Design of composite material for cost effective large scale production of components for floating offshore structures

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The design and testing of composite point absorbers under slamming load is the central theme in this paper. The research is situated within the SEEWEC project which was launched at the end of 2005 in the Sixth Framework of the European Union. The SEEWEC stands for the sustainable economically efficient wave energy converter. First, the energy situation in Europe is discussed to explain the objective of these point absorbers within this research. Next, a small filament winding machine has been designed to produce these point absorbers on the laboratory scale. Also, a set-up for laboratory scale slamming tests was designed and built. Several test samples were produced on the winding machine and tested on the slamming set-up. First, a cone was tested as a reference case. Validation of this case followed suit. Next, a deformable and a non-deformable cylinder were compared. Finally, a possible point absorber was tested. Finite element analysis (FEA) calculations were conducted and computational fluid dynamics (CFD) simulations are initiated.

Keywords: Composite, Filament, Winding, Slamming, Renewable, Wave

Introduction

The Kyoto agreement states that by 2012 an important decrease of greenhouse gasses (GHG), like CO_2, has to be accomplished. The use of traditional fossil fuels can and will lead to the global warming with possible climate changes as a consequence. Also, the environmental pollution gains importance.

The European Union (EU) is dependent on import for 50% of its energy supply. By 2030 this could easily become 70%.[1] This import consists almost exclusively of fossil fuels (oil, gas and coal). First, this supply is finite. Second, fossil fuels are responsible for the production of GHG. Since the supply of these resources is finite, by 2050, other energy sources will need to be used. The reserves of oil are estimated to last for 40 years from now, the gas reserves for 60 years and coals for a bit more than 200 years. In any case, the prices will rise simultaneously with decreasing resources. This makes the EU economically vulnerable.[1,2]

Hence, the EU made an effort to promote renewable energy. At the climate conference of 1997 in Kyoto the EU decided to increase its share in renewables to 12% by 2012. In 2001 the renewable energy sector in Belgium contributed only 2% to the electricity production in the country.[2]

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For example, solar, biomass, wind and ocean energy can all give a small contribution. Wave energy is a small player on the energy market. However, it has a lot of potential. The European Atlantic coast wave climate is characterised by large energy. Waves can travel for thousands of kilometres with almost no loss of energy. Wave energy has some advantages: in comparison with solar energy, waves are more present, certainly at times when energy is needed the most (winter). In addition, waves have more energy per square meter than wind and solar energy.[3]

However, to improve the transition from technology to real wave energy converters and to insure their value on the global energy market, extensive research is necessary on the fundamental as well as on the applied level. The most critical aspect of the development of a wave energy converter (WEC) is the structural design. It needs to be very solid but at the same time the material and fabrication costs have to be limited. This clarifies why wave energy is not exploited on a global level at the moment.

SEEWEC project

Within the Sixth Framework of the EU, the SEEWEC project was launched at the end of 2005. The SEEWEC stands for the sustainable economically efficient wave energy converter. The different partners participating in the project are: Ghent University (Belgium), Spiromatic NV (Belgium), ABB (Sweden), Standfast Yachts (Netherlands), Brevik Engineering A.S. (Norway), Marintek (SINTEF) (Norway), Norwegian University of Science and Technology (Norway), Instituto Superior Técnico (Portugal), Chalmers University of Technology

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1 One third scale model 'Buldra', used for extensive testing at south coast of Norway since February 2005, whose main objective is development of second generation wave energy converter through extensive use of experience gained from monitoring this scale model

(Sweden), Fred Olsen Ltd (UK) and Natural Power Consultants Ltd (UK).

In the project a floating wave energy converter is studied. With the means of point absorbers the energy of the waves will be captured. This floating and offshore platform has the advantage that it can be used in deeper water where there is more energy available. Acknowledgement for the general concept is given to Fred Olsen Ltd. A 1/3 scale model is shown in Fig. 1. The general objective of the SEEWEC project is the development of a second generation wave energy converter. The project is divided into different work packages. The department of Material Science and Engineering of Ghent University is mainly concerned with the fourth one, namely 'the design of composite material for cost effective large scale production.'

The first important steps are taken for the design and production of composite floating point absorbers. These buoys, seen in Fig. 1, are shortly called 'eggs'. The material used for this will be a fibre reinforced composite. The main reasons why metal will not be used is corrosion and maintenance at sea.

The first task consists of choosing the basic fibre reinforced composite, and the determination of the basic mechanical characteristics. Next, the software package Cadwind has been used to calculate the winding path and material orientations. The thickness and orientation can be exported to Abaqus, a commercial finite element analysis (FEA) program, where simulations have been conducted on the egg. Additionally, calculations were initiated in commercial computational fluid dynamics (CFD), Fluent.

Next, a small filament winding machine has been designed to produce eggs on the laboratory scale. For experimental tests on the strength of the egg and pressure distribution of the water, a set-up for slamming tests is designed and built. This slamming set-up is designed to be used for different structures. Validation of the analytical formulas for slamming and gaining more experimental data is the purpose of these tests. A set of samples has been made: a cone, a full cylinder, a hollow cylinder and a possible shape for a scaled point absorber. In the future, further experiments on these test samples will be conducted. Also, other shapes should be considered.

The given information in this paper will be limited due to reasons of confidentiality of the SEEWEC project.

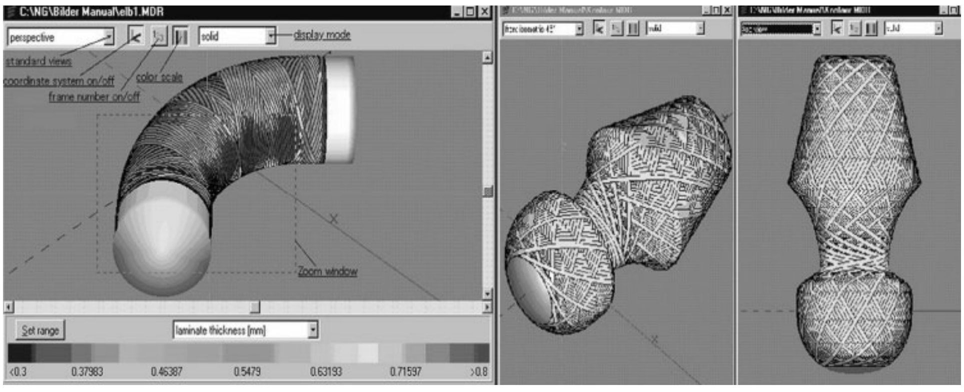
Manufacturing technique

As mentioned, the material used for these structures will be a fibre reinforced composite due to reasons of maintenance at sea and corrosion. The eggs will probably be made of glass fibre and polyester resin due to reasons of costs in view of large scale production.

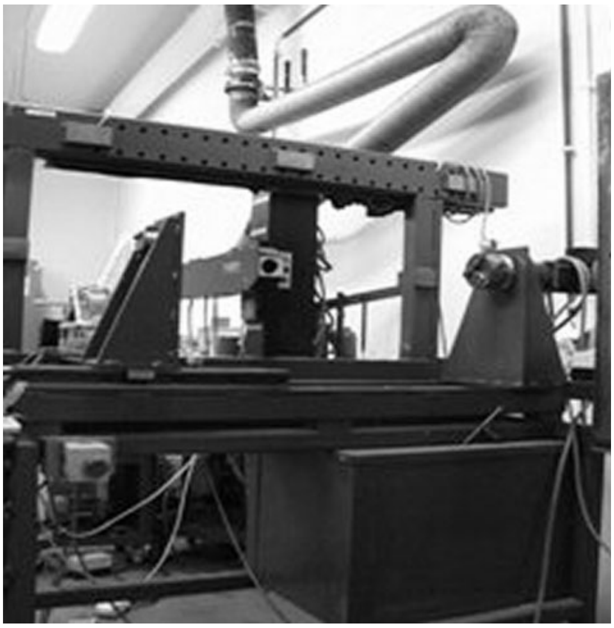
Filament winding is one of the chosen production processes of the egg. First, this production method is suitable for large scale production at low cost, because the main cost is the mandrel. The cost of this mandrel is a one time investment. As soon as it is available the cost per structure decreases drastically. Thus, for series production filament winding is a cost efficient production method. Second, the buoys, which are axisymmetric structures, are easy to wind.[4,5]

A commercial software program, Cadwind, is used to calculate the winding pattern for any mandrel geometry. It determines whether a given shape can be wound. Some examples are shown in Fig. 2.

Not all geometries can be manufactured in a filament winding process. It can occur that the fibres simply fall off the structure when there is not enough friction. Thus, this program is able to predict whether or not a given geometry is suitable for the winding process. Next, it is possible within Cadwind to produce an export file with geometric (mesh) properties which can be used as import



2 Examples of filament wound structures in Cadwind, which is commercial software program used to determine whether certain shape can be wound



3 Small filament winding machine in laboratory of Ghent University which was used to make laboratory scale test samples discussed further on in this paper

4 Different shapes for point absorbers are considered within SEEWEC; this is possible scaled shape of point absorber which was studied extensively during project; it was made on winding machine in laboratory at Ghent University

for Abaqus, in which the strength and deformations can be calculated through FEA.

A small filament winding machine with a new controller and program to operate it has easily been designed to produce, for example eggs, on the laboratory scale, as is shown in Fig. 3. Again, Cadwind proves to be a good tool. It generates all the coordinates for the axes of the winding machine so no geodetic path needs to be calculated manually. This file can be imported in the designed Labview program on the winding machine.

A possible point absorber was made on the laboratory scale for further tests. The result is shown in Fig. 4.

Slamming loads

Slamming is the periodical impact of waves on a floating or sailing structure. It is a complex process where the compressibility of water, the hydro-elasticity and air-cushions/air bubbles can be relevant.

Until a few decades ago, the use of fibre reinforced composites in marine environment was limited to sport vessels and a number of military applications. The composite structure was designed very stiff and quasi-rigid, in order to resist the slamming wave impact. In that case the calculation of the peak pressure of slamming waves is based on the theory of Wagner as is discussed in the section on 'Laboratory set-up' later.

In the literature, slamming is extensively studied for wedge shaped structures, like it is in the case of ships. In extreme cases slamming is the cause of fracture of a ship which can happen due to the pitch and heave of the ship. The probability of slamming of a ship is highest at the front where the maximum relative vertical velocity between the ship and the wave is situated. Another kind of slamming is the breaking wave impact above the waterline.[6,7]

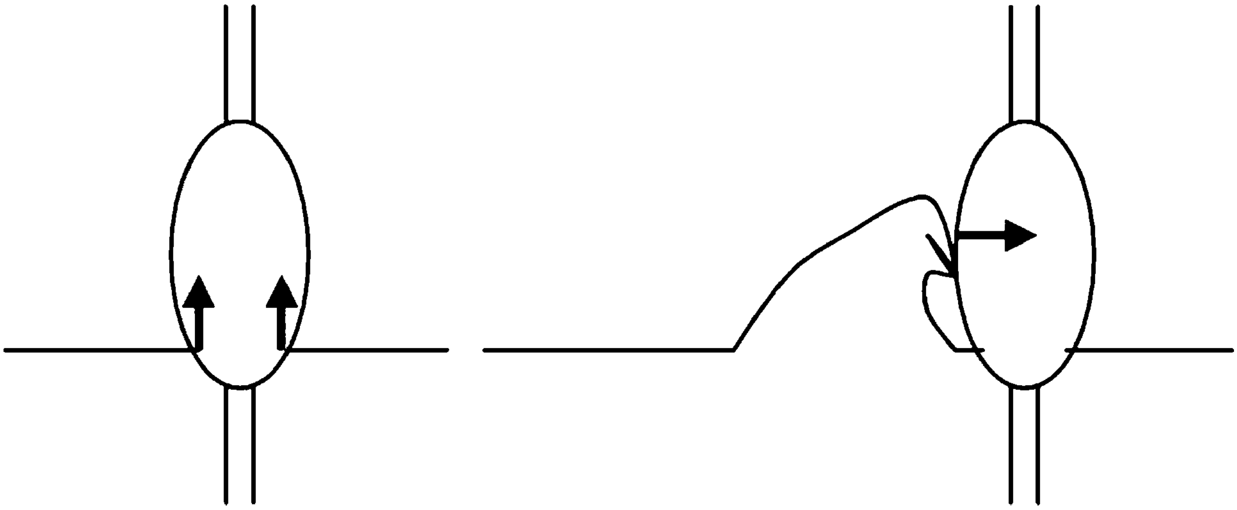
Slamming is also an important factor for the strength of the composite eggs at sea. Here, the two kinds of slamming mentioned above are considered: the bottom slamming, namely the periodical falling of a structure on the water surface and the real breaking wave slamming where a wave breaks just at the moment that it hits the structure from the side. Both kinds are seen in Fig. 5.

The egg can come out of the water. This can occur in situations from normal to high waves and with low penetration depth of the egg (the buoy can come out of the water due to resonance in the presence of high waves or as soon as there is a phase shift between wave and buoy). At the exact moment it goes back in the water (hydrodynamic impact), it can be severely damaged due to high hydrodynamic pressures on its surface. Those impact pressures last only a fraction of a second but they are very local and thus can cause severe deformations of the material.

Waves cannot become infinitely steep. As soon as they reach the height/length ratio of 1/7, they break. The most critical force on the egg occurs when the waves break at such a moment on the vertical surface of the egg.

In recent years, composite materials are applied more and more in ship construction and offshore structures, because of their corrosion resistance, limited maintenance, long lifetime and sometimes even cheaper cost. Also, demands of light weight engineering and reduction of material consumption lead to less massive structures that can no longer be considered as rigid. The effect of slamming impact on deformable composite structures and the evolution of the possible damage has hardly been studied, and there is a need for fundamental research.

A slamming set-up on the laboratory scale was designed and built for experimental tests. With the results achieved from several experiments, it should be possible to gain information about the mechanical behaviour of composite structures such as the strength



5 Slamming is periodical impact of waves on floating or sailing structure; within project two kinds of slamming are considered: egg bottom slamming (left) due to vertical movement of buoy, and egg breaking wave slamming (right) due to horizontal impact of breaking wave on buoy

of the buoys, the deformations and the pressure distribution on the surface. The laboratory scale egg will be studied thoroughly. However, the research was extended to other objects as well.

In general experimental and numerical research about slamming on composite structures is quite limited.[8–11] Industrial Research Ltd, a company from New Zealand, has built a slamming set-up where composite plates were tested but only experimental results were published.[12,13]

At the 13th International Conference on Experimental Mechanics of 2007, Dr. Rajapakse, head of the Office of Naval Research (ONR) of the US Navy, mentioned that slamming of composites is one of the most important research fields for coming years.[14] Until now, no results have been made public.

Experimental

Laboratory set-up

The slamming set-up is shown in Fig. 6. The main objective of this set-up is gaining expertise and validation between the results of the experiments on the laboratory scale egg and the calculations. It is designed not only for the eggs, but also for experiments with other structures. Again, the main goal is obtaining validation between simulation, literature and experiments. In the set-up, a ladder is attached to a shaft. By means of a computer controlled motor the shaft is turned over. A water tank is placed under the ladder. Bottom slamming and breaking wave slamming can both be tested in this set-up.

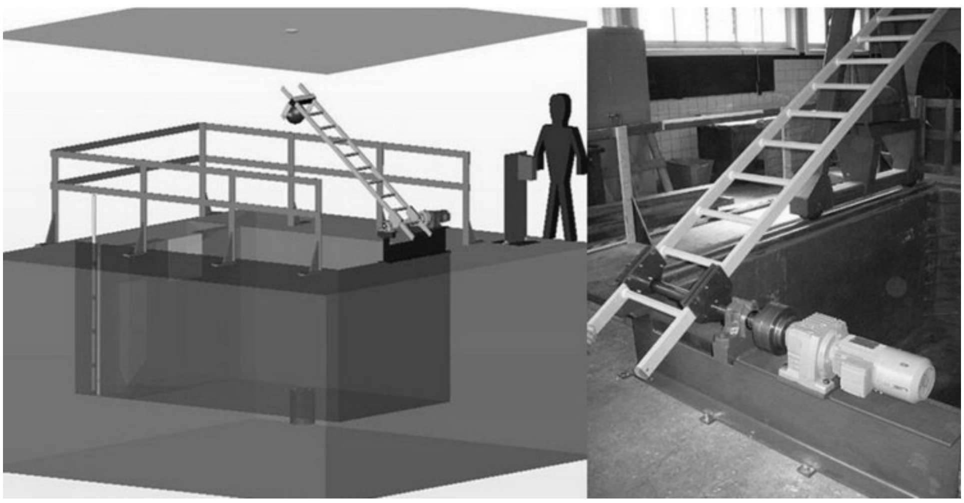
The set-up is designed for repeated drop tests. However, at this moment only standalone drop tests are carried out. A high speed camera will be used during all the tests. For safety reasons (e.g. the water basin breaks down) a mirror will be used, so the camera can be mounted at a distance.

Cone test samples

In the first experiment, a cone will be tested. The cone is made out of polyurethane foam. A topcoat is given to the cone to make it watertight. The cone is shown in Fig. 7.

The cone is instrumented with a pressure sensor, an accelerometer and two strain gages (perpendicular). This will be read out by Labview.

This cone test case is chosen because straightforward information is available in the literature about this specific case. Wagner (1932) studied the impact of a 2D wedge with a small deadrise angle. The deadrise angle is the angle between the free water surface and the cone as is shown in Fig. 8.



6 Design of slamming set-up in CAD software Solid works (left) and realisation of set-up in laboratory (right)

7 Polyurethane cone test sample attached to ladder of slamming set-up: the cone is chosen as reference test case

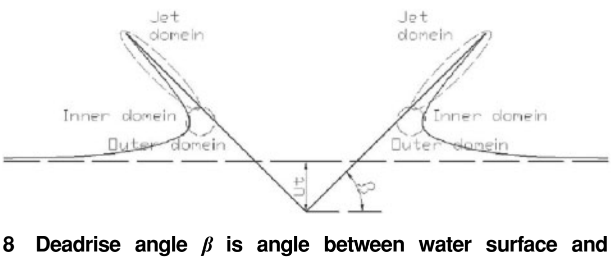
During the time, corrections have been applied to the work of Wagner, e.g. for larger deadrise angles. Later on Wagner's theory has been extended to rigid cylinders and axisymmetric bodies (sphere and cone).[15–19] These formulas have been experimentally validated many times in a drop weight set-up, where a rigid wedge, cone or sphere falls on a calm water surface.[20–23]

For axisymmetric bodies, such as the cone, the 3D flow can be described by a flow around a circular plate. Out of the known complex potential function of this flow, the pressure distribution in time can be retrieved. This has been conducted at the Department of Coastal Engineering of Ghent University[6] by Viktor for a general cone and a sphere. For a cone with a deadrise angle of 45° equation (1) can be used[6,7]

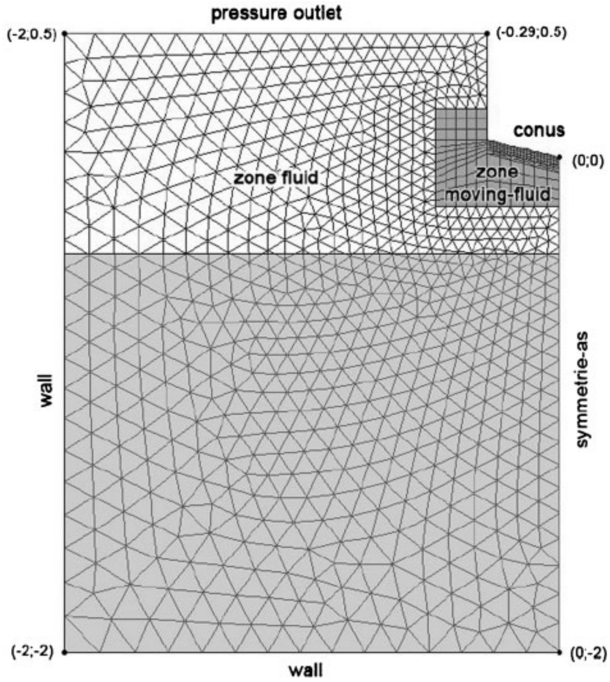
$$P45 = \frac{1}{2}\rho U^2 \left\{ 1 - \frac{4\left(\frac{r}{Ut}\right)^2}{\pi^2\left[\frac{16}{\pi^2} - \left(\frac{r}{Ut}\right)^2\right]} + \frac{64}{\pi^3\left(\frac{16}{\pi^2}\right)^{1/2} - \left(\frac{r}{Ut}\right)^2} \right\} \quad (1)$$

Equation (1) indictes the pressure distribution along the edge of a cone of 45° during slamming, where r is the radius (m), t is the time (s), U is the velocity (m/s) and ρ is the density of fluid (kg/m^3).

This formula, reshaped for smaller deadrise angles, confirms the previous numerical result of the slamming tests conducted by Peseux *et al.*[24] In that paper, a solution is proposed for wedges for a non-deformable and deformable structure with deadrise angles of 6, 10 and 14°.



8 Deadrise angle β is angle between water surface and slope of cone; deadrise angle of 45° has been chosen first to validate results with literature as reference test case and second due to resemblance with proposed shape for point absorber



9 Air and water phase in Fluent: volume of fluid method is used in combination with moving grid

The purpose of the cone test is mainly about finding a good correlation between the theory and experiments. Next, in the case of agreement, the results of this experiment can be used to assess the authors' slamming set-up. Thus, the cone test case is considered as a reference test as a start for other calculations and experiments.

Additionally, calculations in Fluent, a commercial computational fluent dynamics (CFD) code, are initiated. The volume of the fluid method (VOF) was used in combination with the use of a moving grid. In Fig. 9, a phase of water and one of air are used.[25]

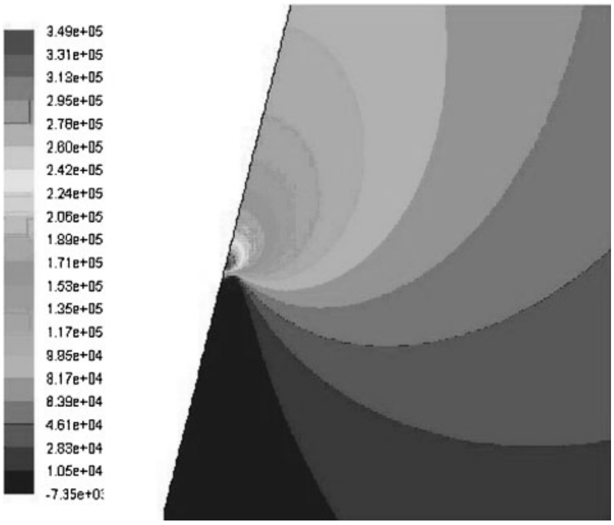
The results of the Fluent calculations confirm that numerical results are conservative concerning the maximum pressure, as is also mentioned in the paper of Peseux himself. Next, the CFD simulations were conducted for wedges and cones. These calculations show that the pressure is lower for the cone in comparison with the wedge. Again, the maximum pressure is conservative in the numerical model. However, there is a global agreement between experiments and calculations. First, the pressure on the cone goes to a peak and second, is followed by a constant value. The peak pressure at a certain time is shown in Fig. 10. It shows the pressure distribution along the edge of the cone.[25]

According to the analytical solution this peak pressure is a constant on the whole body of the cone. However, the experiments show that this is not the case. This result could be expected due to the deceleration of the cone. Of course, in simulations conducted with constant velocity, the peak pressure indeed lingers at a constant value.

The first experiments on the cone are conducted. The results give a good agreement with numerical values. Thus, this cone test case can be seen as a confirmation of previous theories and experiments.

Comparison between full and hollow cylinder

The next test consists of two test samples, namely a full cylinder and a hollow one. Here, the aim of the tests is gaining experience on the effect of slamming on a rigid



10 Pressure distribution calculated with Fluent along slope of cone

and deformable structure of a certain shape, e.g. a cylinder.

First, two cylinder mandrels are made in polyurethane. Next, the mandrels are mounted on the winding machine. The two cylinders have been wound. Next, the production method is different for both cylinders. For the first one the mandrel stays inside, and for the second one the foam is removed. Both cylinders are instrumented with a pressure sensor, an accelerometer and two strain gages again.

The measurements occur in the middle of the cylinder to reduce side effects. The full or rigid (left) and hollow or deformable (right) cylinder test samples are shown in Fig. 11.

The measured pressure distribution in time for the full cylinder is comparable with that for the cone. However, the slope of the pressure–time measurement is a lot steeper in the case of the full cylinder. This means that the slamming occurs faster in that case. Also, the peak pressure is about 30 times higher.

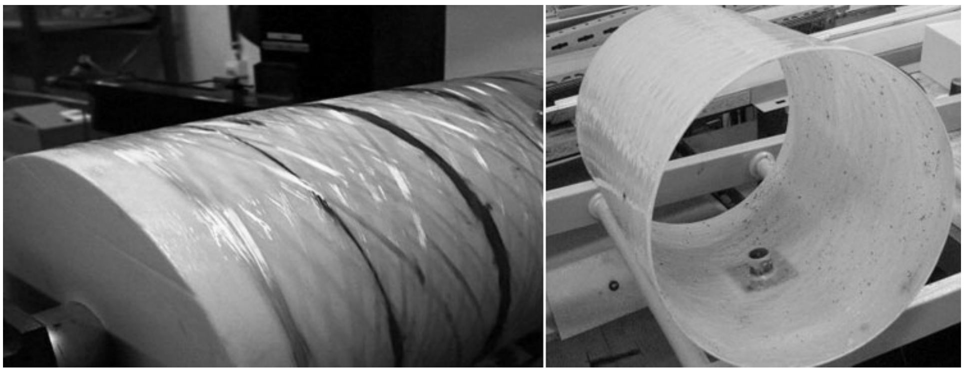
Next, the comparison of the experiments for the full and hollow cylinders gives interesting results. Owing to the deformability of the hollow cylinder, the average peak pressure decreases in the experiments with a factor of two, from about 700 000 Pa for the full cylinder to 335 000 Pa for the hollow one as is shown in Fig. 12. This result was confirmed with the Fluent calculations on both the full and hollow cylinders.

To conclude this paragraph, some images from the high speed camera are shown in Fig. 13, where the deformations of the hollow cylinder to an elliptic shape are seen.

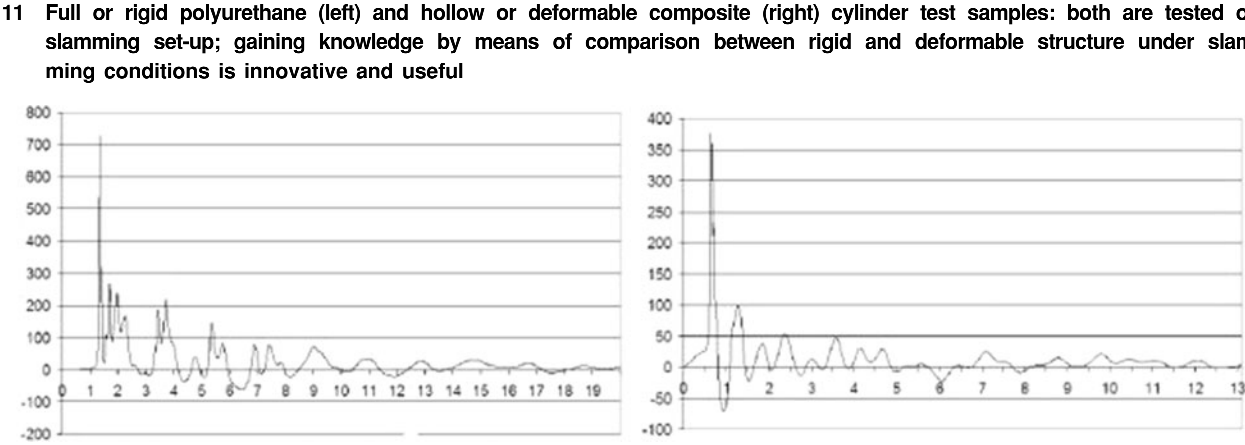
Shape of point absorber

Also, a laboratory scale test of a possible point absorber has been conducted (*see* Fig. 5). Breaking wave slamming is more critical for the eggs in comparison with bottom slamming. This is due to its stiffness. Since breaking wave slamming is the most critical one, the egg has been tested on its side. Pressure, acceleration and strains have been measured again.

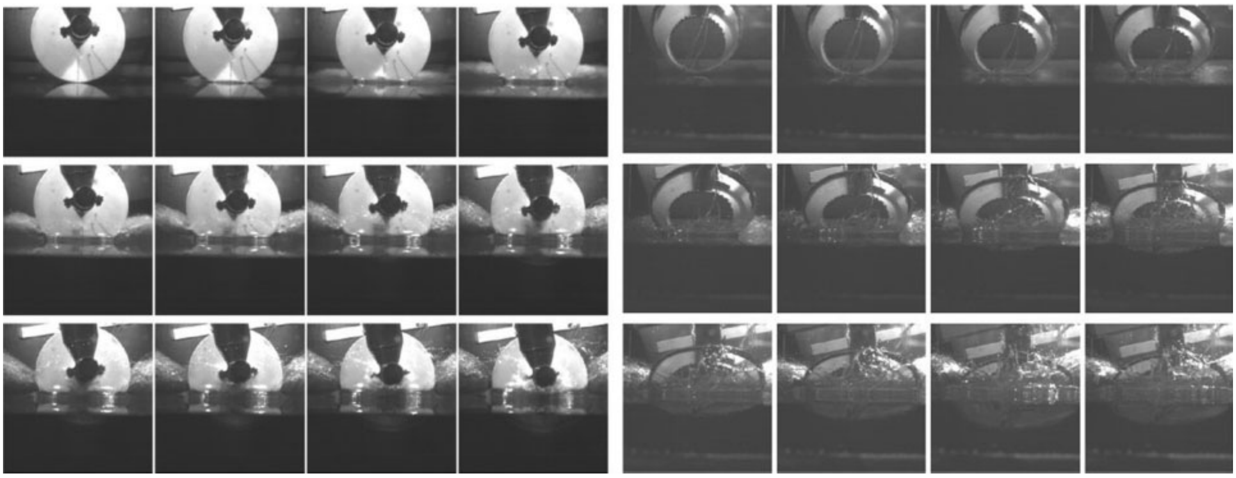
Breaking wave tests will also be conducted in the wave gutter in Flanders Hydraulics Research Laboratory in Borgerhout, Belgium. There, the possibility to generate waves of certain height is available. In the previous set-up, however, a falling speed was given. A twin structure will be tested in the wave gutter in Borgerhout. There, a given significant wave height (corresponding with certain celerity) will result in a certain pressure. If the



11 Full or rigid polyurethane (left) and hollow or deformable composite (right) cylinder test samples: both are tested on slamming set-up; gaining knowledge by means of comparison between rigid and deformable structure under slamming conditions is innovative and useful



12 Results from cylinder test samples from 1 m drop height: pressure distribution (kPa) over time (10^{-3} s) for full cylinder (left) and hollow cylinder (right)



13 Images from high speed camera during drop tests for full cylinder (left) and hollow cylinder (right): notice ellipsoid shape in case of hollow cylinder

velocity of the falling speed in the previous set-up and this celerity are about the same, the measured pressures should also be in the same range. The comparison of both experiments is an assessment of the usability of this slamming set-up for breaking wave slamming.

Conclusions and future work

The first important steps are taken for the design and production of composite floating point absorbers. The material used for this will be a fibre reinforced composite. Some of the reasons why metal will not be used are its corrosion and maintenance at sea. One of the possible production methods is filament winding, which is chosen due to axisymmetric structures and also due to the emphasis on large production series. The software package Cadwind has been used to calculate the winding path and material orientations and Abaqus has been used for FEA calculations on the egg. A small filament winding machine has been designed to produce test samples on the laboratory scale. Also, a set-up for slamming tests was designed and built. A set of test samples has been made: a cone, a full cylinder, hollow cylinder and a possible shape for a scaled point absorber. The results of the cone test give a good correlation with the theory. Additionally, calculations in Fluent took place to predict the pressure distribution. These calculations and the experiment can be considered as a reference case for further work. Next, experiments were conducted on the rigid and deformable cylinder and on the possible shape for a point absorber within the SEEWEC project. Further FEA calculations and further slamming tests need to be conducted. Interaction between Fluent and Abaqus needs to be optimised. Finally, in the long term, it is worth considering looking further than only the maximum peak pressure and researching the full spatial and temporal distributions of slamming pressures.

Acknowledgements

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