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Publication Date	2019-09-01
Publisher	European Wave and Tidal Energy Conference

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Yadong Jiang, Edward Fagan, and Jamie Goggins

Abstract— **This paper focuses on the structural design and optimisation of a 1 MW tidal turbine blade, with the goal of reducing the blade design and manufacturing costs. The blade model optimisation was conducted using an in-house software BladeComp, developed in the Large Structures Research Group at NUI Galway. The blade design and modelling cover a range of properties, namely composite materials and layup distributions. The structural response of the blade is analysed using Finite Element (FE) software. As the material costs contribute a significant proportion to the total blade manufacturing costs, optimisation of the layups is carried out using genetic algorithms to reduce the blade mass. During the optimisation, the blade's safe operation is assured by controlling its stiffness levels. Two resultant blade designs, from different mass ranges, are adopted from a large set of potential blades within the constraints of the problem. The layup thickness distributions and structural responses are compared and discussed.**

Keywords—**tidal turbine, composites, finite element modelling, blade optimization**

I. INTRODUCTION

THE energy needs in the world are raising with the increase of the development of humankind. Giving that the total reserves of fossil-fuel are limited on the earth, various renewable energy sources (e.g. Wind, Hydro, solar, etc.) are essential to be investigated to provide clean and sustainable power in the future. Among these renewable energy sources, windpower and hydropower are optimum choices. Wind/tidal turbines can convert wind/water power to energy, by reducing the wind/tidal current flow velocity. Compared to wind turbines, tidal turbines have advantages of minimal visual impact. Regarding the source of current, the water density is 835 times higher than air density. Thus, the structural performance of a tidal turbine blade is more critical than it of a wind turbine blade under the same power rate, since the same amount of power is transferred through a much smaller structure.

The long-term structural strength of turbine blades is important, as it can ensure the normal operation of the turbine system under the design current loads. Finite element (FE) models are commonly used [1]-[3] to predict the structural response of the turbine blade and in the structural design of the blade. Murray et al [1] developed a tidal turbine blade design tool with the combination of FE model with blade element momentum theory (BEMT). Compared to the fluid dynamics-FEM approach, this design tool requires less computational resources. FE modelling was also employed in the research work of Fagan et al [2] to design the composite layups of tidal turbine blades under design loads. Taking advantage of FE model predictions of stress/strain data for composite materials, the damage mechanics were considered during the design. FE models were also used in the fatigue damage assessment of tidal turbine blades [2], where the stress/strain components from FE analyses were combined with fatigue testing data to predict the blade's fatigue life, with the consideration of material water-saturation. Moreover, BladeComp, a design and optimisation software for wind and tidal turbine blades, had been proposed in this research, and was further extended in the research works [4]-[5].

The material costs contribute a significant proportion to the total blade manufacturing costs. Given a tidal blade with an adopted external surface, the blade manufacturing costs are mainly dominated by the layup thickness, as it governs the blade mass. Thus, the blade layup distribution should be properly designed to reduce the manufacturing costs of the blade. Regarding the

Paper ID: 1583

Track: Structural mechanics - materials, fatigue, loadings

This work was supported in part by Science Foundation Ireland (SFI) through the Marine and Renewable Energy Ireland (MaREI) research centre (Grant no. 12/RC/2302), the European Union's Horizon 2020 research and innovation programme under grant agreement No. 691916 for the FloTec project and through the OCEANERA-NET COFUND from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731200 under the SEABLADE project.

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ISSN 2309-1983

design of wind turbine blades, genetic algorithms [6] are commonly utilised. Using genetic algorithms, the authors of [4] and [5] designed the layup configurations of two wind turbine blades, with goals to reduce the blade mass and to improve the blade stiffness, respectively. Significant improvements of blade self-weight and mass were observed in the two research works. A genetic algorithm based optimisation was conducted in [7], which not only aimed to optimise the blade layup configuration but also to optimise the blade spar cap and shear web locations. Blade design with about 7.2% of reduction on mass was achieved in the optimisation.

Considering that tidal turbine blades have similar material and geometry configuration as wind turbine blades, the combination of FE modelling and genetic algorithms is applicable in the layup design of tidal turbine blades. In this paper, a case study has been performed to determine the composite layup design of a 1 MW tidal turbine blade. The structural response of the blade is the main concern of this research. Multiple-objective optimisation using a genetic algorithm is conducted to generate light-weight blade layup designs. Preliminary optimisations, which aim to acquire suitable objective weight factors of blade weight and stiffness, are carried out. Two blades with balanced weight and stiffness designs have been selected from the main optimisation for analysis.

II. BLADE MODEL DESCRIPTION

A. Geometry

The horizontal axis tidal turbine blade studied in this research is relevant to a new generation of Orbital Marine Power commercial turbine. The rotational axis of the rotor is parallel to the current direction. The blade's external geometry has been designed to have a standard power rating of 1 MW. The blade is approximately 8.5 m long, with a single web. Fig. 1 shows the structural model of the turbine blade. As can be seen, the section tapers along the blade length, to allow thinner airfoil sections to be used with reduced drag. For this reason, the blade layup thickness usually decreases along the blade length. Optimisation of the blade spar was performed in this work.

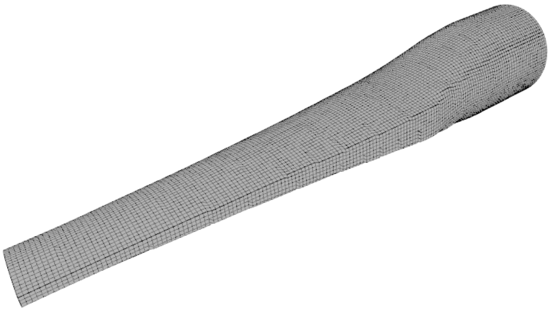


Fig. 1. Structural model of the tidal turbine blade spar.

The blade is made up of 3 components, namely the spar cap, the edge shell and the web, as shown in Fig. 2. The torsion and flatwise loads are mainly resisted by the spar cap and web, whilst the edgewise loads are mainly carried by the edge shell. Considering this functionality difference between blade components, their layup thickness distributions are considered separately, which are detailed in Section E.

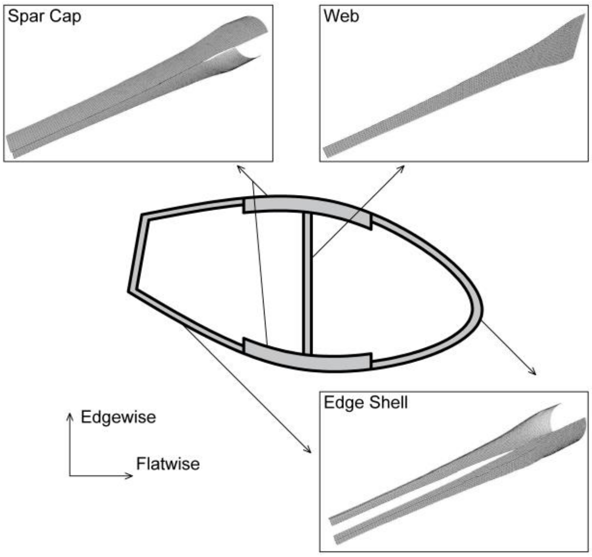


Fig. 2. Blade components.

B. Design loads

The design flatwise and edgewise shear loading of the turbine blade are normalised and shown in Fig. 3. It can be seen that the flatwise loads are significantly larger than the edgewise loads, which indicates that a strong spar cap or web are needed to provide enough resistance in the flatwise direction. To ensure that the blade can bear loads in extreme condition, partial factors of material load and scatter should be considered. It should be noted that due to lacking detailed international tidal blade test standard, the partial factors from the wind turbine test standard (IEC TS61400-23 [8]) are used, as listed in Table II. Therefore, an amplification factor of 1.485 is applied to the design loads. In the structural modelling of the blade, the factored flatwise and edgewise loads are considered.

TABLE I
PARTIAL SAFETY FACTORS FOR BLADE TESTING FROM THE IEC TS61400-23 [8] WIND TURBINE BLADE TEST STANDARD

γ_m Partial material factor	γ_f Partial load factor	γ_s Partial factor of scatter
1.0	1.35	1.1

C. Finite element model

Finite element (FE) model is utilised to analyse the structural response of tidal turbine blade. The FE model is generated by the in-house developed software package, BladeComp. The blade modeller module of BladeComp can generate structural FE models of turbine blade quickly and conveniently.

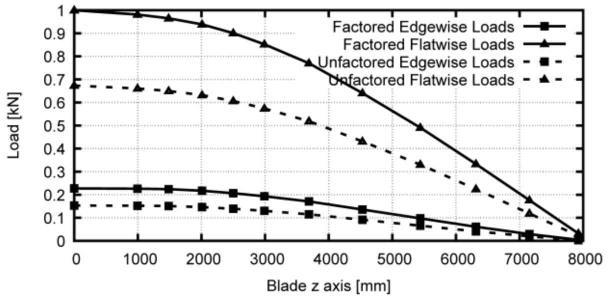


Fig. 3. Normalised factored and unfactored design loads of the tidal turbine blade.

BladeComp uses a smart interpolation algorithm to generate the blade surface from root to tip, based on its section geometry information. As turbine blades made with composite materials can be considered as thin wall structures, the blade is modelled with shell elements. In BladeComp, the blade surface is meshed into shell elements by a smart mesh algorithm. With this algorithm, the generated quadrilateral and triangular elements will have a similar size, which can avoid abnormal data (especially strain and stress values) caused by irregular element shapes automatically generated in FE. Another advantage of this meshing algorithm is that it provides added control of the local coordinate system of the elements, which is useful for assigning orientation of composite (anisotropic) material sections. BladeComp can either use the FE analysis software Abaqus [9] or Ansys APDL [10] as its solver. In this research, all the structural responses of the generated blades are analysed in Ansys APDL [10]. The feasibility of the FE modelling methodology used by BladeComp has already been verified in serval research works [2,5,6].

III. BLADE OPTIMISATION

As the blade geometry has already been adopted, this study focuses on the design of the layup thickness distributions of the three blade components. The layup design goal is to make the blade strong enough to operate normally under current loads, while at the same time, minimising the blade manufacturing costs. As the material costs consist of a significant portion of blade manufacturing costs, a light-weight blade design is preferred. On the other hand, the blade self-weight is related to the layup thickness and thus, will influence blade stiffness. A lower blade stiffness will cause a larger blade deflection, which may exceed the clearance between the blade and its adjacent components and result in the damage of energy system. Moreover, it was found large deformations of the turbine blade will cause the load acting on it to vary from the design load [1], which could introduce uncertainties to the energy system. Thus, the blade stiffness under design load should be constrained. Therefore, the main objectives of the layup design are to have a light-weight blade, whilst keep the stiffness of the blade at a reasonable level. The optimiser modulus of BladeComp is used to carry out the multiple-objective optimisation, with aims to minimize the blade mass and the flatwise tip deflection. The BladeComp optimiser modulus employs the genetic algorithm, a powerful method for solving optimisation problems, to generate multiple blade layup designs by group evolution. The following subsections focus on the description of optimisation setups for current blade laminate design. A more detailed methodology utilised by BladeComp is reported in the research works [4,5].

D. Material properties

Glass-fibre (GF) with a powder epoxy resin is targeted as the material of the turbine blade, to achieve a light-weight and high strength design purpose. Two kinds of layers, namely a unidirectional (UD) layer and biaxial (Biax) layer, are considered in the layup design. The properties of the two layers are listed in Table II. The UD layer consists of GF piles oriented to the blade z-axis, producing high bending moment resistive capacity in its major axis. The Biax layer comprises GF weaved in orientation of ±45° to the blade z-axis. Compared to the UD layer, the Biax layer has a lower stiffness in the major axis and a larger stiffness in the minor axis. Therefore, the Biax is more efficient in providing shear strength to the blade. By a reasonable combination of the UD and Biax layers, it is possible to achieve a light-weight blade solution.

TABLE II
MATERIAL PROPERTIES OF UD AND BIAX

	UD	BIAX
Density [ton/m^3]	1.9	1.9
E_1 [MPa]	38805	25944
E_2 [MPa]	12785	25944
G_{12} [MPa]	3670	3670
ν_{12}	0.26	0.13

E. Layup description

For the spar caps and edge shells, considering that the two components need to bear both the flexural and torsion forces, a combination of UD and Biax layers is adopted. Regarding the web, only Biax layers are used since it mainly provides shear stiffness to the blade. The layup combinations defined for each component are listed in Table III. Take the $Biax_{n_1}/[UD_2/Biax_1]_{n_2}/Biax_{n_3}$ as an example, the $Biax_{n_1}$ means that there are n_1 number of Biax layers at the blade external surface. The $[UD_2/Biax_1]_{n_2}$ means that in the middle surface, the layers are repeated in a pattern of 2 UD layers and 1 Biax layer n_2 times. The $Biax_{n_3}$ represents n_3 number of Biax layers at the blade internal surface. It should be noted that values of n_1-n_7 vary along the blade length.

The layer numbers n_1-n_7 at a given blade length are defined by the layer distributions. There are two kinds of layer distributions considered during design, namely the linear distribution (Fig. 4 (a)) and 3-drop distribution (Fig. 4 (b)). The linear distribution assumes that the layer number distributes along the blade length linearly. For the linear distribution, the layer number can be ascending, descending or constant. Two variables, namely the start and end layer numbers, are required to adopt a linear layup distribution. Fig. 4 (b) shows the 3-drop layer distribution, which consists of 3 drop regions and 4 constant regions. Compared to the linear distribution, the 3-drop distribution can simulate a more complex layer shape. Different from the linear distribution, the layer number of 3-drop distribution is forced to be descending along the blade length. There are 10 variables required to construct a 3-drop layer distribution. As shown in Table III, there are 38 variables required to adopt the blade layup design. These variables will be acquired through the optimisation.

TABLE III
THE LAYUP DEFINED FOR EACH COMPONENT

Component	Layup Definition	Variable number
Spar Cap	$Biax_{n_1}/[UD_2/Biax_1]_{n_2}/Biax_{n_3}$ [a]	14
Edge Shell	$Biax_{n_4}/[UD_3/Biax_1]_{n_5}/Biax_{n_6}$ [a]	14
Web	$Biax_{n_7}$ [a]	10

[a] The left-right order represents the external-internal direction of the blade surface.

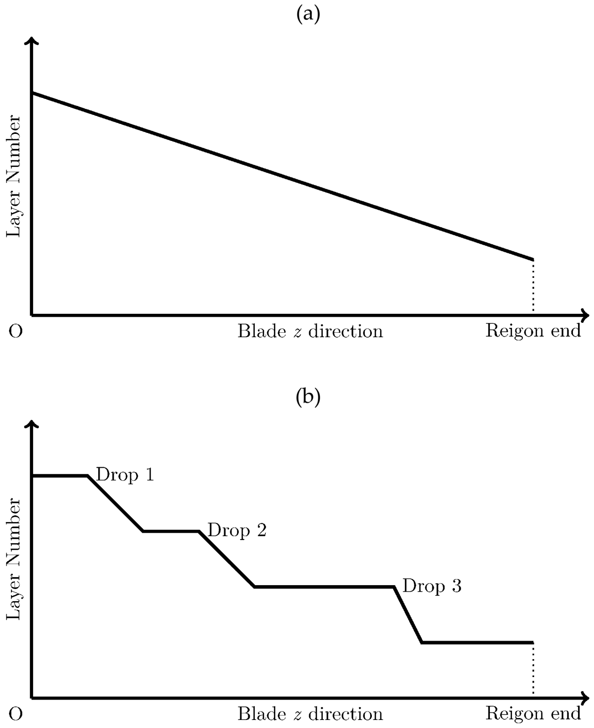


Fig. 4. Two-layer distributions along the blade length (a) Linear distribution, and (b) 3-drop distribution.

In the genetic algorithm, there are no theoretical upper limits for the layer number n_1-n_7. But to reduce the optimisation time, the maximum and minimum layer numbers at blade root tip are proposed, as listed in Table IV. For layers (or layer patterns) with 3-drop distribution, an upper limit of 200 is proposed, as they are expected to provide major flexural and shear resistance to the blade. To avoid a weak layer design, a lower limit of 10 is given to all the layer numbers. It should be noted that due to the limitation of the BladeComp, the minimum tip layer numbers of 3-drop layer distribution cannot be configured. Thus, the default minimum value 1 is kept.

TABLE IV
LAYER NUMBER LIMITS AT ROOT AND TIP FOR EACH LAYER (OR LAYER PATTERN)

		Root		Tip	
	Laminate distribution type	Min.	Max.	Min.	Max.
n_1	Linear	10	50	10	50
n_2	3 Drops	10	200	1	-
n_3	Linear	10	50	10	50
n_4	Linear	10	50	10	50
n_5	3 Drops	10	200	1	-
n_6	Linear	10	50	10	50
n_7	3 Drops	10	200	1	-

F. *Optimisation objectives*

The main objective of the optimisation is to obtain the layup solutions of the three blade components, with goals of keeping the blade weight and stiffness well balanced. Considering that the blade stiffness is correlated with the blade deflection, the tip deflections are used as indicators of blade stiffness. As described in Section B, the flatwise design loads are significantly larger than the edgewise design loads. Therefore, only the blade flatwise tip deflection is used as the blade stiffness indicator, which can simplify the optimisation process. As listed in Table V, a gap of 10% of blade length is considered between blade and other turbine system components. The maximum blade self-weight is limited to 10 ton to speed up the optimisation process. In most cases, a lighter blade mass will lead to a lower blade stiffness and larger blade tip deflection. Thus, the optimisation objectives, namely to minimize the blade mass and tip deflection, conflict to each other. Therefore, proper weight factors should be assigned to the two objectives to balance the contributions of the mass and tip deflection to the fitness value. The weight factors are obtained by conducting preliminary optimisations, which are detailed in Section H.

TABLE V
PARAMETER LIMITS FOR OPTIMISATION

Mass [ton]		Edgewise Deflection		Flatwise Deflection	
Min.	Max.	Min.	Max.	Min.	Max.
0	10	0	845	0	845

G. *Blade Fitness and Optimisation Procedures*

The design methodology of BladeComp employs the genetica algorithm. A fitness parameter is used to direct blade evaluation to the assigned objectives. Regarding the evaluation of the blade fitness, a reference blade is required by BladeComp to provide bottom line values. In this research, the reference blade is taken as the one with layup distributions defined as the maximum layer numbers in Table IV. For a given blade, its fitness can be evaluated by the equation (1).

$$fitness = \frac{\sqrt{w_{mass}\left(\frac{x_{mass}^{max}-x_{mass}}{x_{mass}^{max}-x_{mass}^{ref}}\right)^2 + w_{def}\left(\frac{x_{def}^{max}-x_{def}}{x_{def}^{max}-x_{def}^{ref}}\right)^2}}{2} \quad (1)$$

where:
w_{mass} and w_{def} are the weight factors of the blade mass and tip deflection, respectively;
x_{mass} and x_{def} are blade mass and tip deflection values of the given blade, respectively;
x_{mass}^{max} and x_{def}^{max} are the upper limit values of blade mass and tip deflection, respectively;
x_{mass}^{ref} and x_{def}^{ref} are the mass and deflection values of the reference blade, respectively.

Fig. 5 illustrates the design and optimisation procedures, which are based on the evolution of a turbine model group. These steps include:

1. An initial group, with 50 blade models with randomly generated layup design solutions, are created.
2. The structural response of each blade model in the group is analysed under the factored design loads. The blade mass and tip deflections are obtained. With the given weight factors for the objectives, the fitness of each blade model is acquired. The fitness variable quantizes the conformity of the current layup solution to the objectives.
3. The 60% of blades in the group are selected and randomly paired. According to the BladeComp internal algorithm, a high-ranking blade layup solution will have a larger probability of selection.
4. The crossover process is performed for each blade pair to generate a pair of new layer solutions.
5. Each variable of the newly generated layer solution has 30% of probability to mutate. A random value (within the defined parameter range) will replace the selected variable.
6. The fitness of the 30 new generated blade models are evaluated. Now the group has 80 blades with different layer design solutions.
7. 30 blades among the group will be selected and eliminated from the group.

A layup solution with a lower fitness will have a larger probability of elimination. The procedures 3rd to 7th build up one evolution of the group. By repeating group evolution, the maximum blade fitness value can be increased, which means that the laminate design of the blade is improved. Taking advantage of the BladeComp Optimiser's pause/resume function, the maximum blade fitness value is checked after each 50 evolution increments. If the maximum blade fitness keeps non-ascending in the last 40% of the total evolutions, the optimisation can be considered as converged. It should be noted that this convergence criterial of this engineering optimisation problem is adopted empirically, as there is no statistical convergence analysis performed on the laminate optimisation of this specific tidal turbine blade. Future studies may be performed on convergence problems of blade laminate optimisations. I￼.

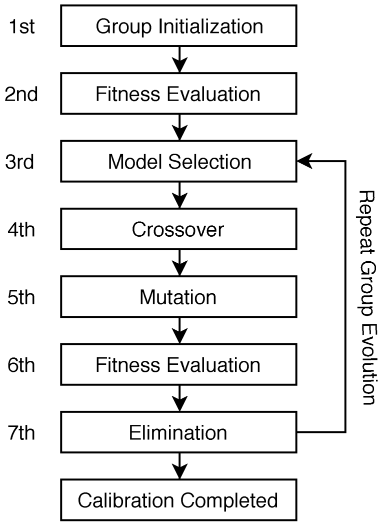


Fig. 5. Optimisation procedures based on Genetic Algorithm.

IV. OPTIMISATION RESULTS

H. *Preliminary optimisations*

As described in Section F, weight factors are required for the two optimisation objectives to guide the blade generation. For this purpose, preliminary optimisations, with 5 pairs of weight factors, are carried out for 100 evolution iterations. As listed in Table VI, the weight factors of blade mass are fixed to 1, whilst the weight factors of tip deflection increase from 0 to 1 with an interval of 0.25.

TABLE VI
WEIGHT FACTORS OF THE 5 PRELIMINARY OPTIMISATIONS

Preliminary optimisation #	1	2	3	4	5
w_{mass}	1	1	1	1	1
w_{def}	0	0.25	0.5	0.75	1

The flatwise tip deflection versus mass plots of the generated blades of the 5 optimisations are shown in Fig. 6. It should be noted that to avoid the low fitness layup solutions generated in early evolutions, only the blades generated from the last 50 generations are included in the plot. Although only 100 evolutions have been analysed, by combing all the 5 scatters together, the blade tip deflection exhibits a decreasing trend with the increasing of blade mass. The scatter distribution also proves that the mass and deflection ranges adopted in Table V are reasonable.

Differences can be found between the 5 scatters. When the weight factor of the tip deflection is 0, the algorithm tends to generate blades with tip deflection close to the upper limit. It means that the optimisation, with a single objective of minimizing the blade mass, is not suitable for this optimisation, as the algorithm tends to generate low stiffness blades, which lacks variety. With the weight factor of the tip deflection increasing from 0 to 1, it can be observed that the scatter gathering location moves from the high deflection side to the low deflection side. When the weight factor for deflection is 0.25, most of the scatter distribution is in the convex region of the plot. Thus, the scatters exhibit large varieties in this mass range. Therefore, the weight factor pair (1, 0.25) is adopted for the main optimisation to have blades generated in the interested mass range (2 ton ~ 8 ton) effectively.

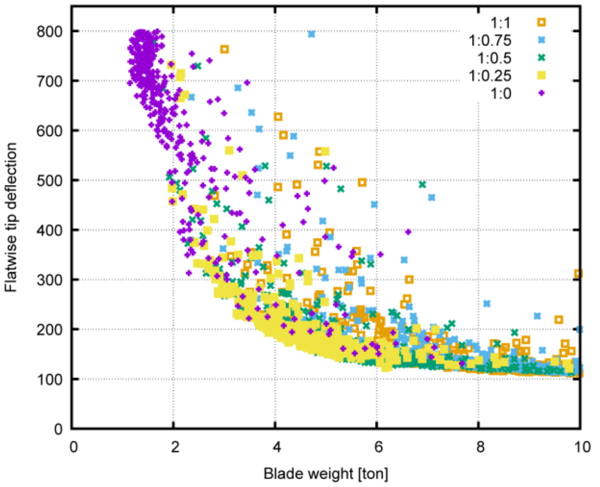


Fig. 6. Blade flatwise tip deflection versus weight plot of the 5 preliminary optimisations.

I. *Main optimisation and results*

With the adopted weight factors, the multiple-objective optimisation is continued in an increment of 50 evolutions. At the 300th evolution, the optimisation convergence criteria adopted in Section H is achieved. Fig. 7 shows the maximum fitness of each evolution versus the evolution number.

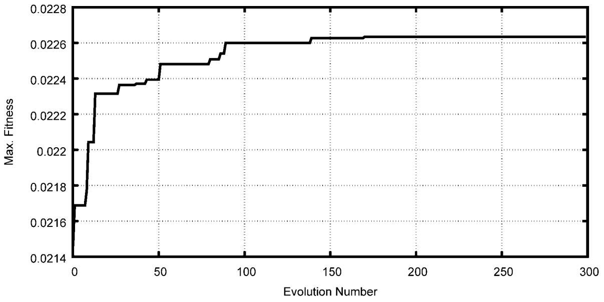
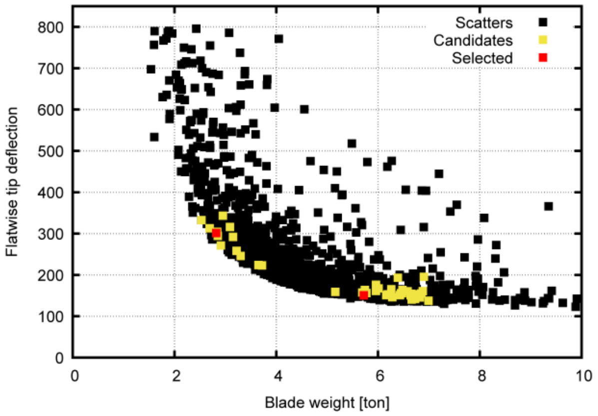


Fig. 7. Fitness versus generation number.

Fig. 8 (a) shows the blade flatwise tip deflection and weight plots of all the blades generated in the optimisation. Compared to Fig. 6, a clearer mass-flatwise tip deflection trend is observed. It can be observed that most of the generated blades are distributed in the interested region (mass range between 2 ton to 8 ton). It further proves that the adopted weight factors are effective, as it provides layup designs with large varieties.

Regarding the edgewise tip deflection versus blade weight plot (Fig. 8 (b)), there is a descending trend between deflection and mass at the lower bound of scatters. However, compared to Fig. 8 (a), the trend is less clear. Therefore, it can be concluded that the mass of blade generated by the algorithm is mainly governed by the blade flatwise stiffness, which is reasonable as the flatwise loads are larger than the edgewise loads.

(a) Flatwise tip deflection



(b) Edgewise tip deflection

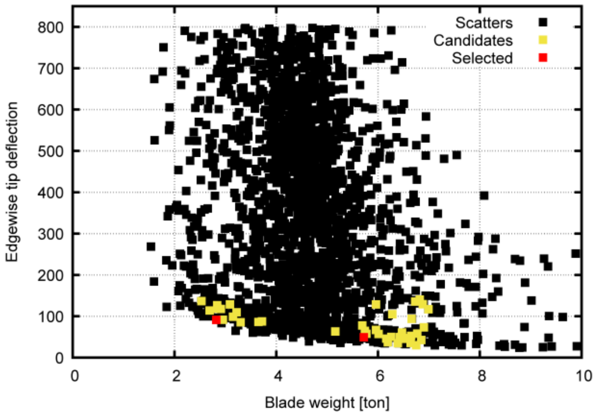


Fig. 8. Blade tip deflection versus weight plots of the optimisation.

To address a layup design with balanced mass and stiffness from the generated blades, a methodology was utilised. Generally, the blades in the lower bounds of the two scatter plots (Fig. 8 (a) and (b)) should be candidate layup designs. The candidate blades, with both flatwise and edgewise deflections located at the lower bounds of the plot, are highlighted in Fig. 8 with yellow markers. For a given blade mass, the candidate blades have a relatively high stiffness. It could be found that the candidate blades can be divided into two groups, around mass levels of 3 ton and 6 ton, respectively. Two blades, one from each candidate group, are selected as the optimised layup design solutions (marked in red in Fig. 8) for further investigation. Table VII lists the properties of the 2 selected blades. The selected blades represent a high-stiffness (blade-4787) and a low-stiffness (blade-9380) layup design solution, respectively. It could be found that the blade layup design is not necessary to have the highest fitness value nor to be from the last evolution.

As the original blade laminate design is not available in current study, only the structural performance of the two adopted blades are analysed and compared. The flatwise and edgewise deflection distributions of the two selected blades are plotted in Fig. 9. With blade weight decreases from 5.7 ton to 2.8 ton, the flatwise and edgewise deflections are almost doubled. The layer thickness distributions of the two selected blades are plotted and compared in Fig. 10 (a) and (b), respectively. It can be found that for the two blades, the spar cap contributes the highest mass to the blade. Considering that the flatwise loads are significantly larger than the edgewise loads, a thick spar cap layup design is logical. It can also be observed that the thickness of the webs of the two blades has a rapid dropping at the root chunk, which means that a strong web design is not an economic layup solution for a single-web tidal turbine blade.

TABLE VII
PROPERTIES OF THE SELECTED OPTIMISED BLADES

Blade#	Evolution	Fitness	Weight [ton]	Flatwise Deflection [mm]	Edgewise Deflection [mm]
9380	187	0.021	2.8	98	313
4787	95	0.022	5.7	51	155

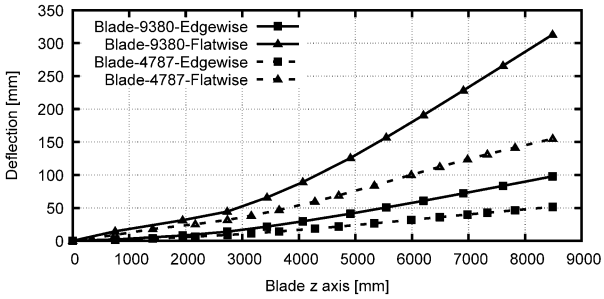


Fig. 9. Blade deflection results of the two selected blades.

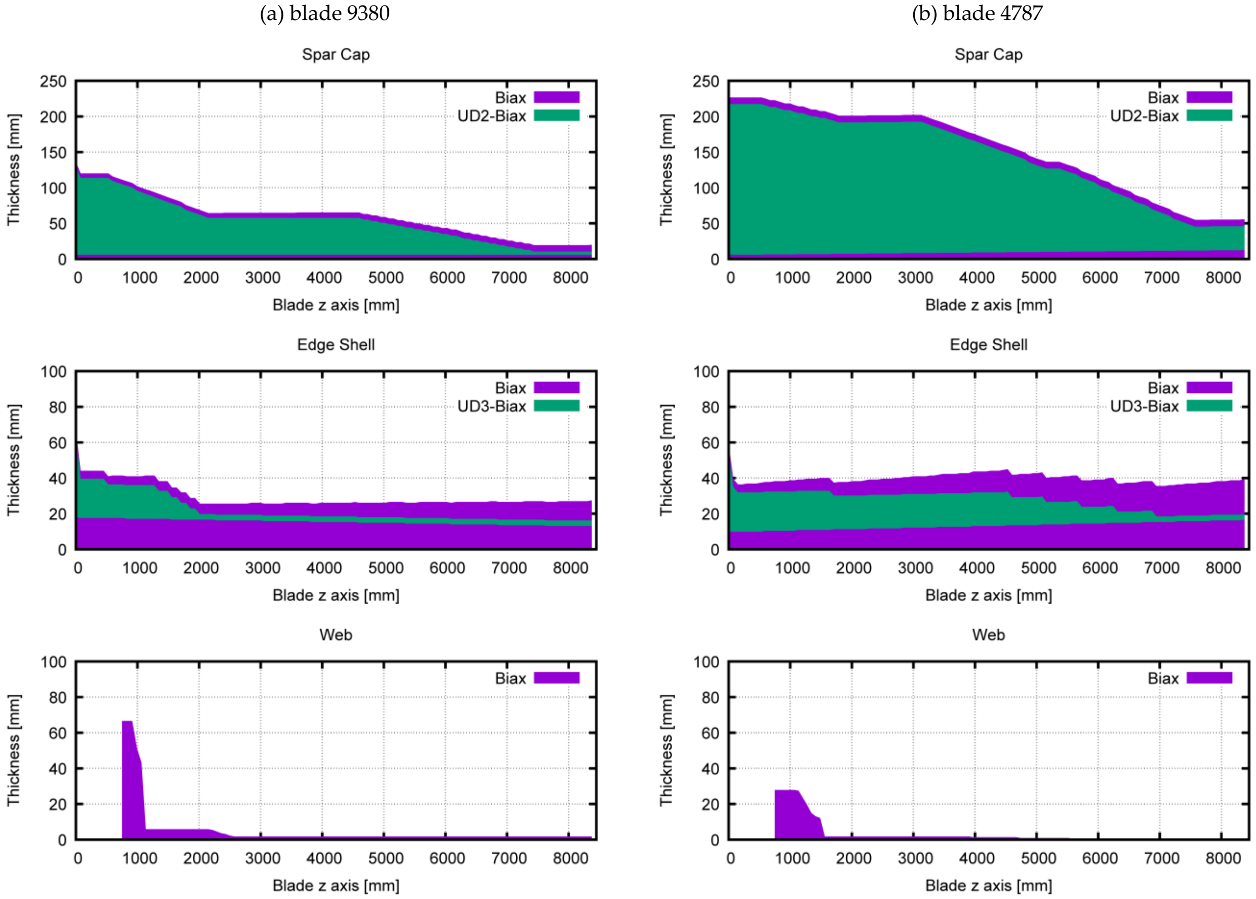

(a) blade 9380
(b) blade 4787

Fig. 10. The blade layup designs of (a) blade 9380 (b) blade 4787.

V. CONCLUSION

This paper demonstrates a blade design optimisation, with the goal of achieving a light-weight layup solution while controlling the blade deflections. The layup design methodology is based on a combined genetic algorithm and FE analysis. According to the structural functionalities, different material layer patterns are assigned to the three blade components: the spar cap, shear web and outer hydrodynamic shell. To reduce the optimisation time, proper mass range and tip deflection ranges are imposed. Five preliminary optimisations have been conducted to find out a suitable weight factor pair for the given mass and stiffness objectives. Candidate blades with various layup designs were then generated in the main optimisation. Two blade layup designs, with different stiffnesses, were adopted from the full set of generated blades. The thickness distributions of the three blade components are compared and discussed. The following conclusions can be summarized:

- BladeComp can effectively optimise the layup design according to the giving loads and objectives;
- For multiple-objective optimisation using genetic algorithms, the solution may not have the highest fitness value nor be from the last evolution stage;
- For the design loads dominated by flatwise forces, increasing the web thickness is not an effective way to enhance the blade stiffness in flatwise direction, for the given single-web blade configuration.

In the future, the structural response of the adopted blades will be further studied with the consideration of composite material failure theory. The fatigue-life assessment analysis of the two blades will also be carried out.

ACKNOWLEDGEMENT

This research was partly funded by Science Foundation Ireland (SFI) through the Marine and Renewable Energy Ireland (MaREI) research centre (Grant no. 12/RC/2302), the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 691916 for the FloTec project and through the OCEANERA-NET COFUND from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731200 under the SEABLADE project. The last author would like to acknowledge the support of Science Foundation Ireland through the Career Development Award programme (Grant No. 13/CDA/2200). Additional thanks are given to the technical staff at NUI Galway and engineering staff at Orbital Marine Power Ltd.

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