Final report

1.1 Project details

Project title	FLOAT2 – New Flexural UHPC Application for Wave Converters 2
Project identification (program abbrev. and file)	Energinet.dk project no. 2012-1-10754
Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	Hi-Con A/S Hjallerup Erhvervspark 1 9320 Hjallerup
Project partners	Wavestar Energy Aalborg Universitet
CVR (central business register)	26020387
Date for submission	10 August 2016

1.2 Short description of project objective and results

The main objective of the project was to demonstrate a new concept for wave energy floaters produced in Ultra High Performance Fibre Reinforced Concrete (UHPFRC) that would be cheaper, faster to produce, more sustainable, with better durability and better resistance to fatigue. Using floaters of this type – and ultimately also other structural parts in UHPFRC - was to help in reducing the price of wave energy. Unfortunately, the project was terminated ahead of time due to the decision by Wavestar to stop their activities, as they were not able to find additional internal funding. With Wavestar as the main user of this technology, it was not possible to continue the project without them. For each of the secondary objectives of the project the conclusions are listed below:

- **Optimization of UHPFRC formulation for the floaters**:
  This objective has been met through testing of a number of different fibre formulations to optimize especially tensile properties and crack control. In addition, two test series were carried out to investigate the effect of casting on fibre distribution and fibre orientation.
- **Optimization of design for the floater and the hydraulic arm that attaches the floater to the body of the Wavestar WEC**:
  This objective was only partially met. The design of the floater has been through several iterations as the requirements were changed, but eventually a satisfactory design was achieved for the C6 (with a 6 meter diameter) floater. For the hydraulic arm, the design was made for the C5 version, but not for the C6.
- **Production and test of full-scale arm and floater on test-site in Hanstholm**:
  This objective was not met. Preparations have been made for the production,

but as the project could not be carried out to its conclusion, it was decided not to carry out the very expensive production phase – and the even more expensive installation on a test-site.

- **Extrapolation of results to other WEC's and other structural elements to achieve further reductions in cost:**
  This objective was not met.

A lot of effort has been invested in the determination of loads for the floater and arm as well as the design of the floater and arm, but as the project was stopped prior to the actual production and testing of a full-scale floater, the design has not been validated.

Wavestar was intended to be the main user of the results of the project – and as they have discontinued their activities, the results of the project will not be used directly. Aalborg University may be able to use their results on load determination on other projects related to wave energy and the results with regard to material optimization could potentially be useful in other applications where the fibres are to provide the main tensile strength. However, while the use of the CRC material – the special type of UHPFRC used by Hi-Con - could certainly be a good solution for other offshore applications, this will be difficult without a demonstration project.

Hovedformålet med projektet var at designe og afprøve en ny type flyder til bølgeenergi baseret på fiberarmeret højstyrkebeton (UHPFRC), der i forhold til eksisterende løsninger i fiberglas skulle være billigere, hurtigere at producere, mere miljøvenlig, med bedre holdbarhed samt med en bedre opførsel i forhold til udmattelse. Anvendelse af flydere af denne type – og på sigt også andre konstruktionsdele i UHPFRC - skulle medvirke til at reducere prisen på bølgeenergi.

Desværre måtte projektet afsluttes før planlagt, da Wavestar ikke længere var i stand til at finde intern finansiering til deres aktiviteter, og derfor måtte trække sig fra projektet. Med Wavestar som slutbrugeren af den teknologi, der skulle udvikles i projektet, var det ikke muligt for de andre partnere i projektet at fortsætte på egen hånd. For hvert af de sekundære mål i projektet er konklusionerne angivet nedenfor:

- **Optimering af UHPFRC sammensætning til anvendelse i flydere:**
  Dette mål er nået gennem afprøvning af en række fibersammensætninger, der specielt skulle optimere matricens trækstyrke og revnekontrol. Efter afdækning af det potentiale, der bl.a. var i at kombinere flere fibertyper, er der desuden gennemført to forsøgsserier, der skulle undersøge hvordan udstøbningen påvirkede fiberfordeling og fiberorientering.

- **Optimering af designet på flyderen og på den hydrauliske arm, der fastgør flyderen til Wavestars bølgemaskine**:
  Dette mål er kun delvist opnået. Flyderen er blevet designet over flere omgange i takt med at kravene til størrelse og udformning ændrede sig, og et tilfredsstillende design blev også opnået for C6 flyderen – den flyder med en diameter på 6 meter, der var det endelige krav på projektet. For den hydrauliske arm blev der lavet et design til en C5 version, men da flyderen blev ændret til C6, blev det valgt at fokusere ressourcerne på flyderen og undlade at gentage designprocessen for armen og dermed opgradere den til C6.

- **Produktion af fuld-skala arm og flyder samt afprøvning i Hanstholm:**
  Dette mål blev ikke nået. De indledende øvelser til element-produktionen er udført (krav til forme, støbefaciliteter, lagring), men da projektet ikke kunne gennemføres fuldt ud, blev det besluttet at undlade den dyre produktion – og den endnu dyrere installation på en ny test-placering offshore.

- **Overførsel af resultater med UHPFRC til andre bølgemaskiner og til andre konstruktionsdele for at opnå yderligere besparelser:**
  Dette mål blev ikke nået.

En stor del af projektets ressourcer er anvendt til bestemmelse af laster på flyder og arm, samt til design af flyder og arm, men da projektet blev stoppet før produktion og afprøvning af en flyder i fuld skala er designet ikke blevet valideret.

Wavestar skulle have været slutbrugeren af projektets resultater, og eftersom Wavestar har valgt at stoppe alle deres aktiviteter, vil de resultater, der blev opnået i projektet, ikke blive anvendt direkte. Aalborg Universitet arbejder stadig med bølgeenergi og kan måske finde anvendelse for de resultater, de har opnået omkring bestemmelse af laster. De resultater, der er opnået omkring materiale optimering, kan potentielt også anvendes til konstruktioner, hvor fibrene skal give det væsentligste bidrag til trækstyrke i betonen. Selv om CRC – den type UHPFRC, der anvendes af Hi-Con – har et stort potentiale for anvendelse i offshore konstruktioner, vil det dog være svært at få afprøvet uden det demonstrationsprojekt, der skulle have været gennemført som en del af FLOAT2 projektet.

1.3 Executive summary

The project – which started in March 2012 - was originally intended to conclude by February 2014, but a number of outside influences have postponed the project several times. The most significant of these was the need to remove the Wavestar test-machine from the test-site in Hanstholm, as the harbour expected to start an ambitious expansion project. Eventually, the project was concluded ahead of time due to the decision by Wavestar to stop their activities – and very little work was done in the last year of the project as Wavestar made an effort to find additional funding for their activities. This meant that the main objective of demonstrating a new concept for wave energy floaters that could help in reducing the price of wave energy was not met.

The major activities in the project involved improved determination of loads on the structure and optimization of the concrete formulation for the floater as well as design of the hydraulic arm and the floater – where several re-designs were necessary as circumstances changed.

Initial work was also done regarding production of the hydraulic arm and the floater, but the project was terminated before production was started, which of course also meant that the activities connected to installation of the floater, exposure on site and monitoring were not carried out.

Wavestar was intended to be the main user of the results of the project – and as they have discontinued their activities, the results of the project will not be used directly.

Aalborg University may be able to use their results on load determination on other projects related to wave energy and the results with regard to material optimization could potentially be useful in other applications where the fibres are to provide the main tensile strength – but this will be difficult without a demonstration project. The design is not expected to be useful for any of the partners – or for others that work in this or related fields.

1.4 Project objectives

The main objective of the current project was to demonstrate a new concept for Wave Energy floaters produced in Ultra High Performance Fibre Reinforced Concrete (UHPFRC). While these floaters should be faster to produce, more sustainable and with better durability and better resistance to fatigue than the current floaters, they should also represent a significant reduction in cost. Ultimately, this should help in reducing the price of wave energy towards similar levels to those of wind energy. The project was to include:

- Optimization of UHPFRC formulation for the floaters
- Optimization of design for the floater and the hydraulic arm that attaches the floater to the body of the Wavestar WEC
- Production and test of full scale arm and floater on test-site in Hanstholm
- Extrapolation of results to other WEC's and other structural elements to achieve further reductions in cost

As a preliminary study had already been carried out, it was expected that the initial stages of the project would not present too much difficulty, but as soon as the project was started up, it was discovered that the initial design for the floater and the hydraulic arm – based on a truss for the arm - would not work. This resulted in a few weeks of intensive investigation into new ideas for the design and eventually Aalborg University came up with a proposal based on a pre-tensioned box structure for the arm with further support by external post-tensioning. This re-design resulted in the first request for a small extension of the time schedule. Since then it has been necessary to revise the time schedule several times. In early 2013 because it turned out that it was necessary to move the WEC from the test-site in Hanstholm (due to an expected expansion of the harbour) and finally because the consortium chose to change the floater design from an ø5m diameter (C5) version to an ø6m diameter (C6) version, that was intended for the new applications envisioned by Wavestar. As this change to a larger floater included a considerable extra design effort, an application for supplementary funding was sent to Energinet – and granted (600.000 in PSO-funding). Originally, the project was to conclude in February 2014, but with the different extensions the final version of the time schedule planned for the project to conclude in February of 2017 – until Wavestar informed the other partners of their decision to terminate their activities as of May 1st, 2016 (see Annex A).

The unforeseen problem – that Wavestar had to vacate their test-site in the Hanstholm harbour and had to relocate to another test-site – was a considerable delay to the project – especially as it took a long time before another possible test-site could be identified. It also added a large cost for Wavestar as the WEC had to be taken ashore and refitted before it could be installed on another site – a cost calculated at 30 million DKK.

This potential cost was probably a contributing factor to the decision made by Wavestar.

1.5 Project results and dissemination of results

Task 2: Design of arm and floater

As described above the initial design for the arm was a truss structure (fig.1), but after it was determined that this would not be strong enough it was replaced by a box design with prestressing (fig. 2). Because of the huge forces involved, this box design is still at the limit of what can be done (only one precasting facility in Denmark has the necessary equipment to produce this kind of prestressing for an element).

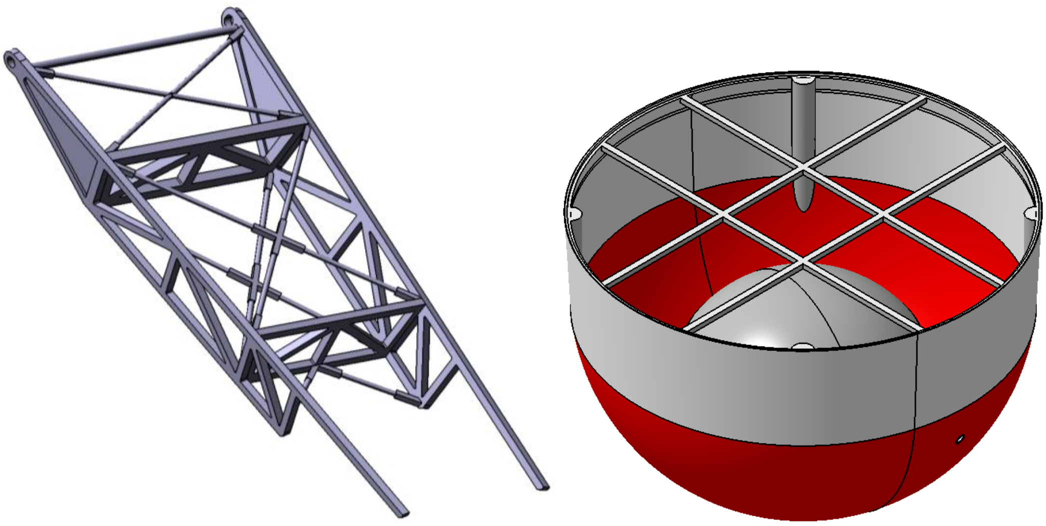

Figure 1 Initial design of arm and floater, where the arm is based on a truss design.

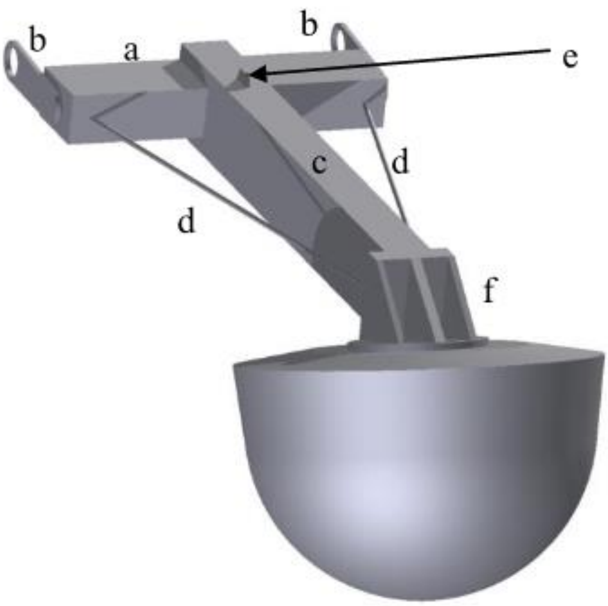

Figure 2 Second design of arm and floater – the arm includes pretensioned wires.

The floater was also tweaked a bit in the design as the combined weight of the arm and floater became a problem. The idea behind the Wavestar design is that the floaters are lifted out of the water if the waves become too high (fig. 3) – and that means that the combined weight of the arm and floater should be within the capacity of the hydraulic piston that is attached to the arm. This capacity is around 20 tons. This was another challenge that had to be met in the design (see Annex B for the design report), and the eventual solution was to move the attack point of the piston slightly.

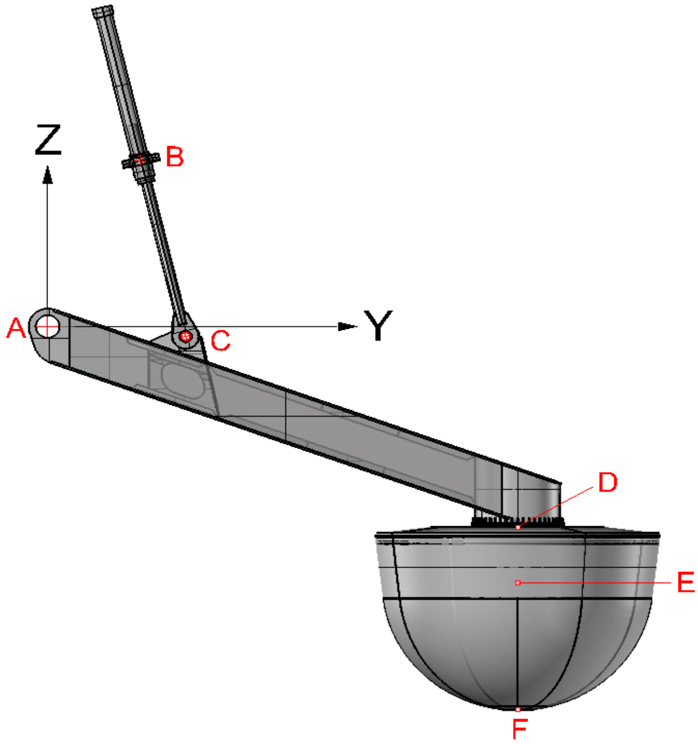

Figure 3 Position of hydraulic piston on the arm of the floater.

The final challenge for the design was based on the Steering Group decision of changing from a C5 design for the floater to a C6 design – a decision that was based on the expectation that the C5 design would probably never again be used in practical applications. With the new loads this would attract it was necessary to do a full redesign – and to concentrate the efforts on the floater it was decided that a redesign of the arm would not be made until a later stage. The final design of the floater is shown in fig. 4. In this version, the struts that were present on the inside to stiffen the structure in earlier versions has been removed, and the inner side is smooth with a bracing at the top. As the lid no longer has to take large loads (as opposed to earlier designs), this is now a thin fibre glass top (see Annex C). The maximum stresses in the body of the floater are achieved with slamming loads, where tensile stresses are between 6 and 9 MPa. This is around the limit of what can be achieved with the material design, but the intention was to use a fibre content of 3% and then employ a tentative approach in exposure. This would mean that initially the floater would be lifted out of the water at 4 m wave heights, after a short period 5 meter wave heights would be allowed and so forth. Unfortunately – as the project was terminated prior to the production of a floater – this could not be tested.

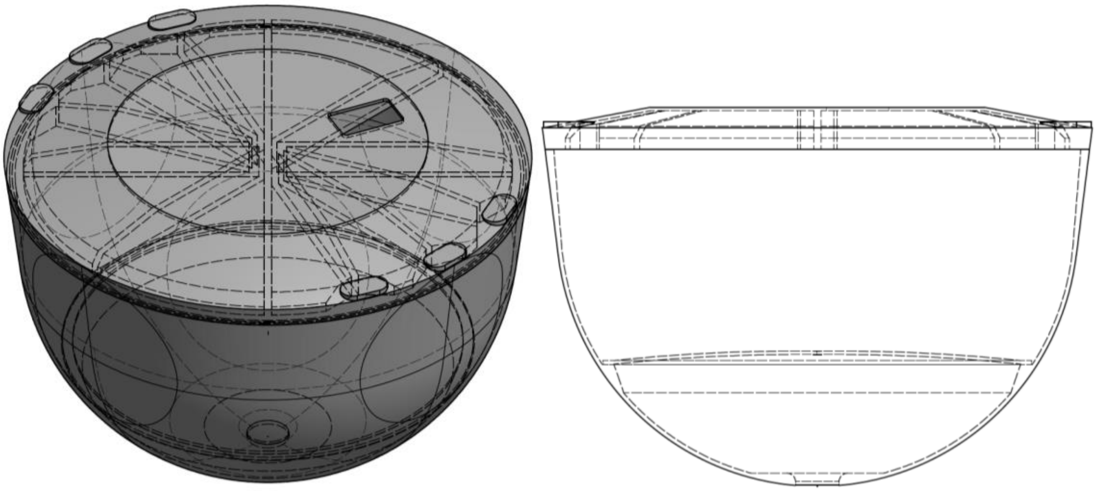

Figure 4 Final design of a C6 floater in UHPFRC.

Task 3: Production and installation of arm and floater
This task was never actually carried out, but the planning of production went on for several years and included a number of visits to mould producers as well as trial castings.

The major challenge for production of the arm was the amount of prestressing necessary, so a couple of initial tests were carried out, where small-scale beams with hollow sections were produced, prestressed and tested at Aalborg University. A picture is shown in fig. 5.

Figure 5 Testing of pre-stressed beam with hollow core.

As mentioned in the previous section, it was decided to refrain from a re-design of the arm when the floater was changed from a C5 design (with a weight of 10 tons) to a C6 design (with a weight of 20 tons). This meant that further production tests for the arm were abandoned.

With regard to production of the floater it was relatively quickly decided that a traditional mould in timber or steel would not be an option – due to cost as well as the problems of accommodating the shrinkage of the concrete until de-moulding. Production of a small ø1m diameter floater had been done in a relatively expensive plywood mould in an earlier project, but with the much larger size of the C5 floater (and later the C6) other materials were investigated. One of these materials were a foam product from the German company WEDI, which would have to CNC-cut the different parts of the mould, and then coat the foam with an epoxy-coating. A small test mould – shown in fig. 6 – was made and a test specimen was cast with good result, but going to the much larger scale was such a challenge, that different options were discussed at meetings at the factory in Germany.

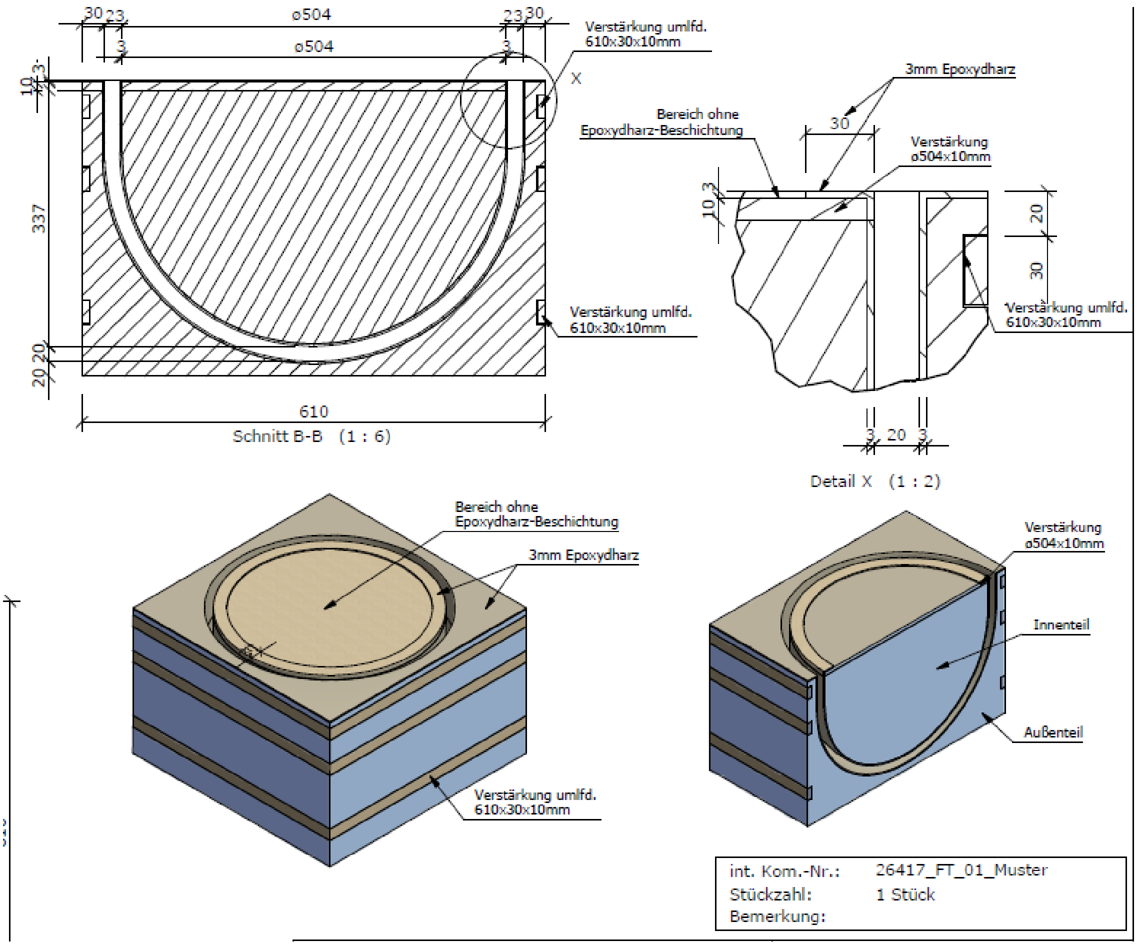

Figure 6 Excerpt from production drawing by WEDI for a floater mould in small scale.

Ultimately, the WEDI design was abandoned for financial reasons and contact was made to a Danish company called ODICO, which had ideas for producing a mould based on a cheaper foam and with a cheaper cutting process. With this new mould it was expected that the price – including the necessary strengthening to cope with the large casting pressure - would be in the range of 800.000 DKK. It was expected that the mould should be reusable, but this was something that would have to be tested.

It was originally the intention that the floater in UHPFRC should replace one of the fibre glass floaters on the test machine in Hanstholm, but as described in the preceding section it was necessary to move the test machine before this could be carried out due to the intended expansion of the Hanstholm harbour. The revised plan for exposure of a UHPFRC floater, was to change the floater diameter from 5 m to 6 m, and then include the UHPFRC floater as one of 4 floaters on a refurbished test machine as it was installed on a new test site. The cost of refurbishing the test machine and installing it on a new site was estimated at 30 million DKK. The considerable cost of this was a contributing factor to the Wavestar decision of finalizing their activities.

Task 4: Development of materials

The main development of materials in the project was based on testing new types and combinations of fibres with CRC – the special type of UHPFRC used by Hi-Con - as a large part of the floater was intended to include only the fibre reinforcement and no conventional reinforcing bars. An early test series demonstrated that it would be possible to achieve bending strengths above 20 MPa by combining small diameter short fibres with larger hooked end fibres (30 mm long). The small fibres were effective in preventing cracking, while the longer fibres provided ductility. This combination seemed to exhibit better – and more stable - performance than mixes with just one type of fibre. A number of different fibre compositions were tested and a few of the results are shown in fig. 7. The mix from 29/8 is the preferred mix for this project – a combination of the hooked end fibres and the small brass coated fibres – which gives a relatively stable pull-out of fibres, where there is a relatively small variation. A mix with just the hooked end fibres (27/8) actually give a higher tensile strength in most cases – but with a larger variation and earlier cracking. A mix with just the small fibres (4/9) provides much less ductility as the short fibres are pulled out early – before the deformations become large. The final graph (29/1) shows the results for a test series made with larger hooked end fibres (60 mm). In this case the fibres act as small reinforcing bars, and it is actually discernible on the curve as the different fibres fail. The long fibres had a poor effect on workability and they were still bundled in the failed specimens as can be seen in fig. 8. The test results for the mix of 29/8 – with appropriate safety factors – were used as input for the design of the floater.

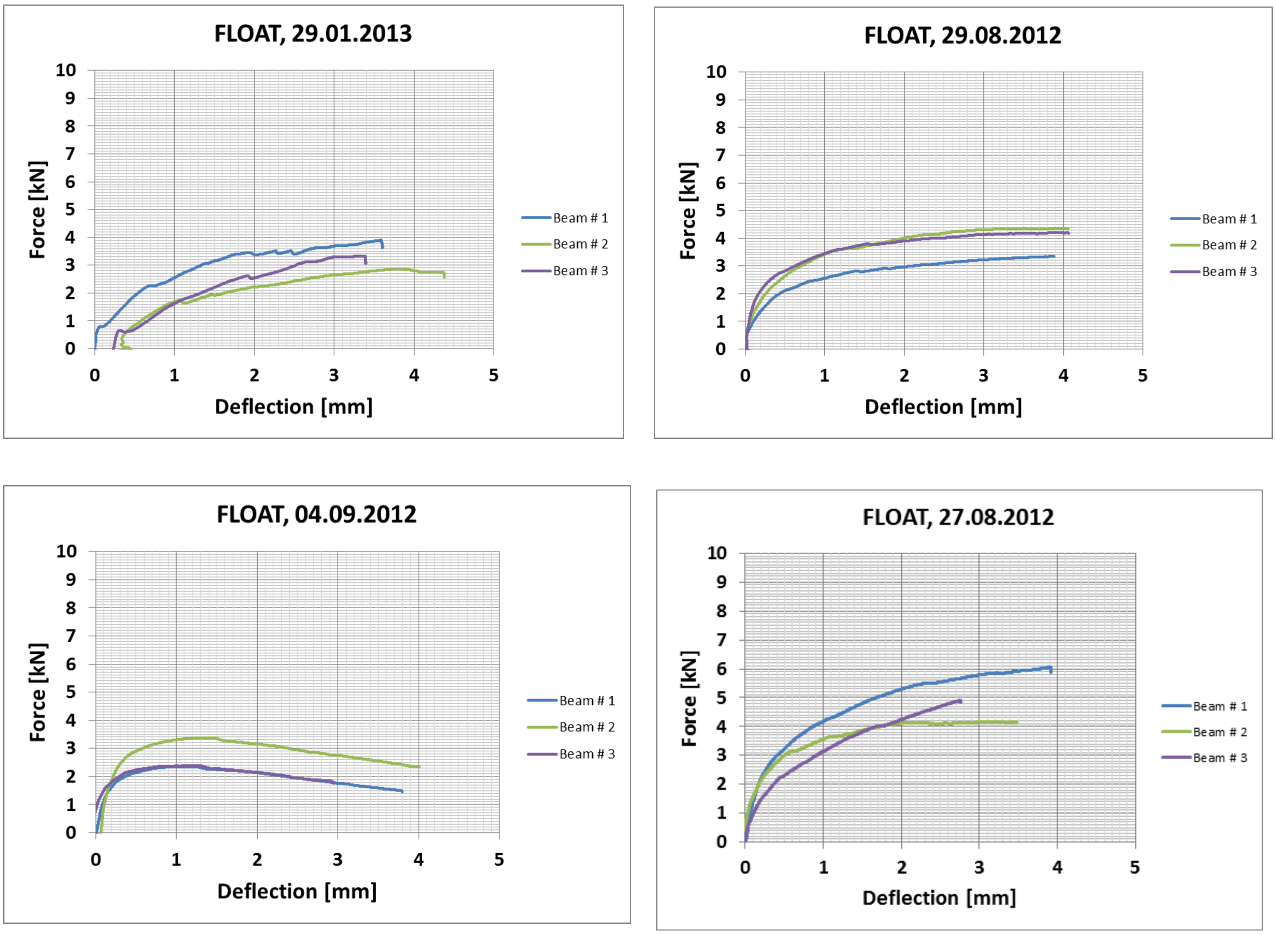

Figure 7 Results from the ductility test on notched specimens.

Figure 8 Failure surface of beam where bundling of the long fibres is visible.

In the normal applications of UHPFRC – at least the ones that Hi-Con are involved in – most of the tensile loads in structural elements are carried by conventional reinforcing bars, while the fibres are mainly used to provide ductility, crack control and to improve the utilization of the bars. In this particular case, however, the design would utilize the fibres for the tensile loads due to the very thin walls in the floater. With thicker walls, it would have been possible to include conventional reinforcement, but then the weight of the floater would have become much too high for the floater to be lifted out of the water.

This meant that the fibre distribution and fibre orientation would be much more important than in usual structural elements. Ideally, the distribution and orientation of the fibres should be as uniform as possible providing uniform tensile properties – if there were areas where there would be no fibres this would be a weak spot that could crack and fail in operation. A separate test was devised for this – explained in detail in annex C – and it was shown that fibre properties could vary depending on the casting direction and depending on where in the element a sample was taken. In general, the fibres had a tendency to align with the direction of casting – and along a boundary such as the edge of the mould – and they had a tendency to settle a little with gravity, so that there would be more fibres in the lower part of the element. Fig. 9 shows the test mould that was used for determination of this effect of distribution and orientation as well as where beams were cut from the cast slab. The beams were then notched and tested to determine the minimum of properties that could be expected in a section. The set-up is shown in fig. 10 and the results of these bending tests are shown in fig. 11. As can be seen, the best results are achieved on reference beams cast in a beam-mould, where the boundaries of the mould and the direction of the casting flow would tend to align the fibres along the beam axis, thus ensuring that a relatively large number of fibres would be active in the loading (description of tests and results in Annex D).

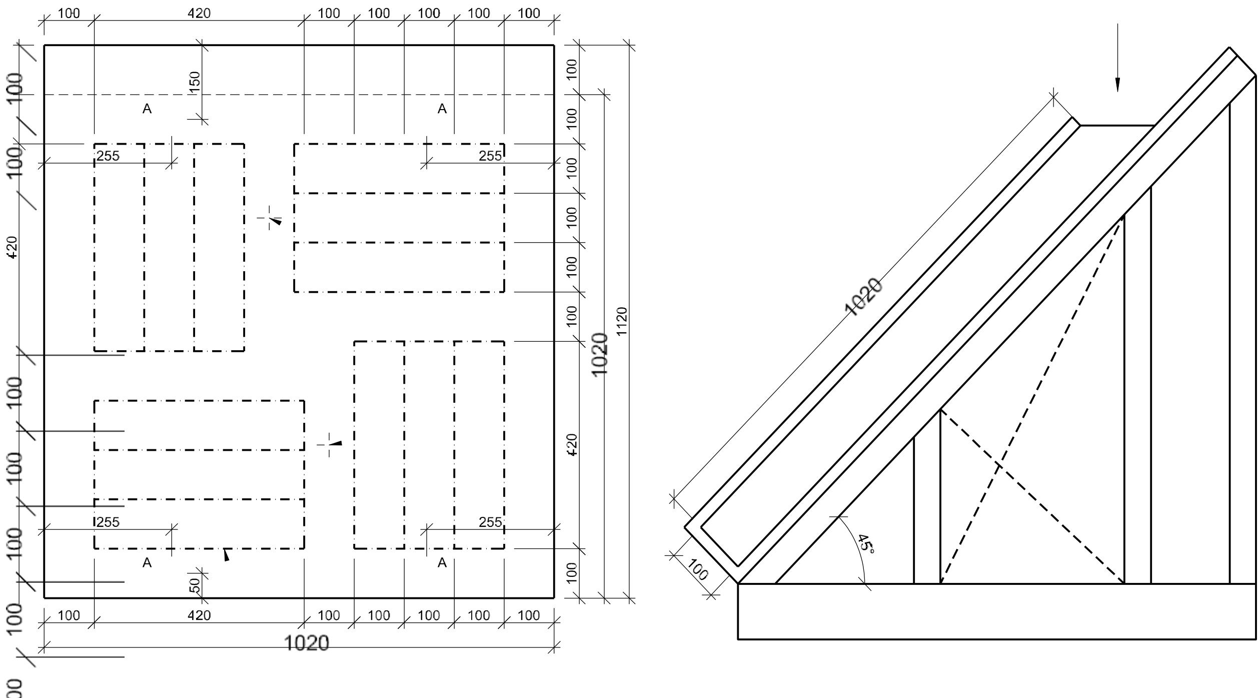

Figure 9 A slab is cast at a 45^0 angle and subsequently beams (a total of 12) are cut from the slab and tested.

Figure 10 Set-up for testing notched beams.

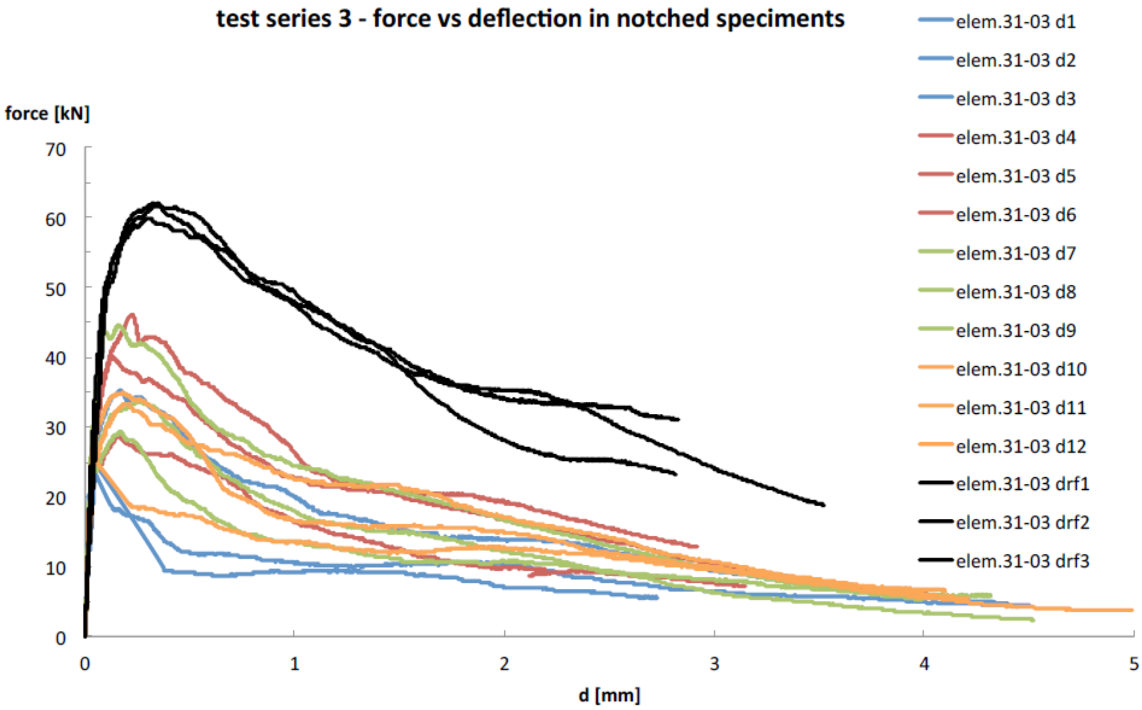

Figure 11 Test results for the 12 beams cut from the slab – as well as the 3 reference beams cast in a beam-mould.

<u>Task 5: Testing and monitoring</u>

Work was carried out by Department of Civil Engineering at Aalborg University in Aalborg to determine loads on the structure and pressure distributions on the shell. The initial results of the work in the department's wave basin and current flume was compared with existing data and sent to the department in Esbjerg for use in structural design. Further testing was done to pave the way for future refinement.

The work started on a 1:40 scale device measuring forces on a single absorber. Access for the wave basin was obtained using Float 2 funding. A six axis force and moment sensor measured directly at the absorber-arm connection and another sensor measured cylinder forces. The float was running with a power take-off that was using optimized dampness and stiffness control to get a more realistic picture of the forces during operation. Reports were written for the project, and a paper [1] was later published on the findings.

Experiments on a 1:4 scale absorber was carried out later (transport and access was financed by Marinet, a European Community research infrastructure initiative). This was done in a larger ocean facility in Plymouth where precise data on the pressure distribution on the hemisphere were obtained. The results of the experiments were presented at a conference [2] and later published in journals [3,4].

The Float 2 project was a central part of Morten Jakobsen's Ph.D. and aided the completion in October 2015 [5]. The results from the experiments were meant for future refinement and optimization of the absorber (read: Reducing safety factors). They were also used to confirm the results of previous experiments. Furthermore it was sought to get concrete knowledge of the forces and pressures during extreme events (during operation where the absorber is in the water) to ensure survivability of the absorber.

More specifically the determination of the non-dimensionalized drag (CD) and inertia coefficients (CI) cf. [6]. The coefficients are used to determine forces on the absorber and arm. These coefficients are used directly e.g. by using the extended Morison equation by Faltinsen and for determination of the non-dimensionalized slamming coefficients (CP) cf. [1]. The coefficient is used to determine peak pressures on a shell. CP is used for instantaneous peak pressure so a selection of the best suited analytical solution can be found.

Main publications by Morten M. Jakobsen through Float2 project.

1) Characterization of loads on a hemispherical point absorber wave energy converter. / Jakobsen, Morten Møller; Beatty, Scott; Iglesias, G.; Kramer, Morten Mejlhede.
In: International Journal of Marine Energy, Vol. 13, No. April 2016, 2016.

2) Control of Point Absorbers and their Performance in Experiments. /Jakobsen, Morten Møller; Ferri, Francesco; Kramer, Morten Mejlhede.
Proceedings of the 11th European Wave and Tidal Energy Conference. Technical Committee of the European Wave and Tidal Energy Conference, 2015. 09B3-1 (European Wave and Tidal Energy Conference Series; No. 11).
Publication: Article in proceeding

3) Experimental Study of Forces on Point Absorber. / Jakobsen, Morten Møller; Iglesias, Gregorio; Kramer, Morten; Vidal, Enrique.
Coastlab 14 Book of Proceedings: Application of Physical Modelling to Port and Coastal Protection. ed. / Valeri Penchev; Francisco Taveira Pinto. 2014. p. 15-22.
Publication: Article in proceeding

4) RANS-VOF Modelling of the Wavestar Point Absorber. / Ransley, Edward; Greaves, Deborah M.; Raby, Alison C.; Jakobsen, Morten M.; Kramer, Morten M.
In: Renewable Energy, TBA.

5) Wave-Structure Interactions on Point Absorbers - an experimental study. / Jakobsen, Morten Møller.
Aalborg Universitetsforlag, 2015. 239 p. (Ph.d.-serien for Det Teknisk-Naturvidenskabelige Fakultet, Aalborg Universitet).
Publication: Ph.D. thesis

6) Hydro-dynamic water-structure interactions on hemispheric WEC. / Jakobsen, Morten Møller. Et. Al.
Technical report for Float2 project.

1.6 Utilization of project results

Unfortunately, none of the partners is in a position where they can utilize the results of the project. The intended main user of the results – Wavestar – have discontinued their activities due to problems with regard to obtaining the necessary internal funding. Hi-Con have been able to develop a material composition that is particularly suited for elements with very little conventional reinforcement – such as the floater – but without the demonstration project that was envisioned, it is difficult to utilize this composition in offshore applications as intended. Aalborg University may be able to use the results from their efforts on load determination, which have been a part of the project, as they are still active in the field of wave energy. The design efforts, however, are probably not applicable to other projects.

1.7 Project conclusion and perspective

Unfortunately, the project was terminated ahead of time due to the decision by Wavestar to stop their activities – and very little work was done in the last year of the project as Wavestar made an effort to find additional internal funding. This meant that the main objective of demonstrating a new concept for wave energy floaters that could help in reducing the price of wave energy was not met. For each of the secondary objectives the conclusions are listed below:

- **Optimization of UHPFRC formulation for the floaters:**
  This objective has been met through testing of a number of different fibre formulations to optimize especially tensile properties and crack control. In addition, 2 test series were carried out to investigate the effect of casting on fibre distribution and fibre orientation.
- **Optimization of design for the floater and the hydraulic arm that attaches the floater to the body of the Wavestar WEC:**
  This objective was only partially met. The design of the floater has been through several iterations as the requirements were changed, but eventually a satisfactory design was achieved for the C6 floater. For the hydraulic arm, the design was made for the C5 version, but not for the C6.
- **Production and test of full-scale arm and floater on test-site in Hanstholm:**
  This objective was not met. Preparations have been made for the production, but as the project could not be carried out to its conclusion, it was decided not to carry out the very expensive production phase – and the even more expensive installation on a test-site.
- **Extrapolation of results to other WEC's and other structural elements to achieve further reductions in cost:**
  This objective was not met.

A lot of effort has been invested in the determination of loads for the floater and arm as well as the design of the floater and arm, but as the project was stopped prior to the actual production and testing of a full-scale floater, the design has not been validated.

While the load determination – as explained in the previous section - can possibly be used in other projects, it is unlikely that the design can be used by any of the partners or by others. The Wavestar system – where the floater is lifted out of the water at high loads – was considered the best option for the use of UHPFRC, as the weight was very important – in addition to high strength, ductility, durability and resistance against fatigue. As the Wavestar activities have stopped – without the chance of demonstrating the performance in a WEC - other applications in wave energy are unlikely for UHPFRC. While other applications in offshore could also be possible for the CRC material, the lack of a demonstration project makes applications in this field less likely.

Annex

Annex A: Letter from Wavestar describing their resignation from the project.
Annex B: Design report for C5 Floater
Annex C: Power Point presentation describing the final design of the C6 Floater
Annex D: Report on task 4.1 – development of materials