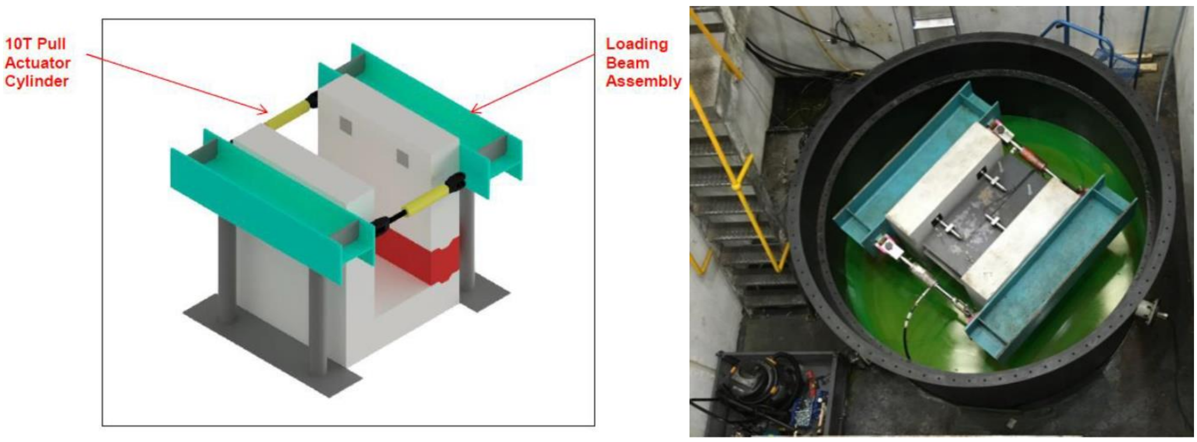


Figure 2: Left - schematic of physical test assembly. Right - image of test specimen 1 at 0.5m water depth.

A comparison of horizontal displacement at the top of the wall and crack width at the precast joint is summarised in Table 4. The results show a good match between the numerical model prediction and the physical test. Crack patterns predicted by the numerical model match closely with those observed in the physical test, see Figure 3. Cores were extracted from the physical text to demonstrate water penetration did not extend through the section, see Figure 4.

The numerical and physical tests have demonstrated the water-tightness and serviceability performance of T-headed precast concrete connections for WEC devices under representative operational conditions.

Table 4: Peak displacement comparison between physical and numerical model at end of test.

	Physical Test 1	Physical Test 2	Numerical Test 1
Precast wall displacement	3.5mm	2.9mm	3.0mm
In-situ wall displacement	2.1mm	2.2mm	2.1mm
Crack width at joint	0.36mm	0.35mm	0.37mm

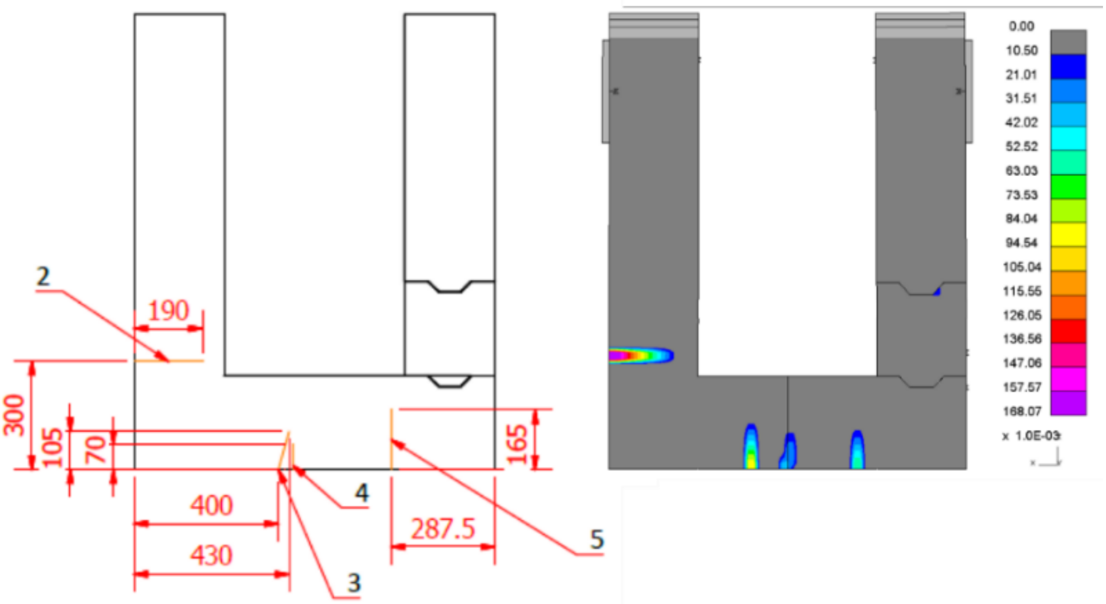


Figure 3: Specimen 1 crack pattern front view; (left) physical test (right) numerical model. Precast connection on right-hand specimen leg.

Cores extracted across the precast connection

Close up view of extracted core across the precast connection

Split core showing no water penetration past the midpoint of the section

Figure 4: Test specimen concrete coring results.

4. WEC Prime Mover Design Development

The Stage 1 concrete BA design was developed into a precast concrete solution during CREATE Stage 2. The precast BA design was developed using interleaved T-headed bars and coupler connections. The 'in-situ' BA design developed in Stage 1, and the precast concrete BA design are shown in Figure 5.

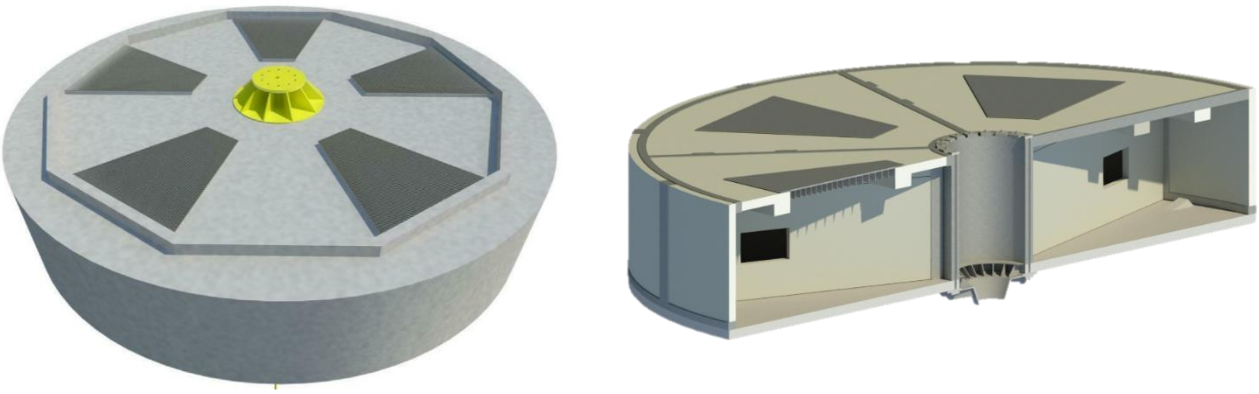


Figure 5: Stage 1 'in-situ' BA Design (left image) and Stage 2 Precast BA Design (right image).

The chosen precast BA scheme was developed in collaboration with the contractor BAM, who provided expertise on manufacturability and large-scale construction. The scheme comprised 25 no. panels with a maximum mass of 40te and a combination of 2-way and 3-way connection details, see Figure 6. BAM confirmed the feasibility of the precast construction method and on-site assembly of the required panel sizes.

BAM also provided general feedback on the final Precast BA design, and their feedback highlighted the potential of a combined in-situ design with precast roof panels as the most cost-effective option. This hybrid design was taken forward for cost assessment, presented below.

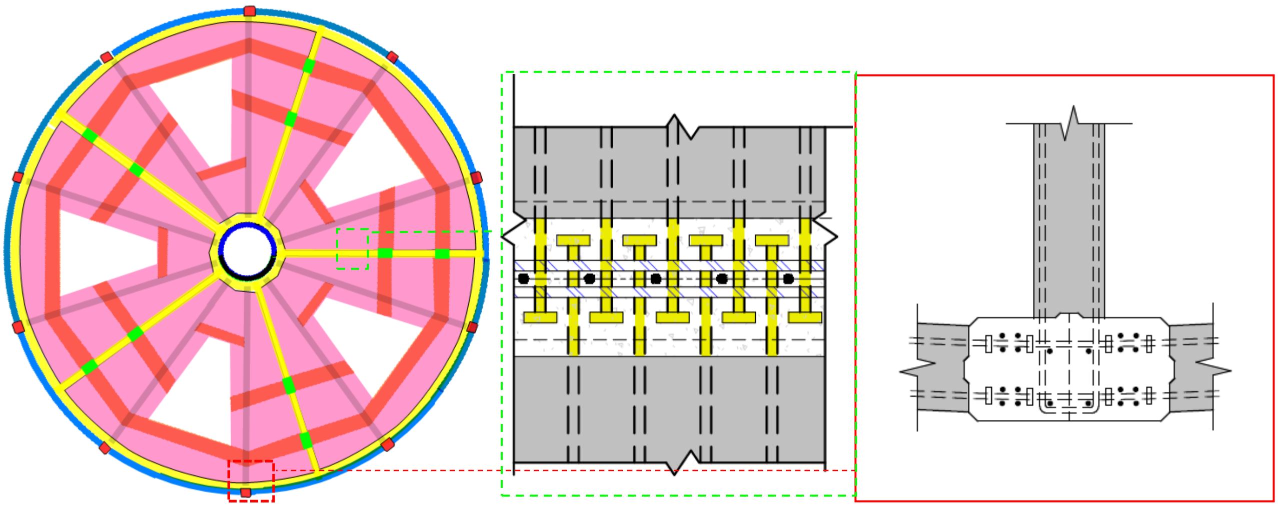


Figure 6: Precast BA Design, and details of two- and three-way connection designs developed during Stage 2.

The Stage 2 concrete BA design is approximately 15% heavier than the steel version. The target mass could be achieved if lightweight concrete was used, however contractor feedback indicated usage of lightweight concrete presents a supply chain risk so standard concrete was considered for design. The concrete BA also comprised a simplified cylindrical geometry compared to the baseline steel device. The increased surface roughness associated with concrete is anticipated to have a negligible impact on device hydrodynamics.

During Stage 2 Carnegie indicated that the power performance is most sensitive to the net buoyancy. The concrete BA was therefore sized to match the net-buoyancy of the steel device. The influence of the simplified geometry and mass increase, on loads and energy performance was quantified explicitly in Stage 2 through numerical performance assessment using the Stage 1 WEC-Sim model with concrete device properties. This confirmed the changes associated with the concrete BA had little impact on the power performance or the magnitude of peak pressures and tether loads, compared to the steel BA device.

Connection Design Development

The CETO 6 BA is attached to a tether, resulting in significant localised loading of the BA structure. A connection for transferring the force into the concrete BA was developed during Stage 2. This aimed to produce a robust and efficient technical solution for the application of significant localised loads to concrete structures that had broad applicability to WEC devices.

The tether connection design is shown in Figure 7. The design features a local steel structure which connects to the tether. This is then connected to the underside of the BA via 20 post-tensioned Macalloy bars running through the height of the BA structure. Following feedback from Carnegie, installation of the pump in dry conditions was considered the favourable option for this WEC device. Consequently, access is required to the underside of the concrete BA, and this would require raised construction for the installation (Figure 8).

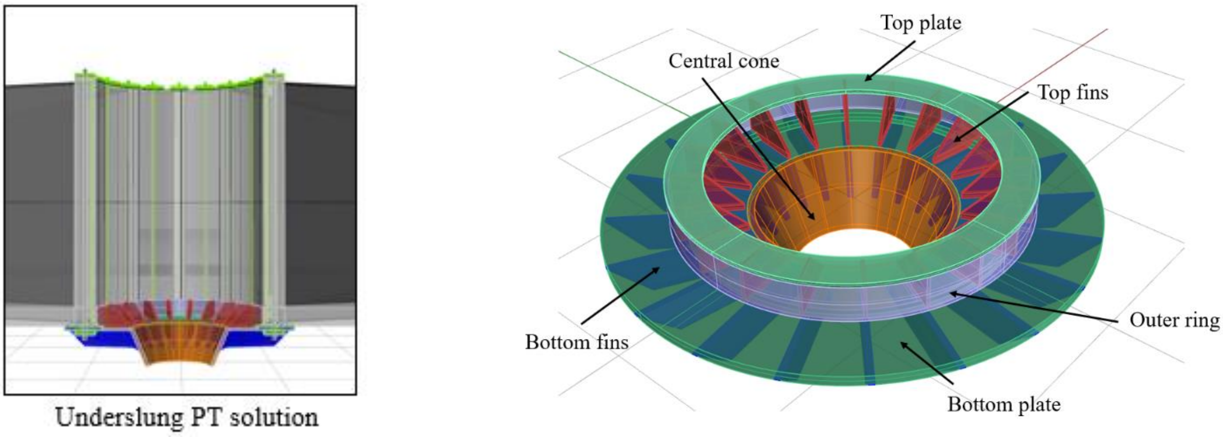


Figure 7: Central tether connection developed during Stage 2. All plated steel specified as S420.

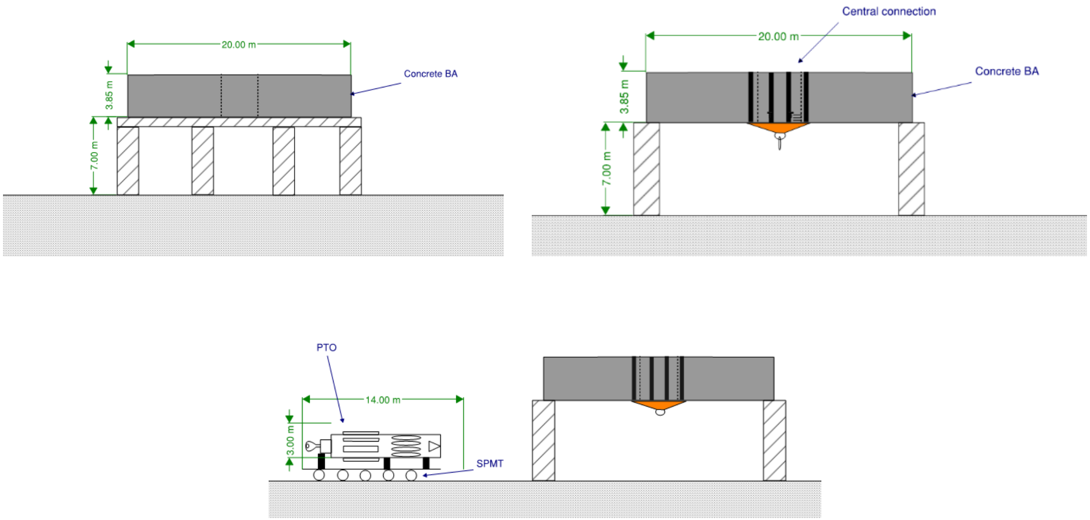


Figure 8: Underslung pump installation with raised construction at dry dock or quayside for CETO 6 WEC device.

The pump Power Take Off (PTO) solution and associated challenges are specific to the CETO 6 device. Alternative PTO options, for example sea-bed mounted or an internally-mounted PTOs, would enable a significantly simpler installation sequence for the BA. The selected tether connection design (PT bar and underside plug) would be suitable for an alternative PTO whilst avoiding raised construction. This would involve attaching the tether connection during construction base slab on the ground as shown in Figure 9.

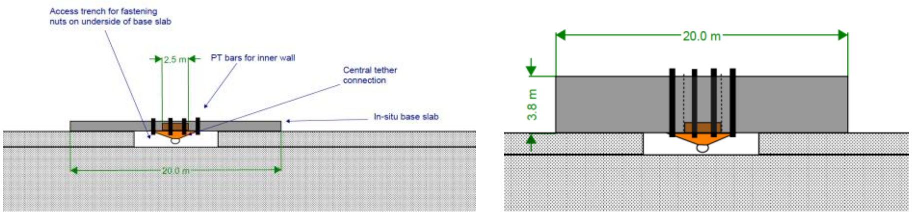
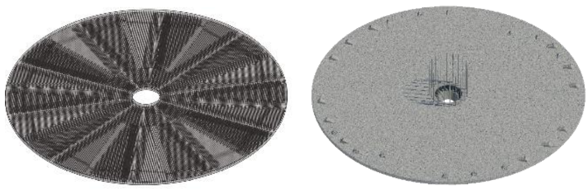


Figure 9: Construction of BA and central tether connection without requiring raised construction.

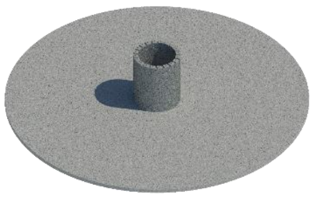
Manufacturing of Precast Concrete WEC Device

The Concrete Centre in collaboration with BAM developed a technical roadmap to enable serial production of the concrete devices. The overall construction methodology is shown in Figure 10. Several feasible methods for launching the concrete BA have been identified. Dry dock construction and launch was identified as the most suitable method for low volume construction at demonstrator scale (Figure 11). For larger production volumes, limited dry dock space would inhibit production rates. Quayside construction and launch using a heavy lift crane or skidding onto a submersible barge represent more effective options for serial production (Figure 12).



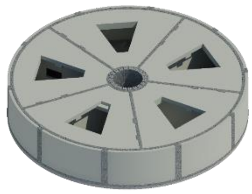
Stage 1a – Install reinforcement and central tether connection and cast base slab

Stage 1b – Manufacture precast wall and roof panels

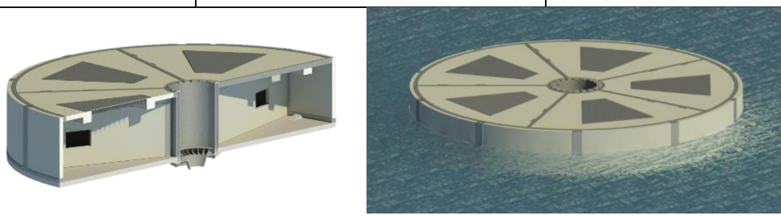


Stage 2 – Cast inner wall

Stage 3 – Install and stitch together precast wall panels

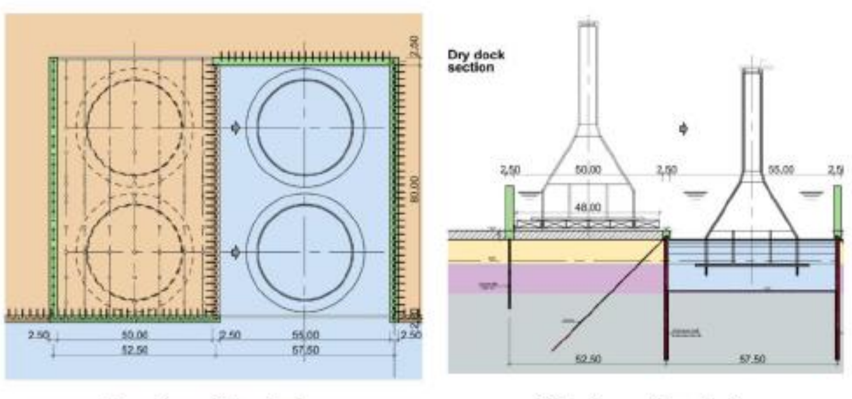


Stage 4 – Install and stitch together precast roof panels



Stage 5 to 7 – Finish, transport and launch

Figure 10: Concrete BA precast construction methodology.



Top view of dry dock Side view of dry dock

Figure 11: Plan and side elevation view of launch methodology for low volume production of concrete WECs from a dry dock.

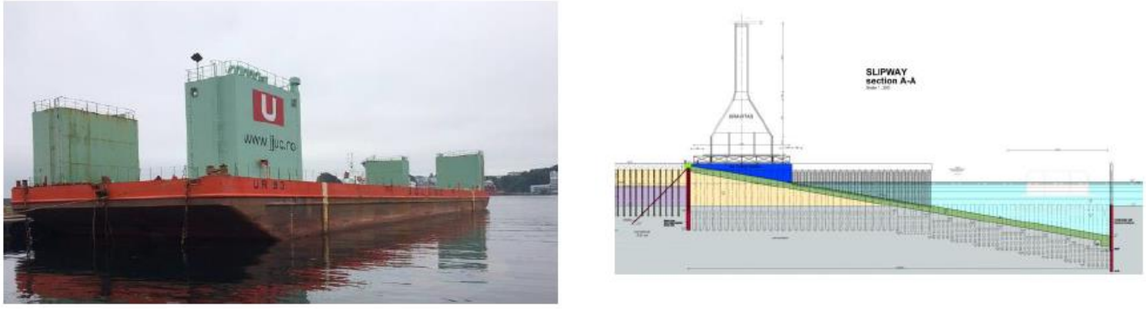


Figure 12: Launch methodology options for serial production of concrete WECs using: (left) a submersible barge; or (right) quayside construction and launch with a heavy lift crane, slipway or skid.

Five potential construction sites in Scotland have been identified for serial production of concrete WECs and a detailed construction sequence for 100 units developed. It is concluded that the Scottish supply chain currently has capacity to deliver 100 units with significant local content. Delivery of the units is estimated to take 178 weeks, including full set up and demobilisation of the construction site, see Table 5.

Table 5: Summary of construction programme for production of 100 concrete BAs.

Item	Duration
FEED study period	26 weeks
Mobilisation and establish factory	18 weeks
Manufacture and launch units (including 2 x two-week Christmas shutdowns)	118 weeks
Demobilisation	8 weeks
Weather risk allowance	6 weeks
Overall duration	178 weeks

Cost and Life Cycle Assessment of Precast Concrete WECs

The findings of a cost comparison between steel and concrete WEC devices is summarised in Table 6. The CAPEX assessment predicted a 55% reduction in the material and labour cost for a concrete BA compared to a steel equivalent.

Construction and launch costs are predicted to be higher for a concrete device, as development of a construction site is required rather than use of a pre-existing fabrication yard for steel devices. Accounting for this, a 6% reduction in total CAPEX is predicted for a concrete BA compared to a steel equivalent. Cost estimates for development of the construction site and device launch vary significantly between Arup estimates and an independent assessment from BAM and represents a significant uncertainty at this stage.

A detailed OPEX assessment was also conducted. Concrete has lower O&M requirements than steel and a 20% reduction in OPEX and 6% improvement in availability was predicted.

Use of a concrete BA is predicted to reduce the LCoE by 12% compared to a steel equivalent. As is typical of concrete structures, the concrete BA has been designed for a 50-year life, both from a durability and fatigue perspective. A concrete BA may therefore enable further LCoE reduction based on an increased design life. If a 50-

year design life for the structure is exploited, with continued refurbishment events assumed at 7-year intervals for mechanical and electrical equipment, the LCoE reduction is predicted to increase to 18%.

Table 6. Cost assessment metric results (per WEC assuming fabrication of 100 units).

	Steel BA	Concrete BA	Difference
Structural CAPEX [Materials and Labour]	£446,000	£203,000	-55%
Structural CAPEX [Total Fabrication]	£494,000	£465,000	-6%
OPEX	£90,000/WEC/yr	£73,000/WEC/yr	-19%
LCoE [25-year design life]	121/MWh	106/MWh	-12%
LCoE [50-year design life concrete BA]	121/MWh	99/MWh	-18%

Overall Achievements

CREATE Stage 2 aimed to justify that concrete is a feasible, cost effective material for WEC applications with a focus on the higher risk structural details. Key areas of interest include:

- Demonstration of precast concrete construction as a technically viable option for WEC devices, including development of the Stage 1 ‘in-situ’ construction concrete buoyant actuator (BA) design into a precast concrete solution.
- Areas of high localised loading, e.g. tether and mooring point connections, which were developed to an indicative level only during Stage 1.

Interleaved T-headed bars and coupler connections were identified as preferred connection options, for external and internal connections respectively. T-headed precast connections are currently used only in simple load applications and there is a limited track record of fabrication, bending performance and water tightness performance for this connection type. Design rules to assess Ultimate Limit State (ULS) and Fatigue Limit State (FLS) capacity exist, but guidance for serviceability (SLS) assessment (crack widths and water tightness) is limited. The use of T-headed bars is an innovative solution, applying an existing approach in a novel situation. A critical T-headed connection was therefore selected for full-scale physical and numerical testing to demonstrate serviceability performance.

The test was subject to cyclic SLS loading in submerged conditions at representative hydrostatic pressure. The outputs of the test included crack width measurements, which were compared against code limits for durability, and a water-tightness check by extracting cores and examining the extent of water penetration through the section. Two specimens were constructed and tested, and both demonstrated acceptable water-tightness and crack width performance.

Displacement measurements from the physical tests were compared with a detailed nonlinear finite element analysis model of the test specimen. The numerical and physical tests showed good correlation in results. This gives confidence in use of the numerical model for sensitivity analysis or design of similar connections, without the need for further physical testing.

Stage 2 also aimed to demonstrate the feasibility of highly localised loading (e.g. tether/mooring connections) for concrete WEC structures, a typical requirement for WEC devices. A robust and efficient technical solution for the CETO 6 tether connection was developed in Stage 2, which has broad applicability for transferring significant localised loads to concrete WEC structures.

Additional Stage 2 activities comprised development of the Stage 1 CETO 6 design into a FEED level precast solution to enable detailed manufacturing and cost assessment to be undertaken. The Concrete Centre in collaboration with BAM developed a manufacturing plan for serial production of the concrete devices. Five potential construction sites in Scotland have been identified and a detailed construction sequence for 100 units developed. It is concluded that the Scottish supply chain currently has capacity to deliver 100 units with significant local content. Delivery of the units is estimated to take 178 weeks, including full set up and demobilisation of the construction site.

BAM also provided contractor feedback on the concrete BA design and an independent CAPEX assessment. Their feedback highlighted the potential of a combined in-situ design with precast roof panels as the most cost-effective option. This hybrid design was taken forward for cost assessment.

The CAPEX assessment predicted a 55% reduction in the material and labour cost for a concrete BA compared to a steel equivalent. Close agreement was achieved between the Arup and BAM estimates. Construction and launch costs are predicted to be higher for a concrete device, as development of a construction site is required rather than use of a pre-existing fabrication yard. Accounting for this, a 6% reduction in total CAPEX is predicted for a concrete BA compared to a steel equivalent. Cost estimates for development of the construction site and device launch vary significantly between Arup and BAM as this represents a significant uncertainty at this stage. A detailed OPEX assessment was also conducted using a detailed operations and maintenance (O&M) model for both concrete and steel BA options. Concrete has lower O&M requirements than steel and a 20% reduction in OPEX and 6% improvement in availability was predicted.

Use of a concrete BA is predicted to reduce the LCOE by 12% compared to a steel alternative based on the example Carnegie CETO 6 device. As is typical of concrete structures, the concrete BA has been designed for a 50-year life, both from a durability and fatigue perspective. A concrete BA may therefore enable further LCOE reduction based on an increased design life. If a 50-year design life for the structure is exploited, with continued refurbishment events assumed at 7-year intervals for mechanical and electrical equipment, the LCOE reduction is predicted to increase to 18%.

5. Recommendations for Further Work

CREATE Stage 2 has further demonstrated that concrete is a feasible material for WEC applications and could enable significant cost reduction. Stage 2 comprised development of the Stage 1 'in-situ' CETO 6 concrete BA into a precast concrete version, a cost-effective option for serial production. The design has been developed to a FEED level and full scale physical and numerical testing undertaken to justify the technical suitability of precast connections in this context.

Given the success of the Stage 2 testing and maturity of the material in an offshore context, additional physical testing is not considered necessary. Further work should therefore focus on commercial exploitation with the aims of priming the supply chain and enabling end-users to exploit the material. Residual technical risks do exist, but these can be mitigated through design and numerical analysis. Proposed Stage 3 activities are summarised below.

Mitigation of Outstanding Technical Risks

Stage 2 Residual Risk	Mitigation Activity
The concrete BA is not suited to the CETO 6 underslung pump PTO due to significant complexity associated with assembly and launch.	Demonstration of compatibility with other PTO technologies. This may take the form of design development of the latest version of the Carnegie device, which includes a rotary PTO.
Additional water ballast is typically not required for concrete WECs. The absence of a ballasting system during installation means stability and pull-in loads need to be comprehensively assessed.	Development of a marine operations and installation plan for an example concrete WEC. This should include dynamic installation and stability analysis.
A maintenance plan, including repair, has not been developed for the material.	Development of a detailed maintenance strategy. This should include comprehensive inspection and maintenance activities. It should also include methods for material repair, for example following impact, to achieve original material strength and durability.
Concrete WEC structures typically have higher total mass and simplified geometry. The influence of this on loads and energy performance was assessed only to a preliminary level in Stage 2 and for a specific device.	A more detailed numerical loads and energy performance assessment should be undertaken. Extending this to provide more generic insight for the main WEC types would enable conclusions to be more broadly applicable.

Development of Expert Design Decision Tool

CREATE Stage 1 and 2 activities have resulted in extensive concrete design knowledge in a WEC context. This includes a comprehensive understanding of key risks, constraints, and opportunities, and development of a robust and efficient design process. Development of a digital expert tool enabling WEC developers to rapidly assess the potential for using concrete in their device designs would enable this knowledge to be consolidated and effectively disseminated.

Detailed Assessment of Manufacturing Requirements and Supply Chain Capacity

The CREATE Stage 2 manufacturing assessment involved significant assumptions associated with the construction and launch method due to unknowns at this stage. It is recommended that an exercise is undertaken to consider a number of manufacturing and launch scenarios based on specific potential manufacturing sites. This will enable optimisation of the manufacturing and launch method and reduction in uncertainty. A detailed set of manufacturing requirements for serial production of concrete WECs should also be developed, to enable the capacity of the supply chain in Scotland to be confirmed.

Development of Business Case and Exploitation Plan

The potential LCoE benefit for an individual concrete WEC has been assessed during CREATE Stages 1 and 2. This should be expanded with a broader market analysis to identifying the types of WEC most suitable for concrete and quantify the total market value. Applications that would be particularly suitable for commercial scale deployment of concrete WECs should also be identified, for example offshore energy generation and storage, i.e. using the WEC hull structure to store e.g. hydrogen or ammonia. The market analysis could further be expanded into other relevant non-WEC sectors, such as the potential of concrete for floating offshore wind foundations. This market analysis will form the basis of a credible business plan.

Development of an exploitation strategy is also recommended to identify the short (demonstrator), medium and long-term (serial production) impacts of the CREATE project and the activities needed to exploit these impacts. This will include developing, maintaining and licencing future IP generation associated with the material technology and associated design methods.

6. Communications and Publicity Activity

The CREATE project has been included in several press releases and on the Arup website, including the links below.

http://renews.biz/106553/arup-signs-for-scots-wave-study/

http://www.waterpowermagazine.com/news/newsarup-to-study-alternative-materials-for-wave-power-devices-5778759

https://www.waterbriefing.org/home/technology-focus/item/13792-arup-to-investigate-alternative-materials-to-advance-wave-power-technology

http://www.scottishenergynews.com/arup-wins-new-scot-govt-wave-power-energy-convertor-contract/

http://www.arup.com/news/2017_04_april/04_april_arup_to_investigate_alternative_materials_to_advance_wave_power

The project was also presented at the 2018 WES annual conference, the poster has been attached to this report.

7. Useful References and Additional Data

Project Documents (available on request)

Ref.	Author	Document Reference	Report Title
	Arup	WES_ARP_MT21_D03	Design Basis
	Cruz Atcheson	WES_ARP_MT21_D04	CETO 6 Loads and Performance Analysis Report
	Arup	WES_ARP_MT21_D05	Design Drawings
	Arup	WES_ARP_MT21_D06A	Precast Connection Technical Report
	Arup	WES_ARP_MT21_D06B	Mocean Concrete Feasibility Study
	Arup	WES_ARP_MT21_D06	Structural Design Report
	Arup	WES_ARP_MT21_D08	Risk Reduction Testing Report
	Arup	WES_ARP_MT21_D09	Manufacturing Report
	Arup	WES_ARP_MT21_D10	Cost of Energy Assessment

Design Codes and Standards (publicly available)

Ref.	Code	Title	Issue
	DNV-OS-C502	Offshore standard: Offshore Concrete Structures	Sep 2012
	BS EN 1992-1-1:2010	Eurocode 2 Design of concrete structures, Part 1-1, General rules and rules for buildings	2010
	BS 4449:2005	Steel for the reinforcement of concrete – Weldable reinforcing steel, bar, coil and decoiled product	2005
	BS 5896:2012	High tensile steel wire and strand for the prestressing of concrete – Specification	2012
	BS 8500-2:2015	Concrete - Complementary British Standard to BS EN 206. Specification for constituent materials and concrete	2015

Publicity Material

Filename	Media Type	Description
WES CREATE S2 Public Poster 2018.pdf	.pdf	Poster presented at WES annual conference 2018
WES CREATE S2 Concrete WEC Drawings.pdf	.pdf	Concrete Carnegie BA structural drawings
WES CREATE S2 Public Poster 2019.pdf	.pdf	Poster presented at WES annual conference 2019