1. Final report: FLOAT – development of new flexible UHPC

1.1. Project details

Project title	FLOAT-ansøgning til udvikling af ny fleksibel UHPC
Project identification	Energinet.dk project no.
Name of the programme which has funded the project	ForskEL
Name and address of the enterprises/institution responsible for the project	Hi-Con A/S Hjallerup Erhvervspark 1 9320 Hjallerup
CVR (central business register)	26020387
Date for submission	17 August 2011

1.2. Executive summary

The current project is a preliminary study intended to clarify the background and give a better basis for an evaluation of the risks and possible rewards of funding a full project with the overall purpose of developing and testing a new concept for wave energy floaters, made of Ultra High Performance Fibre Reinforced Concrete (UHPC), as an enabling technology for the establishment of competitive wave energy production (FLOAT). The consortium behind the application consists of WEC companies Dexa Wave and Wave Star representing a large wave energy converter placed in relatively shallow waters and a smaller, more flexible system placed at deeper water, precast producer Hi-Con – a company that works almost exclusively with High Performance Fibre Reinforced Concrete and Aalborg University.

As an initial step for this preliminary study of FLOAT an investigation has been undertaken in relation to preliminary design of 2 types of floaters, essential properties of UHPFRC – and identification of necessary developments, compilation of existing data from off shore applications and analysis of effect on Cost Of Energy. This work has been divided into 4 tasks and in the following the objectives of each task will be described followed by the conclusions.

Task 1 - Preliminary float design and economical considerations - is a theoretical and numerical study including preliminary float designs and cost estimates. It aims at making a first comparison between the different materials options for DEXA and Wave Star floats and giving a first judgement about the suitability of CRC concrete. This is done through a qualitative assessment of pros and cons of different materials for both types of floats and a design study of the Dexa Wave float. It is concluded that the requirements for the

Dexa Wave float are so that CRC is not able to compete with conventional concrete for the best and most cost effective solution. The good durability (leading to low maintenance costs), the mechanical properties and the ductility of CRC are not important enough to offset the increased cost for this float. For Wave Star on the other hand, there are significant advantages in using CRC as the only other option in this case is fibre glass, which is a much more expensive product.

Task 2 is split into 2 parts. The first part is a state-of-the-art report on CRC properties related to off shore applications and includes a section on considerations for production of these types of elements. The second part is an investigation of methods of optimizing the properties of CRC – customizing them for particular applications in WEC’s. In this case, the method of optimization has been to change the types of fibres in the mix, and it is demonstrated that simply by using a steel fibre with a smaller diameter, it may be possible to decrease the wall thickness of a Wave Star float by approximately 15% and thus save on weight.

Task 3 describes preliminary experience with concrete – and especially UHPC for off shore applications. Emphasis is placed on description of production of a 1:10 scale float in CRC, installing the float at the test site and the results of close to 4 years of exposure.

Task 4 concludes on how this impacts CoE for the 2 WEC’s – based on the figures that can be put together in a preliminary study of this type. For Dexa Wave there is no advantage of using CRC for the floats, and with the short time available it has not been possible to do an assessment of whether other parts of the structure could benefit from replacing other materials with CRC. For Wave Star there is a significant advantage. For the floats – and there are 20 to each converter – there is a 77% saving in price, which means a saving of 4,8 mio. kr. for one converter. A study has also been made for the arm that holds the float, and in this case the reduction in cost is estimated at 45%, or 1,6 mio. kr for the converter.

If a similar assessment is made for other structural parts of the machine leading to possible reductions in cost, this will contribute to meeting one of the 2 main challenges for WEC’s of the Wave Star type, namely bringing down the cost. The other main challenge is to increase effectiveness, either by developing a better control algorithm or by refining and developing the PTO. Both challenges will have to be adressed, and for the Wave Star converter it is necessary to reduce the cost of the machine itself by more than 50% and the most promising way to achieve this is by using alternative materials such as CRC.

The current project has indicated that the first steps to meeting one of the main challenges – lowering machine costs - is possible for certain types of WEC, but it has also been shown that replacing other materials with CRC is not a universal solution. For the Dexa Wave converter there is no advantage in using CRC for the floats, but as for the Wave Star converter, there could still be advantages in replacing other structural parts of the converter.

1.3 Project results

Background

In September 2010 an application was made to the ForskEL programme for the FLOAT project. The overall purpose of FLOAT was to develop and test a new concept for wave energy floaters, made of Ultra High Performance Fibre Reinforced Concrete (UHPC), as an enabling technology for the establishment of competitive wave energy production. The concept behind FLOAT had been established to address known limitations, common to different wave converters, such as loading capacity and environmental resistance, through the development of an enhanced floating structure. This was intended to enable a more sustainable, durable energy production across different wave power concepts, resulting in a reduction of initial investment and maintenance costs, ultimately achieving a lower price of energy produced, in accordance with current priorities of Danish energy programmes. The consortium behind the application consists of WEC companies **DexaWave** and **Wave Star** representing a large wave energy converter placed in relatively shallow waters and a smaller, more flexible system placed at deeper water, precast producer **Hi-Con** – a company that works almost exclusively with High Performance Fibre Reinforced Concrete and Aalborg University.

The activities planned combined knowledge on concrete material science and wave energy harvesting. The project included material optimization, including analysis on the effect of different types and contents of fibres, establishment of load cases, a design phase (balancing factors such as weight and strength), optimization of manufacture logistics and, finally, a demonstration phase where the new floaters produced were to be fully tested in two wave energy converters, from Wave Star and Dexa Wave Energy respectively, covering different market segments (offshore and nearshore) of the wave energy generation market.

The project was not awarded, but funding was provided for a preliminary study intended to clarify the background for the original application and expand on this in order to give a better basis for an evaluation of the risks and possible rewards of funding a full project. As an initial step for this preliminary study of FLOAT an investigation has been undertaken in relation to preliminary design of 2 types of floaters, essential properties of UHPFRC – and identification of necessary developments, compilation of existing data from off shore applications and analysis of effect on Cost Of Energy. This work has been divided into 4 tasks and in the following the objectives of each task will be described followed by the main results. The full task reports are included as annexes to the final report.

Task 1: Preliminary float design and economical considerations

Task manager: AAU

The first task of the FLOAT project is a theoretical and numerical study including preliminary float designs and costs estimates. It aims at making a first comparison between the different materials options for DEXA and Wave Star floats and giving a first judgement about the suitability of CRC concrete.

To that end, some tables have been prepared compiling qualitative (ageing, repairability, environmental impact, etc.) and quantitative data (weight, cost, etc.) with a star-rating system for different materials options: steel, CRC concrete, ordinary concrete and glass-reinforced plastic. These tables permit to compare the pros and cons of each material.

Some calculations had already been done by the Wave Star Float Design Group to estimate the weights and costs of the Wave Star floats depending on the material chosen. For DEXA these estimates have been carried out by Christian Frier of Aalborg University and by Søren Mosegaard Goul Hansen of Hi-Con.

WaveStar

Some important design calculations had already been carried out by the Wave Star Float Design Group (WaveStar Float Design Group, 2011). They considered steel, CRC concrete and glass-reinforced plastic as different material options. For each of these materials, they estimated the weight of the float, the times of design, mould production and float production, the costs of tooling, production and transport and the environmental impact. All the figures of this study for Wave Star are taken from their report "Arm Float Bearing Table Overview".

Aalborg University tried to extend this comparison study to more general criteria (ageing, repairability, strength, etc.). The tables are given in the full task 1 report in Annex 1.

We can deduce from this comparison study that **CRC concrete** can be an interesting option given its low production costs (70.000 kr./float). Another interesting point is its slow ageing in a marine environment. CRC concrete is subject to erosion, chemical action and eventual corrosion of the reinforcements but these phenomena occur at rates slower than the corrosion endured by the steel floats, and no maintenance operations are needed. CRC floats can also be produced relatively quickly (2 days/float), once the mould has been designed and produced (6 months). Lastly, it has considerable fatigue resistance.

The essential drawback of this material is its weight: around 10 tons. It is a very important aspect for the Wave Star structure, because the floats need to be lifted up in storm situation. The low production costs of the CRC floats are a bit offset by high tooling costs, but if we consider the production of 20 Wave Star machines (400 floats), the impact of these high tooling costs is considerably attenuated. Furthermore, as CRC concrete has not been used for applications of this type, some prototypes need to be studied. As described in task 2, there is a number of data available on the material properties of CRC and CRC has been the UHPC used most extensively in the building industry in the world.

Ordinary concrete would also feature very low production costs, but the high weight of ordinary concrete floats is prohibitive for their use with the Wave Star machine.

Steel has the advantages of a very fast production (1 day/float) and that no mould is needed for the float production. Besides, it is a well-known material, so no testing of the steel floats is needed. Finally, steel presents a good repairability (it is easy to repair a damaged piece by welding or screwing) and important mechanical strength.

On the other hand, **steel** floats are heavy (12 tons), and of all the materials studied, it is the one with the worst long-term behaviour in a marine environment: it is prone to corrosion and fouling, so it needs maintenance operations every 10 years to redo the anti-corrosion and anti-fouling coatings. The impact of these coatings on marine life is regulated but still not well known. The environmental footprint involved by the steel float production is very important (426.000 MJ of primary energy and 33.000 kg of CO_2). Steel also presents a bad fatigue resistance.

The feature of **fibre glass composite** floats that makes it very competitive is its low weight: 1.5 tons. As explained before, it is very interesting in storm protecting situation when the floats need to be lifted up. It shows good mechanical properties (high strength and fatigue resistance), and it can be repaired by applying new layers of fibre glass, but the very specific working conditions make it difficult.

However, **glass-reinforced plastic** compensate its good mechanical properties and low weight by high construction costs (310.000-460.000 kr./float). It is corrosion-resistant but it suffers damage due to water intake (hydrolysis), degradation from UV radiation and fouling. Consequently, some maintenance operations have to be carried out once a year. Another drawback of this option is its production time: the production of a composite float lasts 1 week.

Dexa Wave

The task 1 of the FLOAT project regarding DEXA involved more calculations because fewer efforts had been put into preliminary designs than for Wave Star.

The main difference between the two energy converters is that contrary to Wave Star, the weight of DEXA floats is not crucial: the floats are always submerged and don't need to be lifted up. Consequently, the use of concrete, whose weight was a problem for Wave Star, is particularly interesting in this application and can lead to important cost reductions. Glass-reinforced plastic floats, whose essential feature is its low weight, and steel, which brings problems of ageing and maintenance, won't be studied here.

Therefore, two preliminary designs will be carried out: one in ordinary concrete and one in CRC, and this task will essentially consist in comparing these two materials. This study demonstrated that CRC may not be very suitable for DEXA floats compared to ordinary concrete. On one hand, the use of CRC offers a little weight reduction (15.2 tons instead of 16.3 tons for ordinary concrete), but this is not essential in this application as above-said.

Choosing CRC would imply higher costs (50 k€ against 10 k€ for an ordinary concrete float) and higher carbon footprint than ordinary concrete (120.000 MJ of primary energy and 7.000 kg of CO_2 involved in the CRC "cradle to gate" process against 35.000 MJ and 4.000 kg for the ordinary concrete), making ordinary concrete probably more adapted to this application.

Conclusion task 1

The improved properties of CRC combined with its low construction costs make it a very interesting material for wave energy applications.

First, its very low porosity and its resistance to corrosion provide an increased durability, which is a critical aspect in a marine environment. It does not need any coating, making the maintenance needing nonexistent, another very important feature in offshore applications, where all maintenance operations are extremely expensive.

CRC features enhanced mechanical properties that can lead to lower weight, often a determinant aspect in offshore designs. It also offers the good fatigue resistance necessary for a structure subject to wave-induced repetitive loadings.

Finally, despite high tooling costs, the very low production costs of CRC floats compared to steel or glass-reinforced plastic make it an option that cannot be ignored.

For wave energy converters for which the floats weight is not very important factor such as DEXA, ordinary concrete, which also offers good durability and good mechanical properties for lower costs than CRC, might be the most suitable option. But for Wave Star for instance, the crucial lower weight offered by the use of CRC combined with its improved durability and its low cost indicates it probably is a very suitable option.

It is concluded, from the Wave Star example, that the use of CRC for floats of wave energy converters is an option that can lead to important cost savings, given its good mechanical properties, long durability and low production costs.

Task 2.1 CRC properties related to off shore application

Task manager: Hi-Con

In the following is given a short introduction to CRC with special emphasis on those aspects that are of interest for off shore applications, including use in wave energy converters.

<u>Introduction</u>

CRC is an abbreviation of Compact Reinforced Composite – a high performance concrete developed by Aalborg Portland A/S in 1986 and now marketed by CRC Technology. Hi-Con is the leading precast producer of CRC.

CRC has a very high compressive strength and extremely good durability. The incorporation of steel fibres in the matrix provides ductility, which allows utilisation of closely spaced reinforcing bars and small rebar covers. CRC structures will, because of these properties, often be designed with very slender cross sections. The composition of CRC can be varied with i. e. different types of aggregates and different types and contents of fibres, but a typical composition – which has been investigated in a number of international research projects with regard to behaviour in bending, shear, impact, resistance to corrosion, fatigue, fire resistance, shrinkage and creep – is a mortar with a quartz sand, 2-6 vol.% steel fibres and a water/powder ratio of 0.16. The fibres most often used have a length of 12 mm and a diameter of 0.4 mm. The properties of CRC are described in more detail in the full task 2.1 report, which appears in annex 2.

<u>Production of CRC</u>

CRC is very dense concrete with a water/binder ratio considerably lower than for conventional concrete. At the same time a large content of steel fibres is used, but due to the special grading of CRC and the compatibility of the different components it is still possible to mix and place CRC with conventional equipment, i.e. high shear mixers and poker vibrators.

The workability of CRC is dependent on the steel fibre content, but with a content of 2% by vol. – corresponding to 160 kg of steel fibres per m^3 – CRC is still quite workable.

The large content of paste and micro silica in CRC provides a high degree of cohesion in the mix. This is necessary to ensure that no segregation of fibres will occur under vibration, but this also means that CRC is quite sticky and difficult to float.

Pre-cast elements are produced using local materials and only the CRC binder is provided. In most cases maximum size of the sand is 4 mm in order to make it possible to produce the very slender elements with a low cover to the reinforcement, but CRC concrete with larger aggregates have been used for a few projects.

CRC is very suitable for mobile mixing and casting stations that will enable production on sites close to deployment of larger projects. An example could be set-up of a production site close to Esbjerg, where floaters could be placed on a barge or actually floated to site at Horns Rev or another suitable area. As conventional equipment is used for mixing and casting it is also relatively easy to start up a license production.

Conclusion task 2.1

The mechanisms for deterioration in concrete – chloride intrusion and carbonation – act so slowly in CRC that they cannot be used for a reasonable estimate of service life. Other factors will determine the service life, such as whether the technical installations on a platform or on an off shore wind turbine are outdated.With regard to fatigue, CRC shows better performance than conventional concrete and a design using conventional standards – such as the Eurocode – will thus be conservative.

In principle CRC is designed according to the Eurocode (DS/EN 1990, 1991 and 1992), but with a number of exceptions. The general approach of Eurocode 2 is also used for CRC and an example of this is, that CRC is practically always used with a combination of steel fibres and conventional reinforcement, so that all tensile loads are carried by the main reinforcement – even where the tensile capacity of the fibre-reinforced matrix would be able to carry the loads.

The improved properties of the concrete are utilised in designing with a higher characteristic compressive strength and a lower cover to the reinforcement, while the fibres make it possible to place reinforcement much closer and with a shorter length of anchorage. If shear stresses are reasonably low (around 5 MPa) the fibres can be calculated as continous shear reinforcement, so that stirrups are not necessary. The fibres provide ductility for the matrix and aids in distribution of stresses. For the design of the floaters it would, however, be reasonable to use only the fibre reinforced concrete for the Wave Star floater and to use a post stressed design for the Dexa Wave floater rather than incorporate conventional reinforcement.

For production related to the wave energy converters it is feasible to use CRC JointCast as described in the section on anchorage, and the material is also well suited for production using mobile equipment – setting up an installation near a harbor area allowing for easier transportation of the finished elements.

Task 2.2 Testing of CRC specimens

Task manager: AAU and Hi-Con

Introduction

The floating device for the Wave Star converter is a hollow hemisphere, and a hollow cylinder for the Dexa Wave converter. For the Dexa machine there is a certain interest in being able to minimize the thickness of the CRC shell of the floats, whereas for the Wave Star converter the thickness, and thereby the weight of the float shell is of paramount importance in order for the machine to be able to lift the floaters out of the water in rough weather with excessive wave heights. Also, the cost of the floats might be reduced by reducing their shell thickness.

The purpose of the present Task 2 was to investigate the effect of alternative steel fibre types and dosages on the load bearing capacity of the CRC float shell and to evaluate the potential of reducing its thickness.

Experimental

The investigation was carried out by casting specimens with varying steel fibre types and dosages, subjecting the hardened specimens to bending, and monitoring their flexural behaviour during loading until fracture.

The following types and dosages of steel fibres were used:

1. SF - the fibre type most commonly used for CRC, with a diameter of 0.4 mm and a length of 12.5 mm, serving as a reference (ø 0.4 x 12.5 mm). Dosages: 3 and 6 percent by volume.
2. ML – brass coated fibres with approximately the same length as the reference, 13 mm, but with a somewhat smaller diameter of 0.3 mm (ø 0.3 x 13 mm). Dosages: 3 and 4 percent by volume. For the 4% mix the water content was very low while still achieving an acceptable workability.
3. MK – brass coated fibres significantly shorter and thinner than the reference, with a diameter of 0.2 mm and a length of 9 mm (ø 0.2 x 9 mm). Dosages: 1.5 and 3 percent by volume.

Fibre types 2 and 3 are thinner and/or shorter than the reference fibres. At the same dosage level in terms of percent by volume, the surface area of the fibres is inversely proportional to the fibre diameter. Hence, the thinner the fibres the higher the fibre surface area, and the higher the load bearing capacity of the composite if the failure mechanism is controlled by pull-out of the fibres. The drawback of using thinner fibres is that the workability of the freshly mixed material is adversely affected, and the price of the fibres is often higher.

The specimens were produced by Hi-Con and the specimen types chosen for the investigation were:

1. Notched beams, 840 mm long (800 mm span), 100 mm wide, and 100 mm high, with a 50 mm deep notch sawed at the mid-point of the beam, cf. Fig. 1. These specimens were used to measure specific fracture energy of the composites according to a standard method.

2. Regular beams with the same dimensions, 840 mm long (800 mm span), 100 mm wide, and 100 mm high, but without notch, cf. Fig. 1. These specimens were used to measure the flexural capacity of the composites by reference to the standard notched beams.

3. Thin slabs, 840 mm long (800 mm span), 100 mm wide, but only 20 mm high, cf. Fig. 1. These specimens were used to measure the flexural capacity of the composites using thinner and more shell-like specimens resembling the actual float structure.

4. Cylinders with a diameter of 100 mm and a height of 200 mm. The cylinders were used for measurement of the modulus of elasticity and the compressive strength.

   Tests of the mature specimens were performed at Aalborg University, Department of Civil Engineering, using set-ups as shown in fig. 1. In fig. 2 is shown the set-up for measurement of fracture energy.

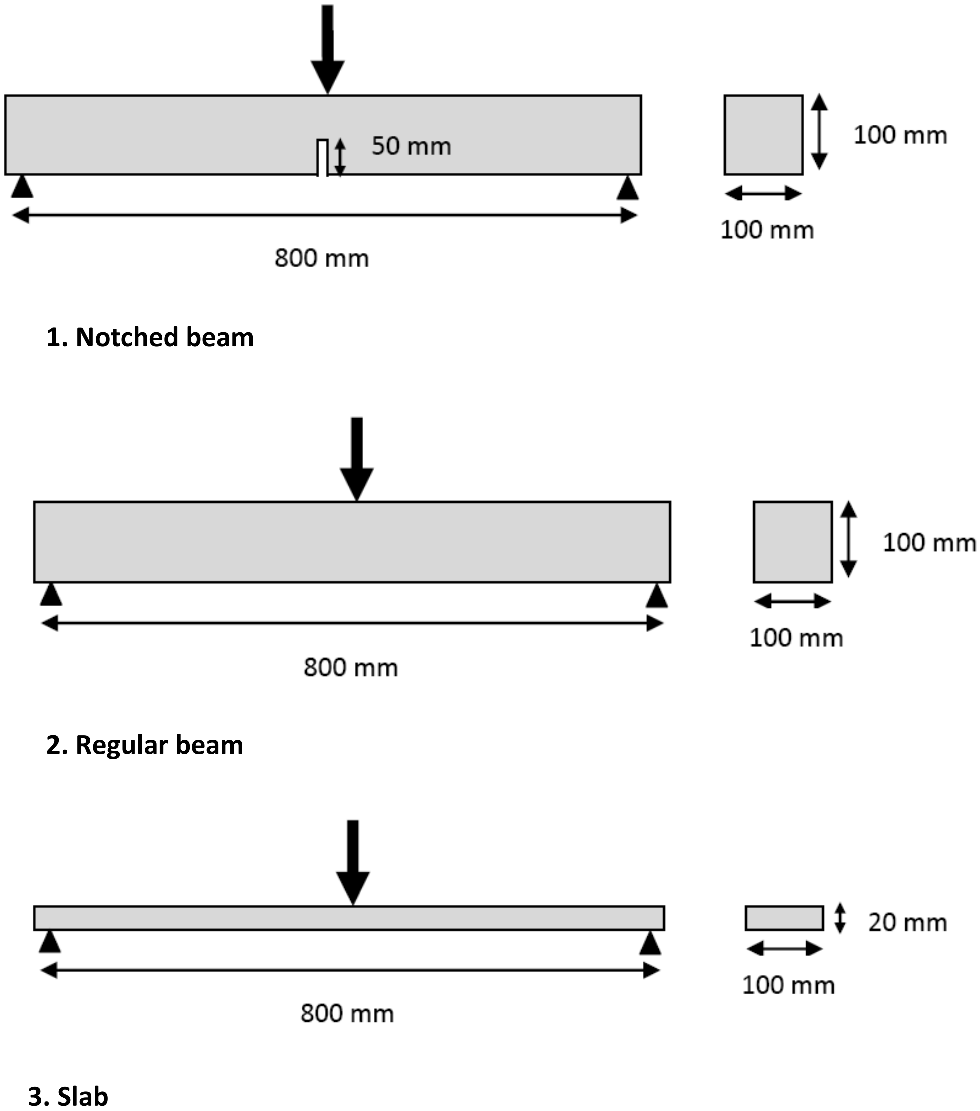


Figure 1. Schematic illustration of specimen types and experimental set-up.

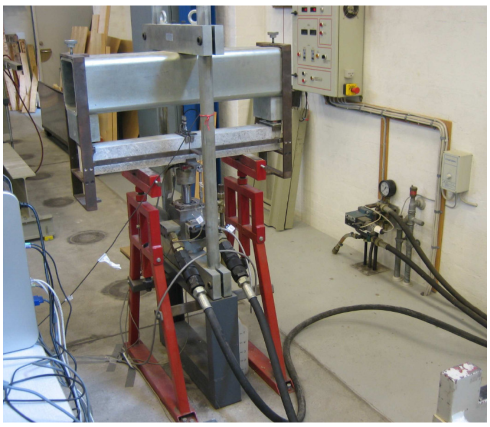


Figure 2. Experimental set-up for measurement of specific fracture energy

Results and discussion

To provide an overview the main results obtained in the project are summarized in Table 1 which will be referred to in the following treatment of the individual results.

Table 1. Summary of main results

Fiber type	**0,4 x 12,5 mm**		**0,3 x 13 mm**		**0,2 x 9 mm**	
Aspect ratio	**31.3**		**43.3**		**45.0**	
Fiber content (% by vol.)	**3.0**	**6.0**	**3.0**	**4.0**	**1.5**	**3.0**
Code	**SF3**	**SF6**	**ML3**	**ML4**	**MK1,5**	**MK3**
NOTCHED BEAM **Max. force (kN)**	2.73 2.36 3.66	4.39 4.31 4.32	 2.97 3.32		2.49 2.60 2.82	 3.84
Mean	**2.92**	**4.34**	**3.15**		**2.64**	**3.84**
REGULAR BEAM **Flexural strength (MPa)**	12.1 12.7 14.7	20.9 20.7 19.2	16.0 17.9 17.6	27.1 24.5 29.5	17.4 15.7 13.2	18.4 19.0 20.5
Mean	**13.2**	**20.3**	**17.2**	**27.0**	**15.4**	**19.3**
SLAB **Flexural strength (MPa)**	10.6 13.5 10.3	17.2 14.0 17.6	7.4 13.9 8.5		11.1 11.6 11.7	11.5 11.0 7.0
Mean	**11.47**	**16.27**	**9.93**		**11.47**	**9.83**
Modulus of elasticity (MPa)	(46.5) - 47.0 (47.1) - 47.4 (45.5)- 45.7	(51.0) - 51.1 (48.0) - 48.3 (48.6) - 49.4	(46.3) - 46.9 (44.2) - 45.3 (45.4) - 46.1		(48.4) - 48.3 (48.6) - 48.7 (47.7) - 48.0	(45.8) - 46.6 (44.8) - 45.6 (45.8) - 46.5
Mean	**46.7**	**49.6**	**46.1**		**48.3**	**46.2**
Compressive strength (MPa)	144 139 132	135 145 137	135 136 135		149 147 130	159 151 141
Mean	**138**	**139**	**135**		**142**	**150**

Fracture energy

The results for determination of the fracture energy are shown in Fig. 4. Each diagram shows the mid-span force versus the mid-span deflection of the beam. Hereby, the area under the curve to the left of a given deflection value, being the sum of the products of deflection increments and force, becomes equal to the work performed by the externally applied force, which in turn is equal to the work (or energy) spent internally in the beam to produce micro and macro cracks, i.e. the so-called fracture energy, up to the given deflection value.

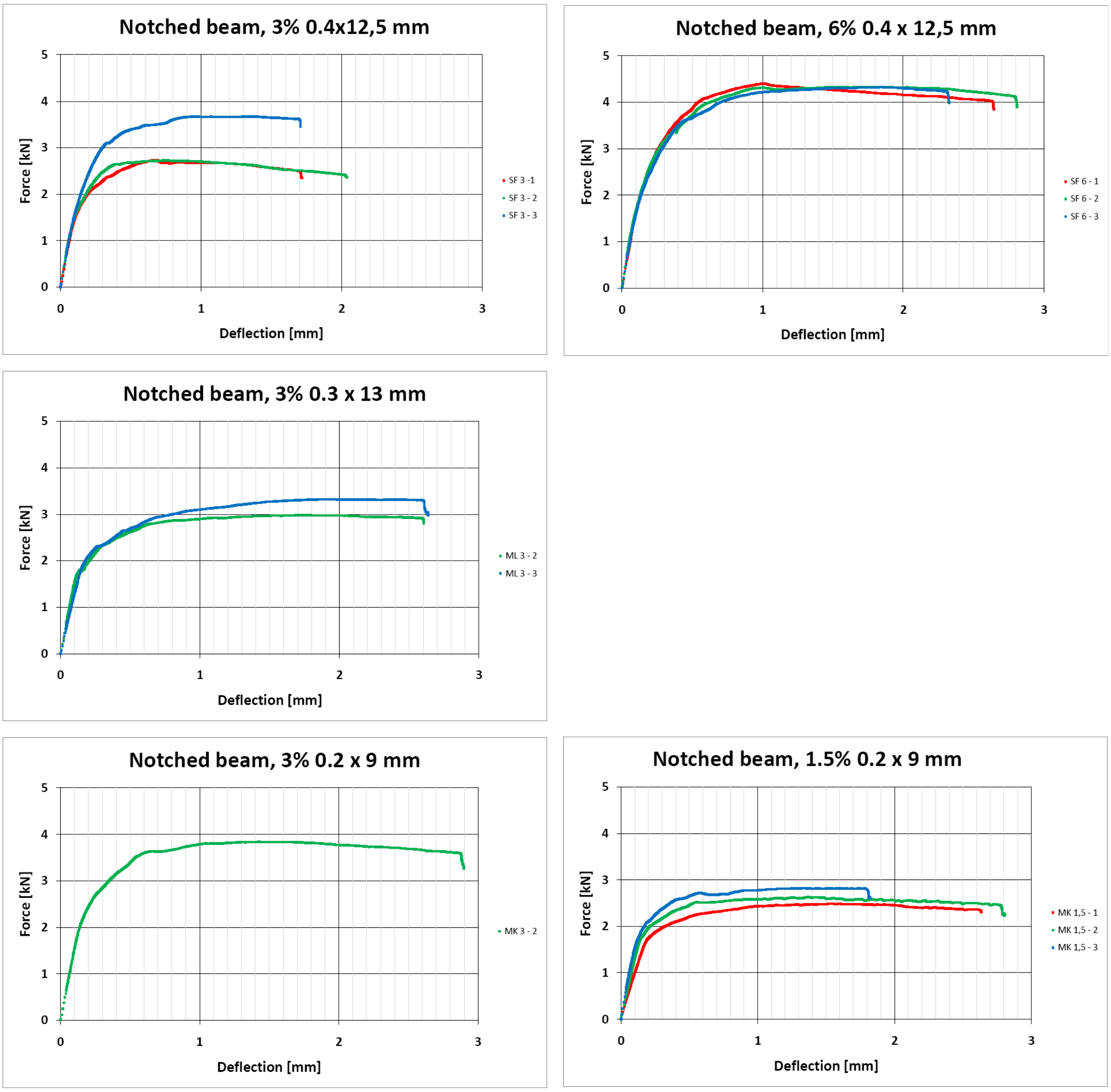


Figure 4. Notched beams: Mid-span force vs. deflection.

Ideally, the test should continue until the force has returned to a value close to zero, to evaluate the total fracture energy of the composite. However, it turned out that the CRC material was so much more ductile than ordinary concrete – for which the test device was built – that it was unfortunately not possible to let the deflection come to its end point.

For some materials it is possible to clearly detect when the first macro crack occurs by analyzing the shape of the force vs. deflection curve. For some of our specimens there is a vague indication, but unfortunately not for all of the beams, and not distinctly enough to allow for firm conclusions.

However, the results may serve to reinforce the conclusions drawn from some of the following test series in the project.

Flexural behavior

The results of the flexural tests performed on the regular beams (840 x 100 x100 mm) are shown in Fig. 5 as the mid-span flexural stress, calculated from the applied force using elasticity theory, versus the mid-span deflection.

It can be seen that the scatter between the three specimens in each test is relatively small, i.e. the tests demonstrated good reproducibility.

The three diagrams in the left column of Fig. 5 all refer to composites with 3 % fibres by volume. It is seen that the flexural strength (the maximum flexural stress) increases progressively with reduction of the fibre diameter from 0.4 mm to 0.3 mm and 0.2 mm. When comparing with the upper right diagram it appears that the flexural strength obtained by doubling the dosage of the reference fibres is equal to what can be obtained by just replacing the reference fibres by ø0.2 x 9 mm fibres.

The results in the diagram for 4% ø0.3 x 13 mm fibres are actually obtained with a matrix material which is somewhat stronger than and different from the matrix of the other specimens in the project. This might explain part of the drastic increase in flexural strength by going from 3 to 4% fibres. Nevertheless, the result is encouraging and deserves to be further pursued.

The flexural strength increase by replacing the reference fibres by ø0.2 x 9 mm fibres is about 46% which theoretically would allow the specimen thickness to be reduced by about 15% at the same load bearing capacity which makes an opening for weight reduction and possibly cost reduction – or for increased safety at unchanged thickness.

By comparison with the results from the beams it is clear that the flexural strengths determined on the slabs are much lower, and considerable scatter in the results is observed. The slabs had been cast “flat”, i.e. so that one 840 x 100 mm surface was plane because it was cast against the form, whereas the opposite face had slight undulations. Also, it looked like some fibre segregation might have taken place. In order to investigate this discrepancy further, 5 slabs (MK3–7, MK3–8, MK3-9, ML3-7, and ML3-8) were sawed on each side of the crack to form 2 new short specimens each with a span of 280 mm. Out of each set of two companion specimens one was then tested with the plane face in tension, and the other one with the undulated face in tension. The short slabs generally showed significantly higher flexural strengths than the original long slabs, and particularly the short slabs tested with the plane face in tension. Also, visual inspection of the sawed faces revealed some fibre segregation.

Hence, for the time being the results for the slabs will be disregarded.

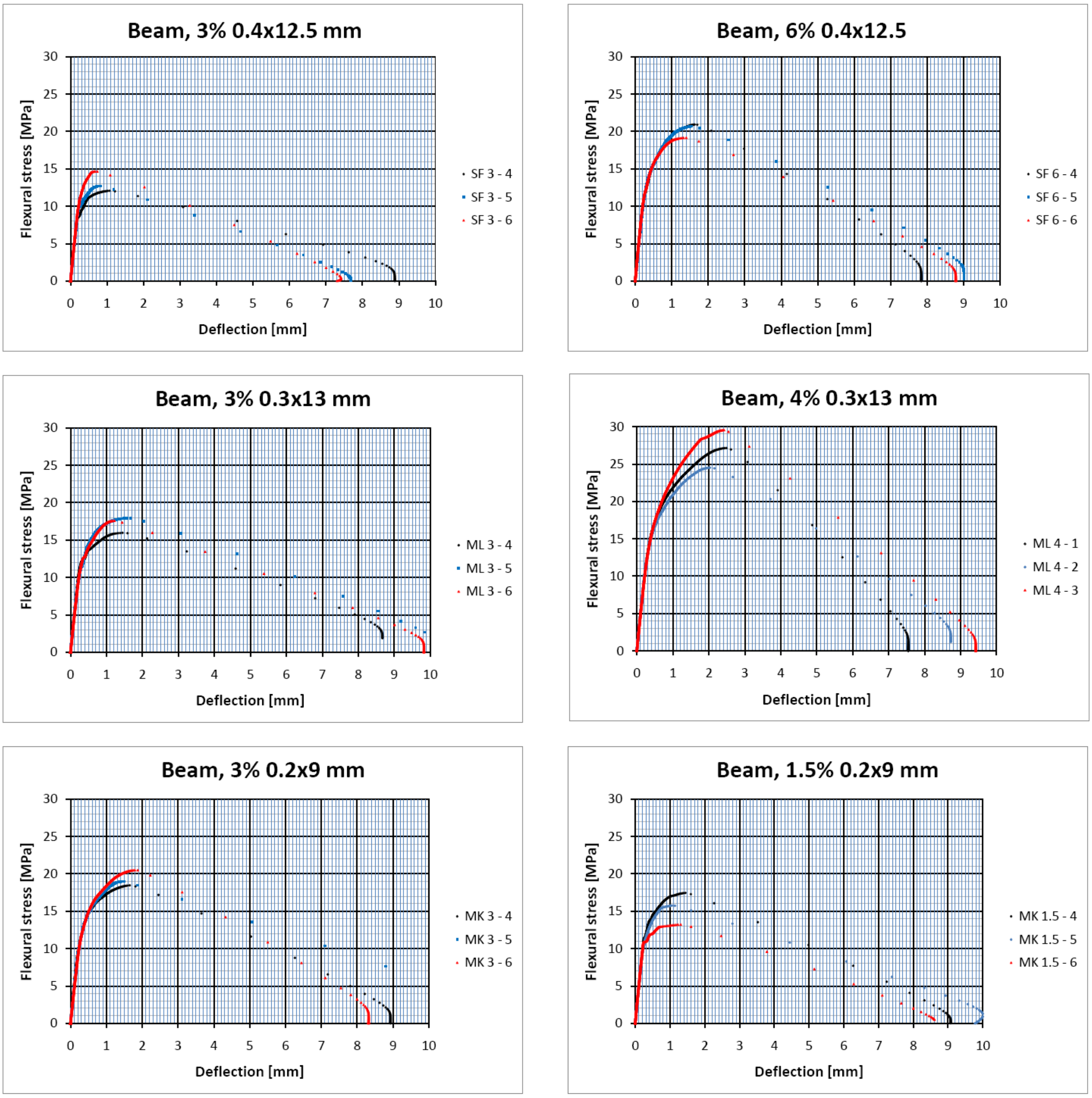


Figure 5. Regular beams: Mid-span flexural stress vs. deflection.

<u>Conclusion task 2.2</u>

The present investigation - Task 2 of the FLOAT project - showed that there is a considerable effect of steel fibre type and dosage on the load bearing capacity of CRC.

Both of the steel fibre types ø0.13 x 13 mm and ø0.2 x 9 mm could be mixed into CRC at a dosage of 3 vol% as is the usual dosage of the reference fibres ø0.4 x 12.5 mm, while maintaining acceptable and operable workabilities compared to the reference.

The modulus of elasticity was not significantly affected by the type and dosage of fibres used, whereas the compressive strength was slightly increased by use of the finest fibers.

Based on tests performed on beams with a span of 800 mm, a width of 100 mm and a height of 100 mm, the flexural strength was found to increase about 46 % by replacing the reference fibres by ø0.2 x 9 mm fibres. Theoretically this would allow the specimen thickness to be reduced by about 15% at the same load bearing capacity which would allow for weight reduction and possibly cost reduction – or for increased safety at unchanged thickness.

Task 3 Preliminary experience

Task manager: Wave Star

In 2005 the first grid connected scale 1:10 model was designed and built for operation in the sea at Nissum Bredning where the waves are approx. 1:10 of North Sea waves. It was designed as if it was a big scale machine in order to learn about the practical issues of operation in the sea. The system contained all the instrumentation and control systems necessary to work unattended round the clock.

Nissum Bredning installation at Helligsø Teglværk.

After the final dry testing, the scale 1:10 model was installed on 6 April 2006 and put into round the clock operation on 24 July 2006. Since then it has logged more than 15,000 operational hours in the sea and been through 15 storms without any damage. By international standards, it is quite an achievement because nobody has test systems in the sea which just work, without major technical problems.

The machine is equipped with 40 floats of 1m in diameter made in fiber glass. Each floats is separated controled build like an half ball and fixed in the midle of it to an arm. The arm can move up and down, it is connected to an hydraulic cylinder which harvest the energy from the wave.

Scale 1:10 Wave Star Energy in operation in Nissum Bredning.

It was decided in 2007 to test the use of CRC concrete for one of the floats. A prototype has been built in may 2007:


Preparation of the internal mould


Outside mould


Dismounting of the outside mould

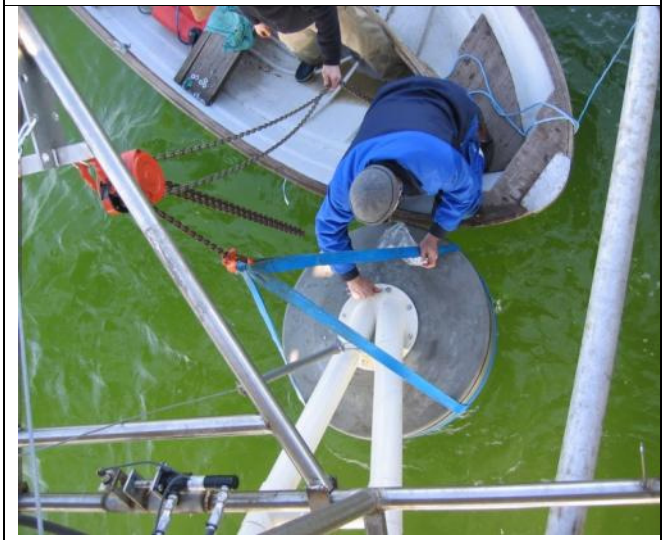

Critical operation to separate the mould

	
Taking the float out of the mould	The float is ready
	
Mould for the top side	The top is taking out of the mould

	
The top is ready	Top and float assembled, ready for installation

The production proces have to be quite long by building an internal mould to maintain a thin wall (3cm). The top and the float are glued together and a stainless steel plate has been fixed to the top of the float using anchoring from the bottom of the float. The surface had also to be polished at the process end:

The CRC concrete float has been mounted on the Nissum machine during the sommer 2007:

	
The float is floating	Mounting the sealing
	
Mounting the nuts	CRC float fixed and ready for test

	The CRC float has been in operation since 2007 and is still on the machine (2011)

The CRC float has been in operation since 2007 and no change or damaged have been noticed on it. It has worked satisfactorily during all the periode, and maintenance operations have been conducted, only cleaning of the surface by high pressure water.

It has to be noticed also that we have had serious hard winter periode, specially in winter 2009-2010 where for the first time, ice has been observe in that area:

(photo by Bendy Poulsen, 12-01-2010)

The machine is actually under dismounting. It is agreed with AAU that the float in concrete will be examined to see if any inclusion of water occur during these years.

Other applications of UHPC or concrete for off shore is described in the task 3 report included as annex 4.

Task 4 The importance for Wave Energy utilisation

Task manager: Dexa Wave and Wave Star

As explained in task 1, the type of floaters for Dexa Wave and Wave Star are quite different and the design limitations imposed on the 2 types are floaters are different. The main difference are the limitations on weight imposed on the Wave Star design, which means there is a huge advantage in having a strong, thin design, whereas there are no such limitations on the Dexa Wave design, which means that much cheaper materials can be used. The advantages – if any – of using CRC is addressed for the 2 different WEC's in the following.

Dexa Wave

The Dexawave converter consists of 4 main parts:

1. Pontoons
2. Main Frame
3. Power Take Off
4. Mission Control

In the original calculation based on conventional concrete PONTOONS represent 40 % of the total initial cost of the machine. Refinements of the calculation, based on gathered data and a survey of the possible suppliers has indicated that costs for PONTOONS can be reduced by around 80 k€ per converter, which would mean that the costs can be reduced to represent 18 % of the total initial cost of the machine.

For comparison a decision to use steel for the PONTOONS would result in a rise in cost of more than 500 k€ per converter. In addition the cost of maintenance would increase significantly.

The motivation for the current projct has been to investigate whether it is possible to reduce the wall thickness of the PONTOONS – or floats – by using CRC instead of conventional concrete, and thus achieve a lighter and stronger structure.

According to the tentative calculations and the conclusions of task 1, the reduction in wall thickness and the better durability, fatigue resistance and ductility that can be achieved with CRC is not significant enough to offset the added cost that would be incurred by changing to CRC. Actually, even though there is a reduction in wall thickness for CRC, the tentative calculations indicate that due to the higher density of CRC there will be no reduction in total weight for the PONTOONS.

The material cost of CRC is more than 5 times as high as the cost of conventional concrete, which means that CRC PONTOONS can represent as much as 52% of the total price of the machine. As the cost of moulds, casting, transport and post tensioning will be similar for CRC and conventional concrete, the difference in price for the 2 options will be somewhat alleviated, but the CRC floats will be considerably more expensive than those in conventional concrete – without adding much in terms of expected performance.

Based on this it would appear that the use of CRC for the PONTOONS is very unlikely. Even though the first calculations have been very simplified, a further and more detailed study would not be expected to change anything with regard to the conclusion, that concrete would be the preferred option in comparison with CRC.

A CoE analysis has been carried out for conventional concrete as well as for CRC and these are included in the full task 4.1 report, which is included as annex 5. The main results are shown in the table below.

DEXAWAVE Converter	CAPEX (Mill DKK/MW)	OPEX (DKK/kWh)	Production Cost (mill DKK)
CRC	11,3	1,89	2,8
Concrete	6,5	1,46	1,6

Conclusion Dexa Wave

In the floats for the DEXAWAVE converter no advantages are evident in using CRC. Conventional concrete is the best and most cost effective option based on structural, functional and economic considerations.

It can also be concluded that with regard to the DEXAWAVE converter CRC is by no means critical to the future use of waves as a source of energy.

Wave Star

The aim in the following is to examine the positive results in term of economy by using CRC concrete instead of glasfibers or steel for structural element of the Wave Star machine.

Introduction

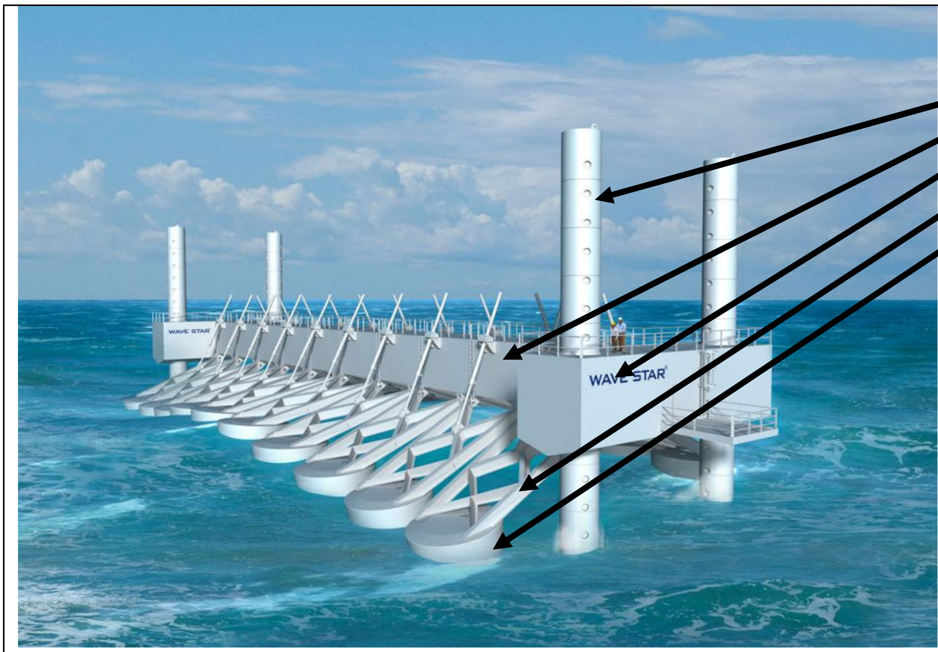
The Wave star machine is principally built in steel for the structural part of it and others elements like floats are built in glasfibers.

Due to a prototype building machine, the coast has been very high for the all construction. By analysing the cost distribution, we can conclude that the structural part is taking an important part of it (60%).

By reducing the cost of it, it is obsious to find out that it will have a postive impact of the total cost of the machine and in consequence, reduce drastically the cost of energy of the machine (COE).

Data analysis

The machine is built arround a steel bone with 20 arms and floats on each side of the bone:



Main structural components:

Legs in steel

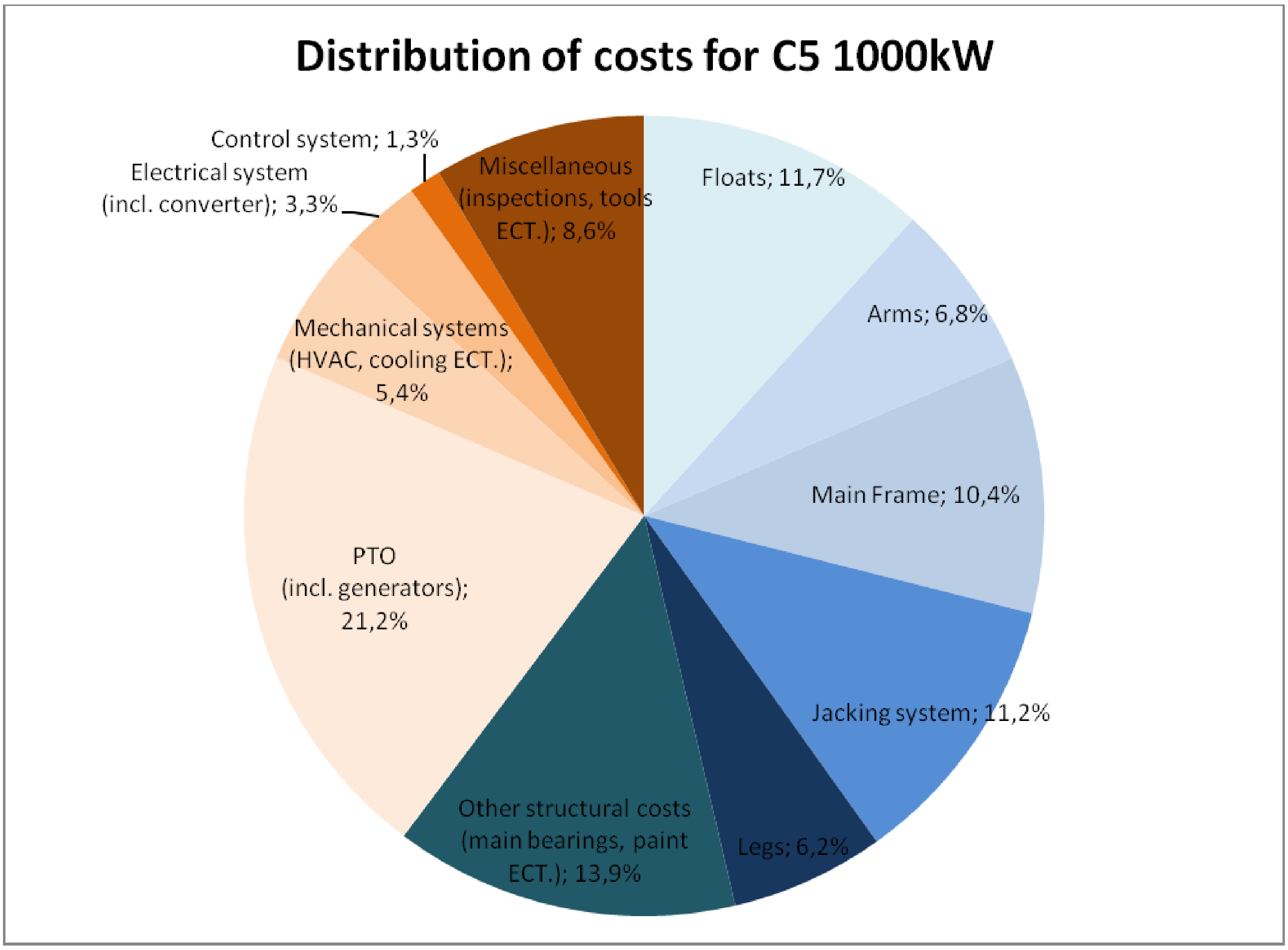
Main frame in steel

Jacking house in steel

Arms in steel

Floats in fiberglas

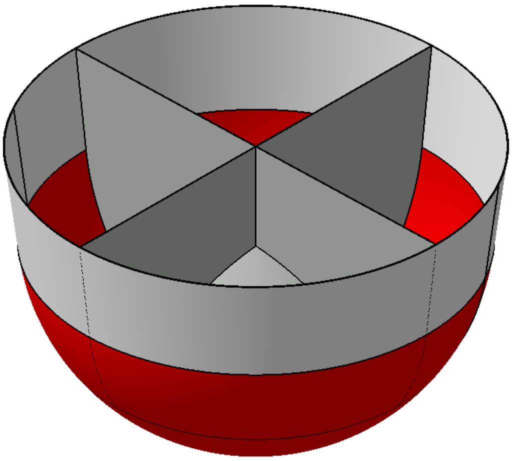
The cost distribution for the full machine is as follows:



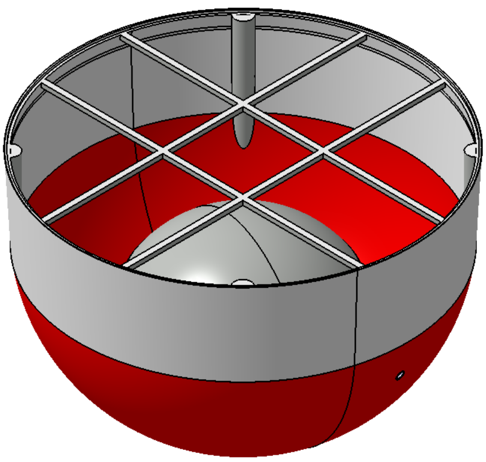
We chose two main elements of the structure: float and arm to analyse the real potential of decreasing costs by changing the existing material to CRC concrete.

Floats in CRC concrete

The existing float is made of fiberglass and has a of 310.000 kr per float, 20 floats represent a total cost of 11,7% of the all machine. The float has a weight of 1,5 tons.



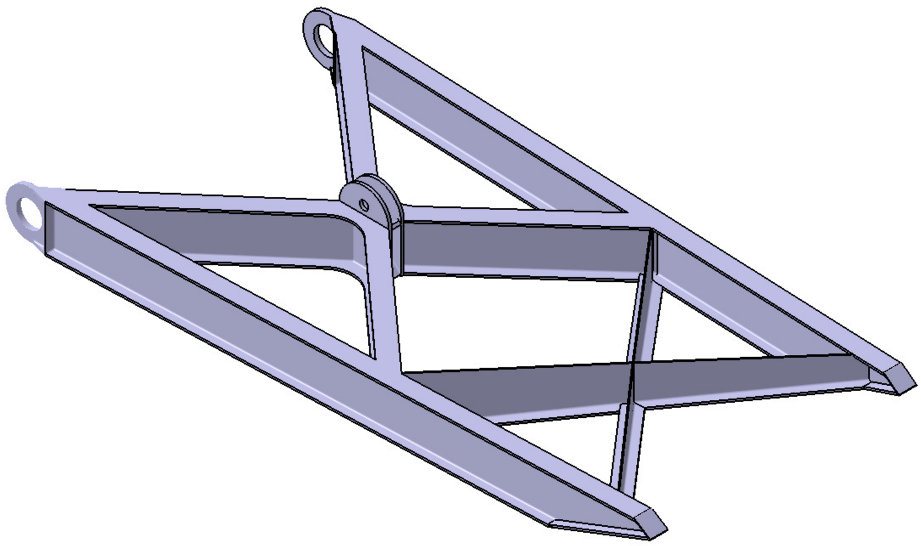
A new design of the float has been proposed in CRC concrete, it has been made in collaboration between Hicon and Wave Star. The structure of it is quite diferent from the existing structure as the material is quite different. The proposed CRC concrete float will have a cost of 70.000kr per unit. The calculation does not take in account the cost for the forming. The float will have a weight of approximatively 10 tons.



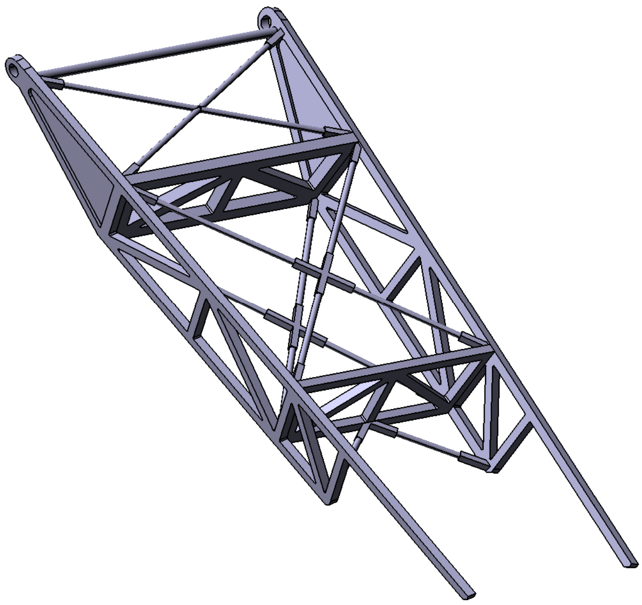
This is giving a significant saving of 77% per float.

Arms in concrete

The existing arm is made of steel and has a cost of 180.000kr. per unit, 20 arms represent a total cost of 6,8% of the full machine. The steel arm weighs 12 tons.



An updated design has also been proposed using CRC concrete. The proposed arm will have a cost 100.000 kr. The CRC concrete arm will have a weight of 8 tons.



This is giving a significant saving of 45% per arm.

Total reduction in cost

By replacing traditional material like steel and fiberglass, we can assume important saving on the cost price of the machine. For the floats itself, the saving is 77% per unit and for the arm 45% per unit. On the full machine, we achieve a complete saving of 12%.

Other potential cost reductions

It is obvious that others parts like legs, main frame, and jacking house could be redesigned using CRC concrete. No exact calculations have been made for these parts but we can assume that we can obtain savings and a conservative assumption using 20, 30 and 40% of savings will be used for that calculation.

unit	Actual cost	Savings by 20%	Savings by 30%	Saving by 40%
Leg (1)	816.000	652.900	571.300	490.000
Main frame	3.606.000	2.885.000	2.524.000	2.164.000
Jacking house (1)	920.000	736.000	644.000	552.000
Potential savings on the full machine incl. previous savings for floats and arms		15,3%	17%	19%

Conclusion Wave Star

The use of CRC concrete on the Wave Star WEC is definitively a way to go for reducing the total cost of the machine. An analysis has been made on two real examples, the floats and the arm where we calculate a potential reduction in cost of 12% on the full machine.

By anticipating the model on other potential structural parts of the machine, we can find out that there is still a potential of 20% of cost reduction.

Conclusions

The current project – as a preliminary study for a possible future project on using UHPC for significant parts of Wave Energy Converters – has had objectives that fall into 2 categories: Establishing the state-of-the-art and evaluating how – and if - UHPC can be utilized in optimizing WEC's and bringing them closer to being a viable option for energy supply.

The first category of objectives has been met by expanding on the preliminary designs of floaters for Wave Star and Dexa Wave and comparing designs in different materials in task 1, by describing CRC properties with relation to use off shore – including emphasis on production requirements for these types of structures - in task 2.1 and by describing the experience with a prototype float in CRC exposed for close to 4 years in task 3.

The second category – taking a further look at whether CRC can bring the WEC closer to being competitive – is mainly described in task 4, but the results of task 2.2 are also significant in this respect, as this task investigate possibilities of further optimizing CRC for the particular application in floaters and other structural parts of the converters – and demonstrates that a reduction in wall thickness of more than 15% can most likely be achieved by changing the type of fibres that is used.

For Dexa Wave there is no advantage in using CRC for the floaters – conventional concrete is a more cost-effective solution as described in task 4.

For Wave Star, however, there is a possibility of significant savings in changing the float design from fibre glass to CRC – in this case a reduction in cost of 77% for the float itself (even though the CRC float will be considerably heavier than the float in fibre glass). A study has also been made of replacing the arm – which is currently made in steel – with a CRC arm, which would give a saving of 45% per arm. As a Wave Star converter has 20 arms and 20 floats this will add up to a saving of 12% for the machine.

If a similar assessment is made for other structural parts of the machine leading to possible reductions in cost, this will contribute to meeting one of the 2 main challenges for WEC's of the Wave Star type, namely bringing down the cost. The other main challenge is to increase effectiveness, either by developing a better control algorithm or by refining and developing the PTO. Both challenges will have to be adressed, and for the Wave Star converter it is necessary to reduce the cost of the machine itself by more than 50% and the most promising way to achieve this is by using alternative materials such as CRC.

The current project has indicated that the first steps to meeting one of the main challenges – lowering machine costs - is possible for certain types of WEC, but it has also been shown that replacing other materials with CRC is not a universal solution. For the Dexa Wave converter there is no advantage in using CRC for the floats, but as for the Wave Star converter, there could still be advantages in replacing other structural parts of the converter.

While it may be difficult - from these preliminary results – to envision how cost reductions of more than 50% can be achieved for the converters, the studies made on the Wave Star floats and arms are certainly a promising first step on the way to establishing competitive wave energy production with the benefits to the environment that will follow.

1.4 Utilization of project results

This has only been a preliminary study, but the results are promising enough that most of the project partners intend to submit an application for a larger study. Such an application has been sent in earlier, but based on the results of the current project it has been decided to change the scope of the new application significantly. The budget – and time scale – will be reduced significantly and the aim will be towards more of a demonstration project. Included will, however, be a task dealing with optimisation of other parts of a converter by replacing materials as well as a task dealing with an evaluation of other types of WEC's and the possibility of reducing structural costs for those. All partners, except Dexa Wave, will participate in the new project application. Dexa Wave will not participate directly, but will of course be a relevant partner in the evaluation of other WEC's and the possibility of reducing cost for the machine frame.

1.5 Project conclusion and perspective

The current project – as a preliminary study for a possible future project on using UHPC for significant parts of Wave Energy Converters – has had objectives that fall into 2 categories: Establishing the state-of-the-art and evaluating how – and if - UHPC can be utilized in optimizing WEC's and bringing them closer to being a viable option for energy supply.

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While it may be difficult - from these preliminary results – to envision how cost reductions of more than 50% can be achieved for the converters, the studies made on the Wave Star floats and arms are certainly a promising first step on the way to establishing competitive wave energy production with the benefits to the environment that will follow. As described in the previous section, AAU, Wave Star and Hi-Con intend to apply for a demonstration project developing further on the results of the current project.