DEVELOPMENT OF HIGH PERFORMANCE COMPOSITE BEND-TWIST COUPLED BLADES FOR A HORIZONTAL AXIS TIDAL TURBINE

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SUMMARY

Development of a design methodology for a composite, bend-twist coupled, tidal turbine blade has been undertaken. Numerical modelling was used to predict the response of the main structural member for the adaptive blade. An experimental method for validation is described. The analysis indicates a non-linear blade twist response.

Keywords: Adaptive, bend-twist coupling, renewable energy, smart materials, tidal turbine.

INTRODUCTION

An adaptive textile composite, sometimes referred to as a smart material or intelligent material, is a structure tailored to exhibit desirable elastic deformation behaviour not necessarily proportional to the imposed load. An example of such a structure would be a box beam so tailored that an imposed cantilever load results in twisting as well as bending, although no torsional load was imposed, commonly referred to as bend-twist coupling.

There is an interest in the use of composite materials for potential improvements in hydrodynamic and structural performance of Horizontal Axis Tidal Turbines (HATTs). In addition to the obvious advantages of high strength-to-mass and strength-to-stiffness ratios, anisotropy of the laminated fibre composites can be designed to allow three dimensional tailoring of the blade deformation. Passive control of a turbine blade can be achieved by integrating advanced composite materials into the blade structure and taking advantage of the directionality of anisotropic composite material. Anisotropic structures show different levels of elastic coupling, depending on the ply angle in the layers that comprise such a material. This type of behaviour has been identified as a potential method for load reduction and enhanced stall control of wind turbines [1 – 6]. Although many advances have been made in the use of composites to improve the performance of aerospace structures, only limited work has been carried out in the marine industry [7 – 9].

In the course of one revolution, the HATT blade will encounter a non-uniform inflow velocity, with implications for the design of the blade. Using a relatively simple bend-twist coupled spar as the main structural member of a HATT blade (Figure 1) could enable the turbine to deal with the severe complex loads induced upon it whilst also maximizing the energy capture of the device. Preliminary studies have since shown that the use of bend-twist coupled blades may also improve the performance of HATTs [10,11].

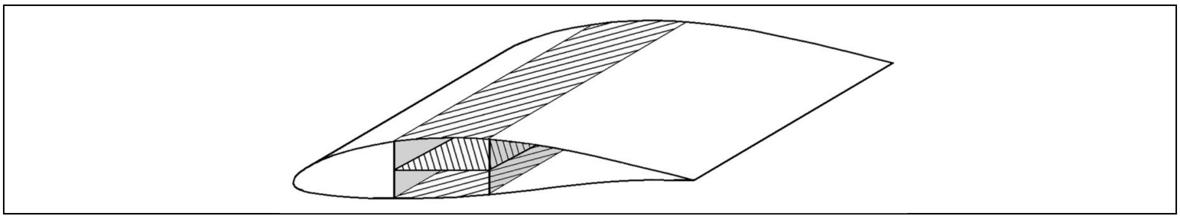

Figure 1: Position of a bend-twist coupled beam as the main structural spar in tidal turbine blade

The purpose of this work is to develop a tool to be used as part of the design process of an adaptive composite HATT blade. This paper discusses the numerical analysis of a bend-twist coupled double box beam using Finite Element Analysis (FEA), including the effect of varying different aspects of the composite layup of such a beam. A method is then proposed for experimental testing of a physical carbon double box beam in order to validate the FEA. A rectangular beam with a conventional cross section and without any taper in any dimension was used as it is more straightforward to construct such a beam. Once the numerical analysis has been validated with such a beam it can then be used as a design tool to form beams with more complex taper and twist arrangements.

NUMERICAL ANALYSIS

There are two main parts to this study: Experimental testing - namely the manufacture and testing of bend-twist coupled box beams, and numerical modelling – developing a Finite Element (FE) model of the coupled beam which can be validated with the experimental data and subsequently used to asses design variables. This paper concentrates on the latter of these, the numerical analysis, and proposes a suitable method for experimental validation at a later date.

Methodology

A 1.25m bend-twist coupled double box beam was modelled in ANSYS 11.0 using SE84LV HEC 300/400 UD carbon prepreg, the mechanical properties of which are shown in Table 1.

Table 1: Mechanical properties of SE84LV HEC 300/400.

Property	Value
Fibre weight	300 g/m^2
Tensile modulus	129.2 GPa
Cured ply thickness	0.281 mm
Poisson’s ratio	0.335

Each individual box beam was effectively laid up, and then the two placed together before the final outer wrap was laid over the assembly. It is intended that the physical experimental beam is to be laid up in a similar manner. As such the resulting beam has the mirror layup necessary for bend-twist coupling. Figure 2(a). This is thought to be significantly more robust than the patch layup technique for creating bend-twist coupling, which has joint strain incompatibilities and is prone to delamination when exposed to cyclic loads, Figure 2(b).

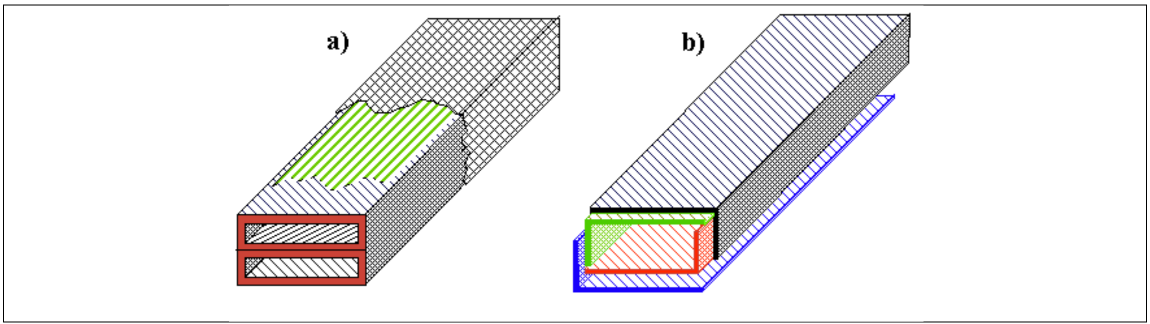

Figure 2: Achieving the mirror lay-up for bend-twist coupling a) the double box beam, b) patch lay-up technique

The models were meshed using the SHELL 99 element. Each model consisted of 11340 quadrilateral elements. One end of the beam was fixed in all degrees of freedom and a static load applied to the free end. Figure 3 shows the meshed and loaded beam.

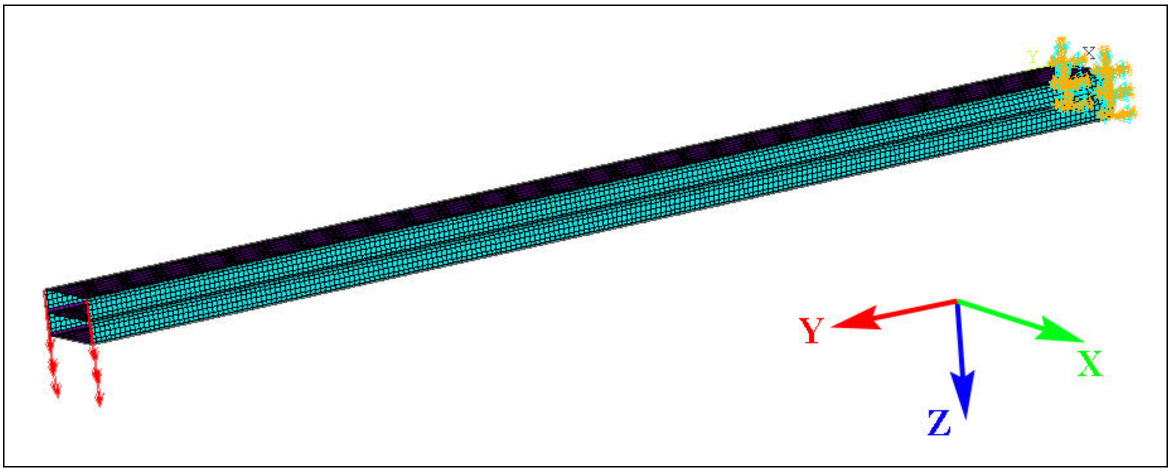

Figure 3: The meshed and loaded beam in ANSYS 11.0

The displacements in the global coordinate system of several key points along the beam were analysed and the bend and twist occurring over both the top and bottom surfaces of the beam were calculated.

Each of the following variables were altered whilst the others were held constant and the effect on the amount of bending and twisting achieved with a 200N load was assessed:

- Inner skin ply angle
- Mid layer ply angle
- Number of mid layer plies

- Outer roving ply angle
- Number of outer roving plies

For the fibre orientation and number of plies that are to be used to construct the physical specimen, the load was also varied such that the numerical and experimental results may be compared.

Figure 4 illustrates the layup of the beam, and indicates the different layers.

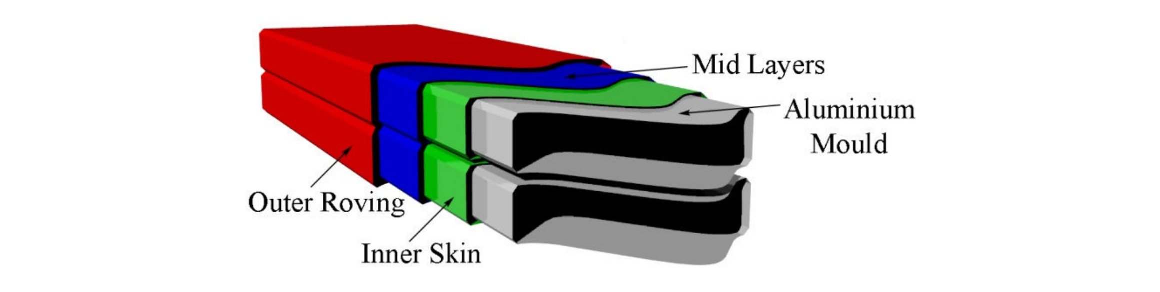

Figure 4: Layup of the double box beam.

Numerical Results

In this section the majority of the results presented are regarding the induced twist in the beam as this is considered to be the more important variable with regards to improving turbine performance. Only those variables with results that are deemed to be significant have been discussed due to space limitations.

Typically the beam bent (deflected in the global Z axis) to a greater degree than twist was induced. This relationship is apparent in Figure 5 where the contour plot of the overall vector displacement along the beam, compared to the undeformed shape clearly indicates bending is occurring.

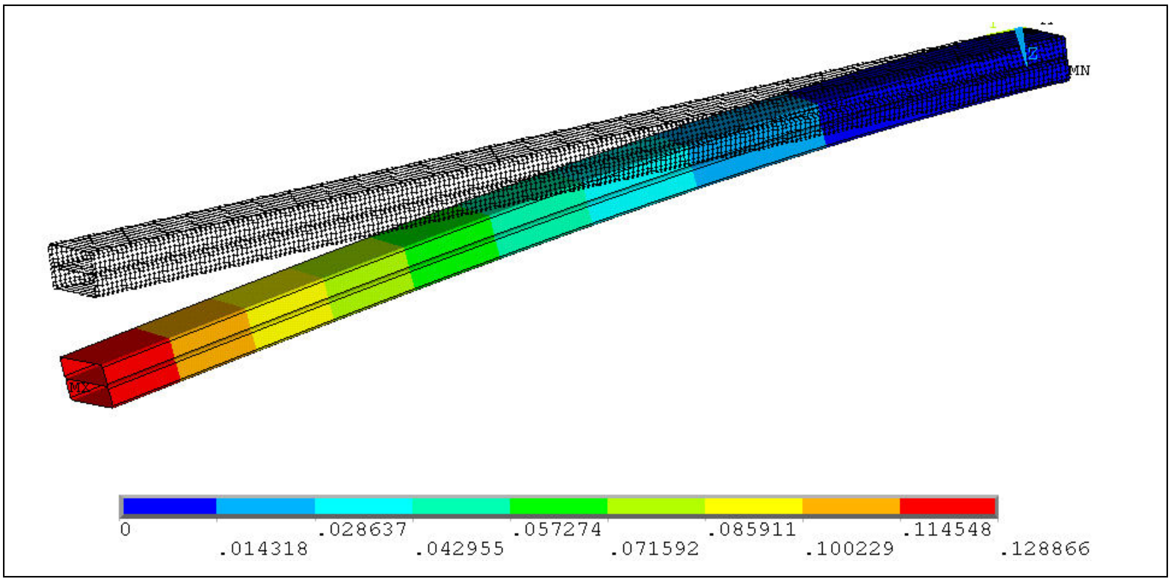

Figure 5: A contour plot of the overall vector displacement of the beam compared to the undeformed edge.

The degree of twist, however, is difficult to determine. The vector displacement scale shown at the bottom of Figure 5 is in metres.

The following Figures (6 – 11) illustrate the results of changing different aspects of the beam layup with respect to the deformation of the beam. It can be observed that the distribution of twist as non linear along the length of the beam, Figures 6, 8 and 10. Towards the end of the beam (1.25m) the data points deviate from the general trend more. This is thought to be due to the fact that the beam is not a continuous object and the composite layup being truncated at the end results in a difference in behaviour. In each case the relationship between bend and beam length is non linear but to the same degree and thus the majority of results presented here are with respect to induced twist.

Altering the number of mid layer plies in the beam construction results in a decrease in twist with an increase in number of plies, Figure 6. This decrease, however, is not linear as can be seen in Figure 7.

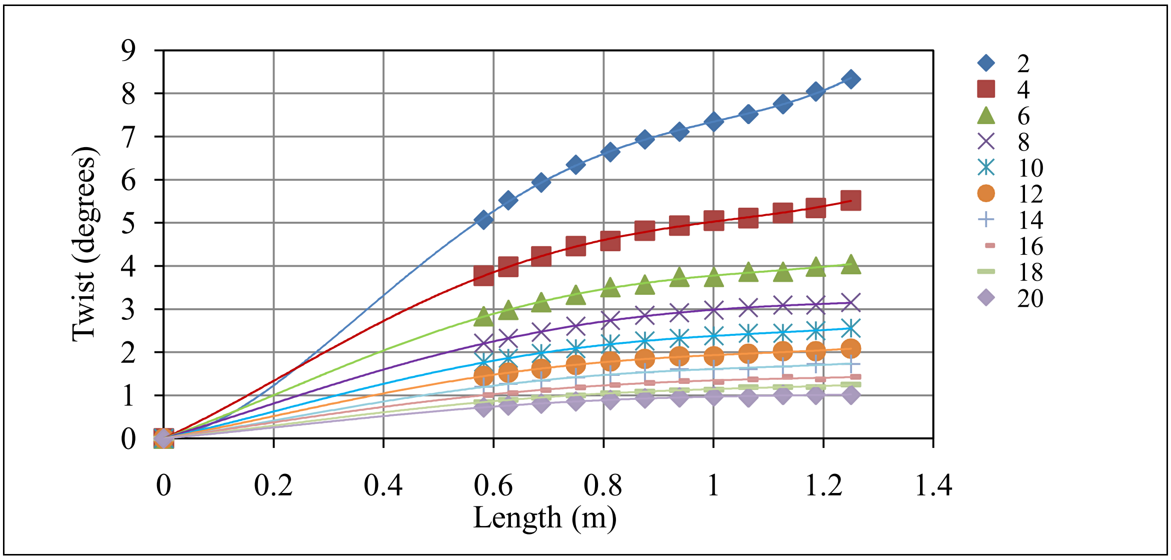

Figure 6: Induced twist angle against beam length for different numbers of mid layer plies with a tip load of 200N.

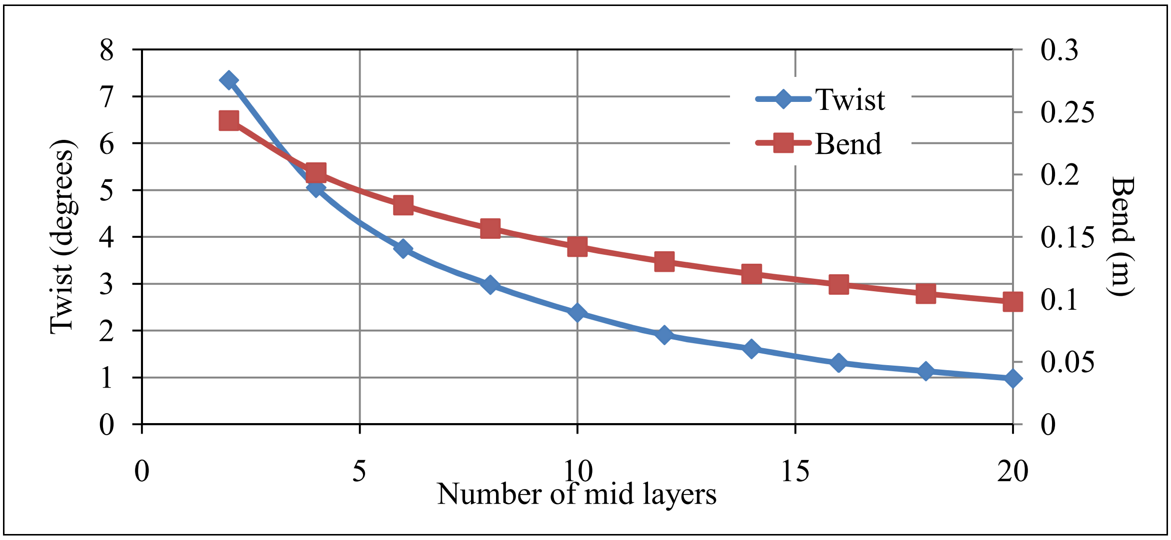

Figure 7: Beam twist and bend against number of mid layer plies at a length of 1m

Significant levels of twist can be obtained with less plies, i.e. a thinner beam; however this has a profound effect on the bending increasing the maximum bend from 13.6cm, exhibited by a beam with 20 mid layer plies, to in excess of 33cm, exhibited by a beam with only 2 mid layer plies.

Variation of the outer roving ply angle on the twist of the beam, Figure 8, indicates that there is an optimum roving angle for maximising the amount of induced twist present in the coupled beam.

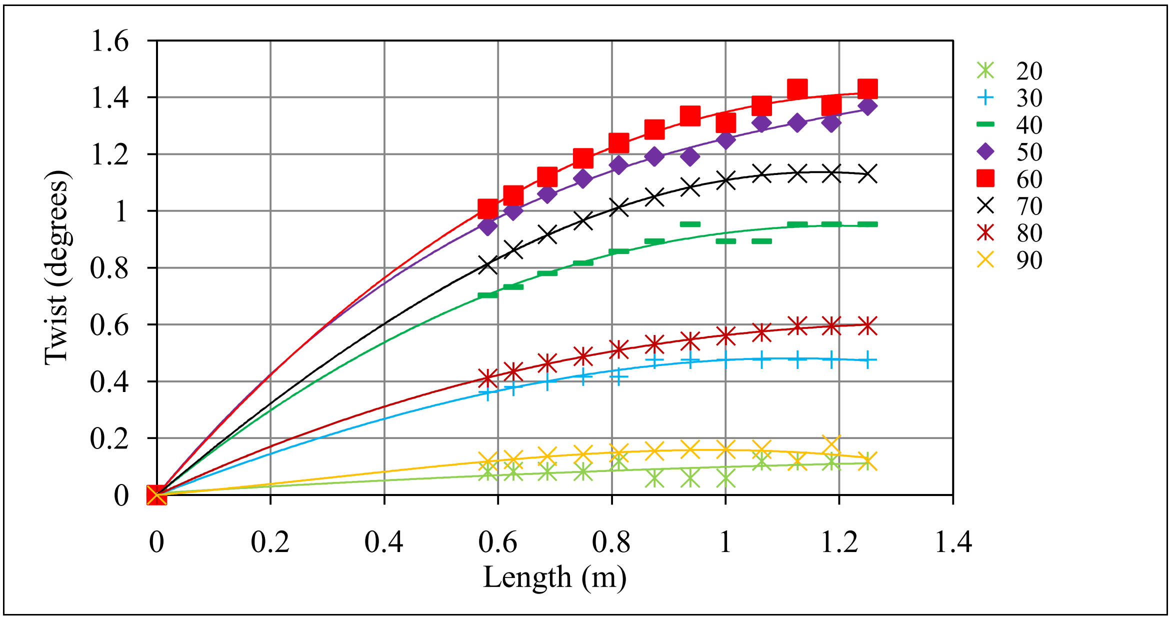

Figure 8: Induced twist angle against beam length over a range of outer roving ply angles with a tip load of 200N

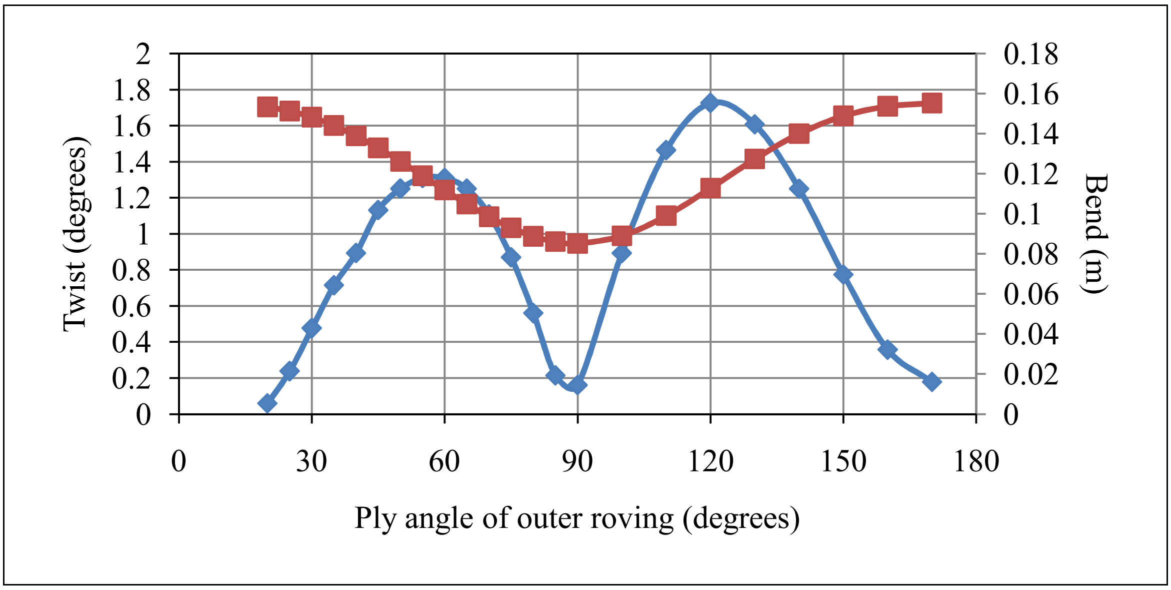

Figure 9: Relationship between twist angle and outer roving ply angle at a length of 1m

Plotting the relationship between twist and roving angle at a length of 1m, Figure 9, shows that there are in fact two optima when the roving angle is varied from 20^{o} to 180^{o}; one at a ply angle of 60^{o} and another at a ply angle of 120^{o}. Initial studies indicate that the optima at 120^o is the better of the two as both exhibit similar levels of bending. The effect of outer roving ply angle on the bend of the beam is also non linear, Figure 9. It should be noted that the level of bend apparent in the beam at these points of maximum twist is not the greatest.

It can be observed in Figure 10 that while the induced twist due to a pure bending load does not vary linearly over the length of the beam for a range of tip loads, the relationship between induced twist and tip load taken at a length, L, on the beam is linear, Figure 11. The relationship between bend and tip load is also linear.

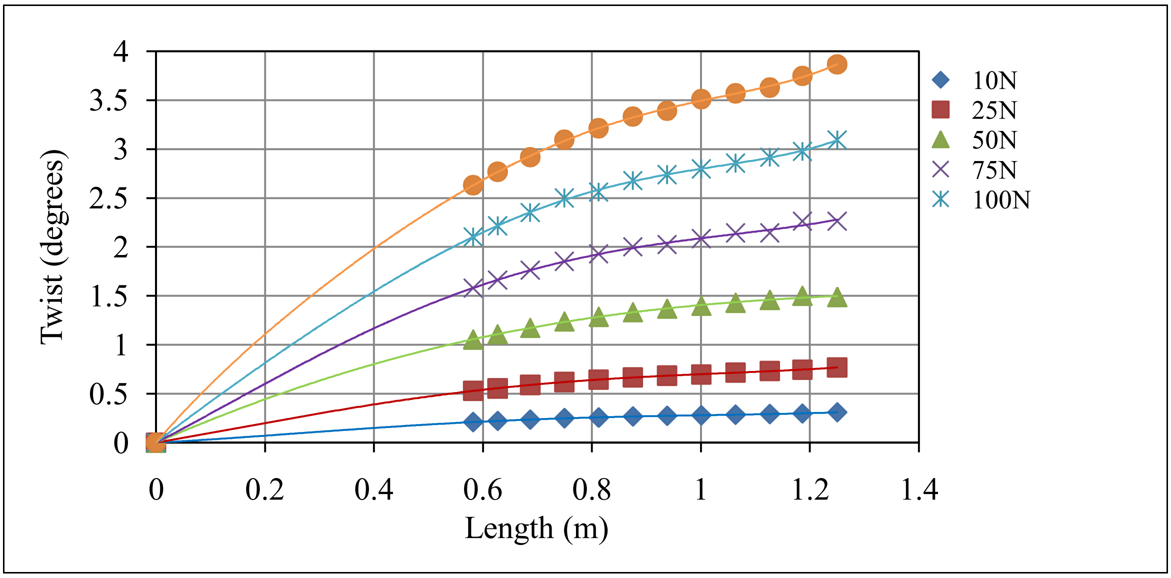

Figure 10: Induced twist angle against beam length over a range of tip loads

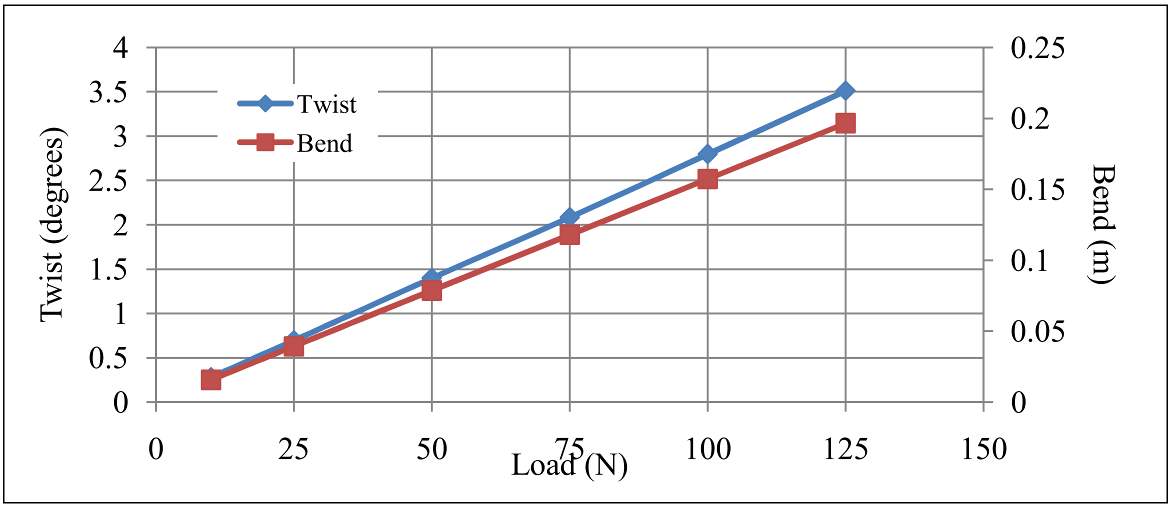

Figure 11: The relationships between bend and twist, and tip load at a length of 1m.

Initial studies have indicated that the combination of a fixed pitch and passively twisting blade is likely to increase the profitability of a free stream tidal turbine in comparison with a rigid fixed pitch or variable pitch mechanism turbine [10]. Increases in annual energy capture of around 2% and a reduction in thrust coefficient of around 10% were observed for a blade which was able to produce a tip twist in the region of a few degrees. These studies were undertaken assuming a distribution of twist of the form

$0.5SV^{1/2}$, where S is the blade span and V is the tidal flow velocity. This twist distribution is very similar to those that the FE analysis has shown are exhibited by the bend twist coupled spar suggesting that performance improvements similar to those mentioned previously may be expected.

EXPERIMENTAL ANALYSIS

To date no experimental data is available, however it is intended that physical testing be carried out in the near future in order to validate the numerical analysis. This section details the manufacture and testing procedure which will be undertaken.

It is intended that the unidirectional carbon fibres are wound around a polished aluminium mould to make a box beam with orientation $[45,20_4]$. Two similar sized composite wound/mould systems will then be placed on top of one another to achieve the required mirror layup, Figure 2(a), and a final outer roving wound around the complete assembly of orientation $[60_2]$. The complete beams will then be cured in an autoclave at 120°C for 45 minutes at a pressure of 3 bar. The aluminium moulds will then be removed and the resulting composite beam tested.

Figure 12 shows the experimental set up. The beam is to be fixed at one end, A, and a load hung off the free end using a sling to maintain the central aspect, B, whilst leaving the beam free to bend and twist. Lasers pointers will be affixed to the upper surface of the beam at predefined points along the length, C, such that a beam of light intersects a grid on two surfaces at a known distance either side of the test specimen, D. The initial positions of the beams at each station will be marked. As the beam is loaded and subsequently bends and twists, the laser beams will move over the grid and the loaded position may be marked. As the distance from the pointers to the surfaces, and the difference between the initial positions and loaded positions are known, the angle of twist and bending displacement can be calculated at each station.

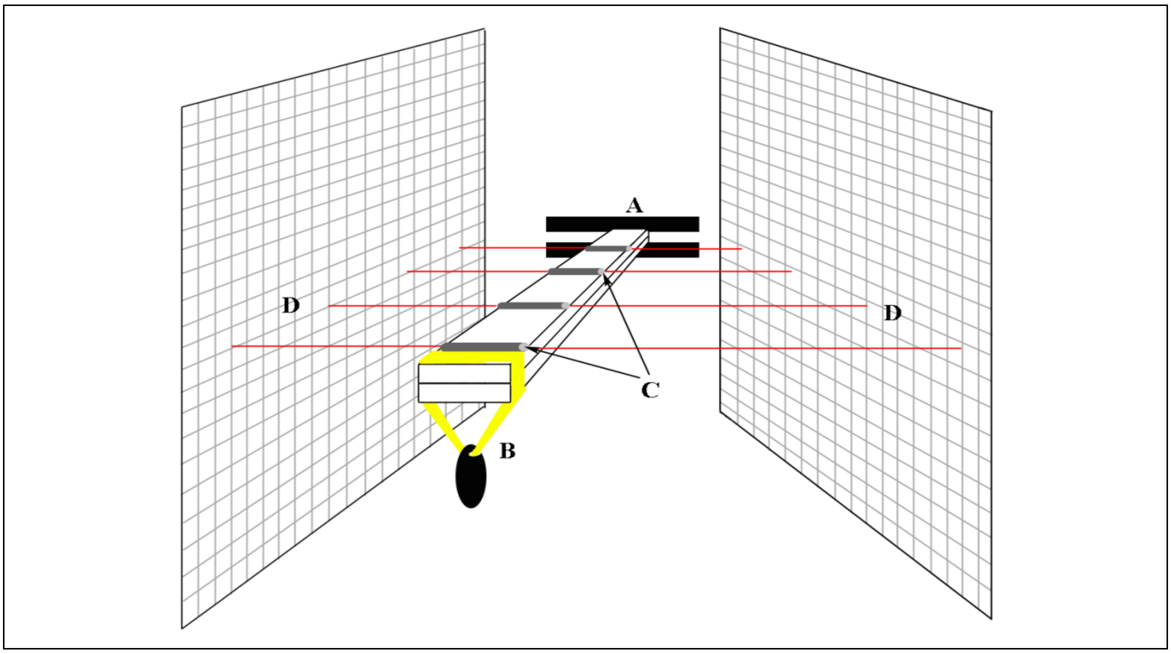

Figure 12: The experimental set up

Digital image correlation will also be used on the cross-section at the free end of the beam to obtain the angle of twist and level of bending at this point.

The data from these tests can then be compared to that obtained during the numerical analysis of a box beam of the same layup.

CONCLUSIONS

Finite Element analysis of a uniform section, bend-twist coupled, carbon composite, double box beam has been carried out as part of a study regarding the use of such a beam as the main structural spar for a free stream, horizontal axis, tidal turbine blade.

It has been found that the distribution of twist along the length of the beam does not vary linearly. Previous work has found that the use of the bend-twist coupled beam as the main structural member of a HATT blade improves the performance of the device. Such work used a twist distribution similar to those found through the numerical analysis suggesting that a similar performance improvement may be achieved – this is in the order of an increase of 2% in annual energy capture, and a reduction of around 10% in detrimental thrust force.

Altering the number of mid plies in the beam construction appears to decrease the level of twist induced in the beam, albeit in a nonlinear manner.

It appears that the effect of altering the ply angle of the outer roving creates two optima, at which the induced twist present in the beam is maximum, for a bend that is significantly less than maximum. The relationship between tip load and induced twist is shown to be linear.

A method for experimental validation of the FE results has been discussed. Such tests will be conducted in the near future, and the results compared and contrasted to those of the numerical analysis.

This analysis has been undertaken using a uniform section beam with no taper. This is due to the fact that it is significantly less complicated to manufacture a uniformly shaped beam for validation tests. Once the numerical tool has been validated it is intended that it be used as part of a Fluid Structure Interactions simulation to analyse several different design concepts of tapered beams as the main structural spar of a HATT blade.

ACKNOWLEDGEMENTS

The PhD of R. F. Nicholls-Lee is supported in part by a 50% scholarship from the School of Engineering Sciences, University of Southampton, U.K.

R. F. Nicholls-Lee would also like to thank MARSTRUCT for their support of her PhD.

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