# Chapter 6

# Spar Shape Optimization of a Multi Megawatt Composite Wind Turbine Blade: Modal Analysis

Mostapha Tarfaoui[*1], Owaisur Rahman Shah[1]

[1]ENSTA-Bretagne, MSN/LBMS/DFMS
2 rue François Verny, 29806 Brest Cedex – France
[*1]mostapha.tarfaoui@ensta-bretagne.fr

## I. INTRODUCTION

The problem of energy that we face today revolves around two main factors: energy generation/transmission and greenhouse gas emissions. Renewable energy sources are an inevitable part of the solution, and wind energy is, at the moment, the fastest growing installed production technology.

We are currently witnessing a substantial growth in the wind energy sector worldwide. This growth is expected to accelerate even more in the foreseeable future. This means that a massive number of wind turbine blades will be produced in the forthcoming years. There is a large potential for economizing material in these blades. Commercial wind turbines have increased consistently in size during the past thirty years, largely for the economic reasons in an attempt to reduce the cost of electricity generation. This is due to the fact that the wind speed – and hence the wind power captured – increases with altitude and that reducing the number of individual turbine units helps reduce the overall cost of a wind farm, especially in the case of offshore farms. Currently the largest machine; has a rated output of 5MW and a rotor diameter of 124m and so the question arises as to what the ultimate limits on size might be? The increase in diameter also makes the requirements related to rotor and blade mass more severe. For a complete discussion of design requirements, interested readers can refer to Burton et al. [1].

As part of the certification procedure, all wind turbine blade prototypes are subjected to an experimental test procedure in order to ensure that the produced wind turbine blade fulfils the actual design and safety requirements. In addition to experimental tests of load carrying capacity under extreme loading, and tests of its fatigue resistance, it is common practice to compliment with these the tests related to basic dynamic properties of the blades, such as natural frequencies and damping properties, as these are essential for the structural integrity of the entire wind turbine. Usually, these dynamic characteristics are determined for the first 3 - 4 flexural bending modes and for the first torsional mode.

However, detailed knowledge of natural frequencies and structural damping characteristics does not in itself guarantee/ensure an optimal dynamic behaviour of the wind turbine, when subjected to aerodynamic forces arising from the applied wind field. In recent years, stability problems in wind turbine structures have obtained increased attention due to the trend towards larger and more flexible structures. A well-known example of a stability problem, that eventually might lead to failure of the whole structure, is the occurrence of dynamically unstable edgewise vibrations (flutter). For aerodynamic loading in general, and for dynamic stability problems in particular, the deflection patterns of the wind turbine blades are of vital importance. For a wind turbine blade, the deflections of interest include; lateral translations (flapwise, edgewise) and cord rotation (about the blades longitudinal axis).

For reasons of simplicity the wind turbine blades are usually modelled as beam structures for running aeroelastic computations. Warping is usually neglected, justified by the fact that the main components are structures with closed cross sections, whereas the structural couplings between flexural bending in the two principal directions and structural couplings between torsion and flexural bending are usually included, as such structural couplings may significantly affect the aerodynamic load characteristics of a wind turbine blade. Although, in principle, included in the traditional Euler or Timoshenko beam modelling of wind turbine blades, the correct specification of such structural couplings is a delicate matter.

Modal analysis is by far the most common method used to characterize the dynamics of mechanical systems, and it produces very illustrative and easily interpretable results. Modal analysis has also been used to identify approximate mode shapes, associated with the dominating deflection direction only (i.e. mode shapes excluding structural coupling between torsion, flapwise and edgewise deformations), of medium size wind turbine blades [2].

Large wind turbine blades are typically manufactured with thin skins made of composite materials. Glass fibre/epoxy and wood laminates/epoxy are the most commonly used materials, but carbon fibre composites are also finding their way in recently. Wind turbine blades are usually constructed from several parts glued together: compressive side, tensile side and shear webs. Their external geometry is fairly complex, made of 3D surfaces resulting from the aerofoil sections put together with varying twist angles, chord lengths and pitch axis locations. With regard to of the internal structure, the manufacturing methods often result in thick adhesive joints in key structural locations and this can be represented in numeric/computer models by 3D adhesive mesh elements.

The design of a wind turbine structure involves many considerations such as strength, stability, cost and vibration. Reduction of vibration is a good measure for a successful, safe design of the blade structure. It may foster other important design goals, such as low cost and high stability level. A good design philosophy for reducing vibration is to separate the natural frequencies of the structure from the harmonics of rotor speed. This would avoid resonance where large amplitudes of vibration could severely damage the structure. Frequency placement is one of the techniques used for separating frequencies. An objective function is formulated for minimizing the discrepancies between the desired frequencies and the actual ones [3]. The chosen design variables were the values of a set of lumped masses located at specified points along the blade span as well as the distribution of the wall thickness of the main box-beam cross section. The resulting optimum solutions were strongly dependent on the values of the desired (target) frequencies, which are chosen fairly arbitrarily. Pritchard and Adelman [4] formulated a mathematical programming optimization model by considering minimization of the induced shearing forces at rotor hub as a measure of vibration reduction. Design variables were taken to be the sizes and locations of the tuning masses along blade span, which has the disadvantages of increasing structural mass. Other techniques, sometimes referred to as “modal shaping” or “modal tailoring”, alter the vibration mode shapes of the blades through mass and stiffness modification to make them less responsive to the air-loads [5, 6].

This chapter describes the creation of a numerical model which parametrically describes the geometry of the blade with composite materials for wind turbines of 5MW. Full FE models of the blades are constructed and solved in the time or frequency domain to capture all relevant behavioural aspects and stability issues. Two different issues are discussed here. First, being the choice of three degrees of freedom in each cross-section to describe the motion of the blade. Whereas the second is the extraction of mode shapes and natural frequencies of the blade.

## II. BLADE GEOMETRY

The main objective in the design of wind turbines is to find a rotor that meets the basic conditions required. The most important condition is to get a rotor to deliver the required power output at a particular wind speed. It is necessary to take into account the importance of the geometry of the rotor, first and foremost taking into consideration the aerodynamic performance, strength and stiffness conditions and most importantly, the costs.

The turbine has an intended power rating 5MW with a blade length of 48m, aerodynamic characteristics were obtained through a study of commercially available examples, where we had the distribution curves of chord, the twist, the pre-bend, thickness, and the distance between the pitch axis and the trailing edge of several blades used at our disposal. A numerical model was created by averaging all the above mentioned data.

Once all the values have been determined, we selected the airfoil profiles. The chosen standard was that of DUWind (Research on wind energy at the Delft University of Technology). Then, we searched the published data, the original coordinates of each of these airfoils (raw sections), and both the extrados and the intrados. Four different types of airfoils were selected, excluding the circle and transitions, as illustrated in Fig. 1.

The blade that we will study is assembled on a three-bladed offshore wind turbine which generates a maximum power of 5MW. The general specifications of the studied blade are given in Table 1.

- *Circle*
- *CircleTrans172*
- *CircleTrans144*
- *CircleTrans71*
- *DU-00-W2-401*
- *DU-00-W2-350*
- *DU-91-W2-250*
- *DU-93-W-210*

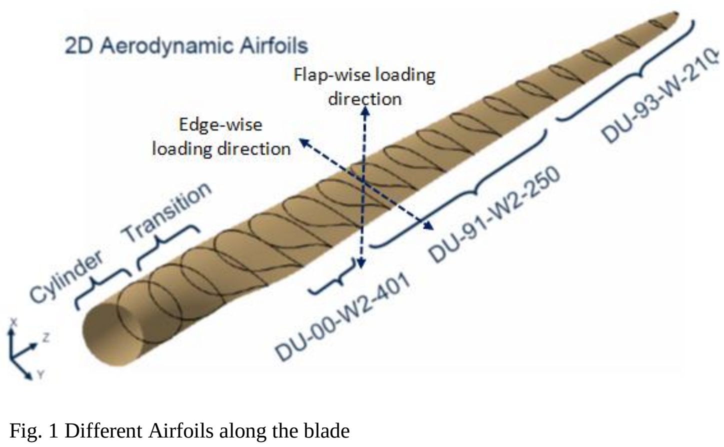



Fig. 1 Different Airfoils along the blade

TABLE 1 GENERAL SPECIFICATIONS OF THE BLADE

| | |
|---|---|
| **Length (mm)** | 48000 |
| **Maximum cord (mm)** | 3932 |
| **Position twists maximum (mm)** | R9000 |
| **Fluid speed upstream of blade (m/s)** | 25 |
| **Angular velocity (rpm)** | 15,7 |
| **Frequency of solicitation: Fr (Hz)** | 0,26 |
| **Power (MW)** | 5 |

### *A. Choice of the Profile*

Fig. 2 shows the variation of the optimum power coefficient ($C_p$) with the designed tip-speed ratio (TSR) for a blade made of NACA 4-digit airfoil families. It is seen that $C_p$ increases rapidly with TSR up to its optimum value after which it decreases gradually. The optimum range of the TSR is observed to lie between 6 and 11, depending on the type of airfoil. The effect of wind shear and tower shadow result in a reduction of the power coefficient by about 16%. The value of the designed TSR at which $C_{p,max}$ occurs is also reduced by about 9%. It is also observed that blades with NACA 1412 and 4412 produce higher power output as compared with other airfoil types. Fig. 3 gives a schematic representation of initial profile NACA 4412 selected with the blade representation. The results of the optimal distribution of the cord for a blade of 48m in diameter and having various profiles are summarized in Fig. 4.

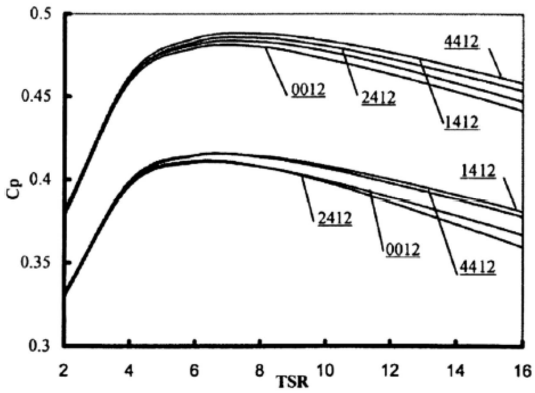



Fig. 2 Variation of the optimum power coefficient with TSR for a three bladed rotor of NACA 4-digit airfoil [1]

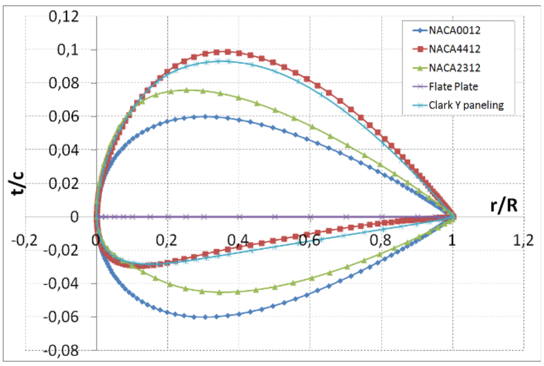



Fig. 3 Section profiles, NACA 4412

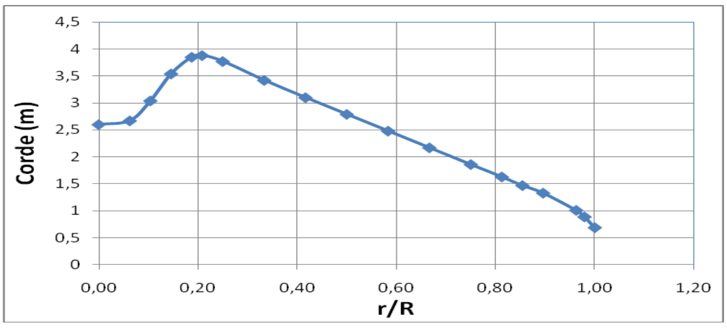
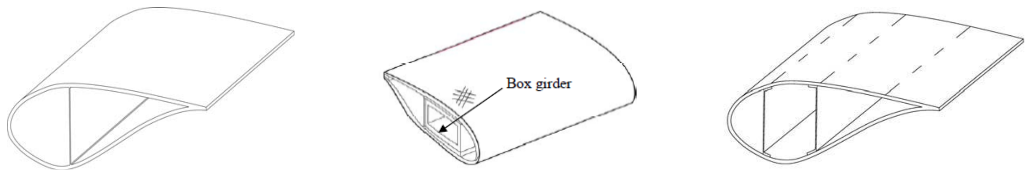



Fig. 4 Evolution of the blade chord; profile NACA 4412

*B. Extrados, Intrados and Spar*

The design of the aerofoil profile of a wind turbine blade is a compromise between aerodynamic and structural (stiffness) considerations. Aerodynamic considerations dominate the design of the outer two thirds of the blade while structural considerations are more important for the design of the inner one third of the blade. Structurally the blade is typically hollow, with the outer geometry formed by two shells: one on the suction and one on the pressure side. To transfer shear loads, one or more structural webs perpendicular to the airfoil cord, are fitted to join the two outer shells together, as shown in Fig. 5.




*(a)* *(b)* *(c)*

Fig. 5 Sketches of different blade concepts

## III. FINITE ELEMENT MODELLING AND STRUCTURAL DESIGN OPTIMIZATION

The finite element method (FEM) is very useful and has traditionally been used in the development of wind turbine blades in order to investigate the overall behaviour in terms of, for example, eigen-frequencies, tip deflections, and global stress/strain levels.

Only a limited number of publications on Finite Element (FE) modelling and structural analysis of wind turbine blades are available in the current literature [7-13]. This research field is becoming increasingly important as the blades gradually are becoming sufficiently large enough to cause flutter instability.

*A. Shear Web Transverse Placement*

The transverse placement of the shear webs within the aerofoil sections naturally influences the structural properties of the assembly. Due to the twist angle variations along the blade length, a bending loading state always induces torsion in some sections of the blade. This torsion modifies the angle of attack of the aerodynamic surfaces; in turn causing a modification in loading: such a phenomenon is generally described as aero-elastic.

The finite element method has traditionally been used in the development of wind turbine blades, mainly to investigate the general behaviour in terms of, for example, its eigen-frequencies, tip deflections, and global stress/strain levels. This type of FE-simulation usually predicts the global stiffness and stresses with a good accuracy. Another factor is that a relatively simple shell model can be used for representing the global behaviour, while a computationally more expensive 3D-solid model may be necessary to predict this localized behaviour.

The influence of the shear-web placement on the blade mass, bending stiffness and bending-torsion coupling is studied in this chapter. Five different geometries are examined as shown in Fig. 6. In each one, the shear-webs are moved in opposite directions further from one another, from being very close to one another to being near the leading and trailing edges.

(1) Blade with web of form T (39% length of the cord)
(2) Blade with one shear web (39% length of the cord)
(3) Blade with two shear webs (between 49% and 29% length of the cord)
(4) Blade with three shear webs (between 49% and 29% length of the cord)
(5) Blade with web of form H (between 49% and 29% length of the cord)

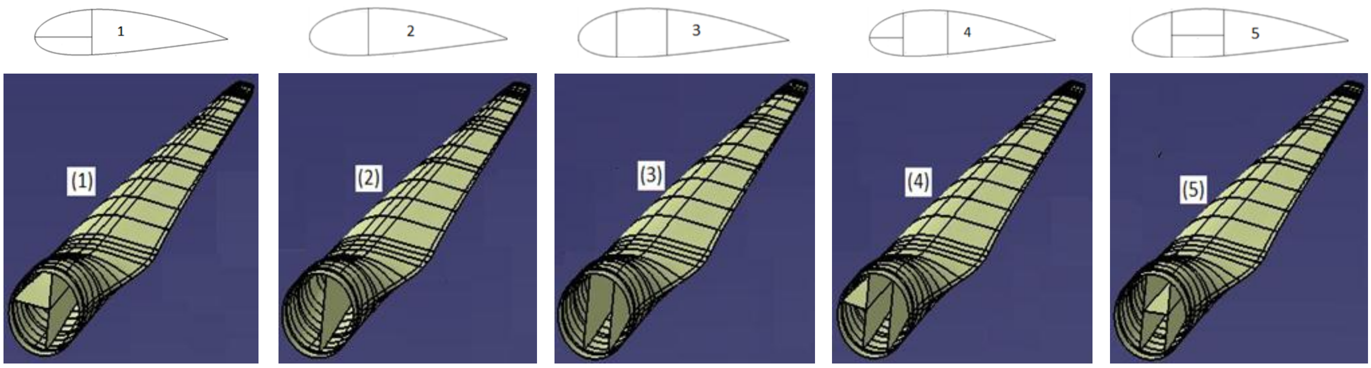
In a concern of being most precise and of formulating the most adequate model, we chose to carry out two types of modelling:

- The first one uses shell elements for the modelling of the blade formulated in only one part.
- The second models the components of the blade with separate part:
    - The blade alone (modelling with shell elements).
    - The spar (with a 1 or 2 shear webs, modelling with shell elements).
    - The adhesive (modelled by 3D elements)).

For an optimization study of the blades, Fig. 6 shows the finite element models associated with different geometrical shapes of webs. In the next section of this work one will consider that:

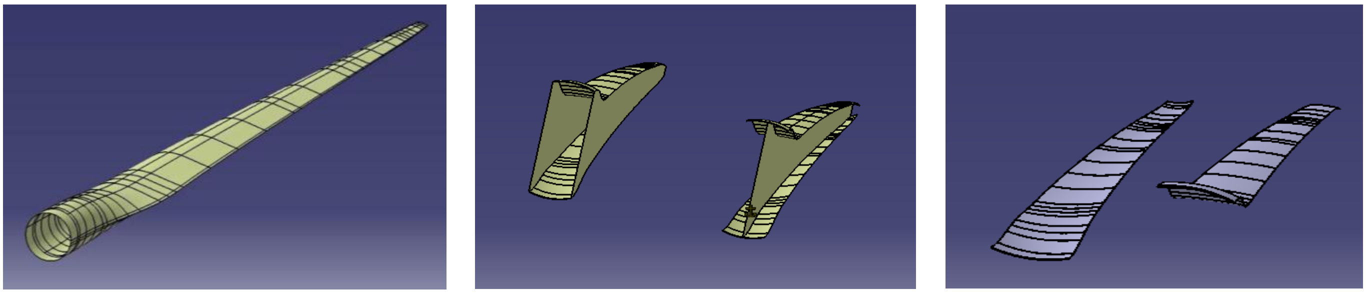
✓ Model 1: blade with spar with only one web (created with only one part).
✓ Model 2: blade with spar with two webs (created with only one part).

- ✓ Model 3: blade with spar forms H (created with only one part).
- ✓ Model 4: all (created with 4 independent parts): blade, spar with only one web and adhesive, Fig. 7.
- ✓ Model 5: all (created with 4 independent parts): blade, spar with two webs and adhesive, Fig. 7.




*Model (1)* *Model (2)* *Model (3)* *Model (4)* *Model (5)*

Fig. 6 Blades with different shear-web transverse placement



*(a) Blade, intrados/extrados, shell elements* *(b) Spar, shell elements* *(c) Adhesive, 3D elements*

Fig. 7 Blade FE model with 4 independent parts

## B. *Materials and Lamination Strategy*

A wide range of materials and manufacturing techniques are utilized in the wind turbine industry. The material combinations used are predominantly composite laminates with embedded threaded steel rods in the root section connecting the blade to the turbine hub. In bolted connection polyester, vinylester and epoxy resins are common, matched with reinforcing wood, glass and carbon fibres. Some designs integrate carbon and glass fibre as well as birch and balsa wood [14-15].

Both the materials and the lamination strategy are selected through the UpWind data. UpWind is a European project funded under the Sixth EU Framework Program. Its task is to design powerful wind turbines (8-10 MW) for both onshore and offshore installation. The materials used were of 5 different types: UD, Triax, R4545, Foam and Webs, whose properties are shown below in Table 2a. The mechanical properties of composite materials are given in Table 2b. The laminates used, consist of plies with various orientations. Here, the UD, the Triax and the R4545 are composite materials (orthotropic) while the rest are isotropic materials, in order to achieve the best cost and weight saving. The materials and lamination strategy chosen for blade of 48m long was: a triax stack with adhesive to decrease the natural frequency of the blade. Also, within the UpWind strategy, the Shear Webs will be changed to Foam, because it has higher density and a lower natural frequency. To better understand, Table 3 shows the lamination which we will consider, section by section. Fig. 8 shows the lamination zones of the blade. The distribution thickness over the blade length is given in Table 4.

TABLE 2 MATERIAL SPECIFICATIONS

| **Materials** | | **$E_{11}$ (MPa)** | **$E_{22}$ (MPa)** | **$G_{12}$ (MPa)** | **$\nu_{12}$** | **ρ (kg/m³)** |
|---|---|---|---|---|---|---|
| **Orthotropic Composites** | UD | 38887 | 9000 | 3600 | 0,249 | 1869 |
| | TRIAX | 24800 | 11500 | 4861 | 0,416 | 1826 |
| | R4545 | 11700 | 11700 | 9770 | 0,501 | 1782 |
| **Isotropic Composites** | SKINFOAM | 256 | 256 | 22 | 0,3 | 200 |
| | ADHESIVE | 3000 | 3000 | 1150 | 0,3 | 1200 |

*(a) Mechanical properties of materials used*

| Laminates | Plies (°) |
|---|---|
| UD | 0 |
| TRIAX | [-45/0/45] |
| R4545 | [-45/45] |

*(b) Orientation of the layers of the laminates*

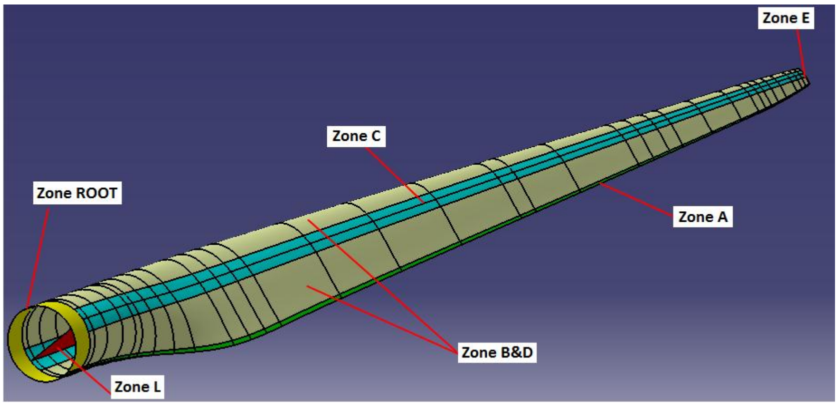



Fig. 8 Lamination zones of the blade

TABLE 3 PARTITION ZONES

| Zone | Localization |
|---|---|
| L | Shear webs |
| ROOT | Zone fixing of the blade |
| A | Zone joining of the blade |
| B&D | Zone leading and trailing edge |
| C | Contact blade/Shear webs |
| E | Blade tip |

TABLE 4 DISTRIBUTION THICKNESS ALONG THE BLADE ON THE CONTACT ZONE: BLADE/SPAR

| r (m) | e (mm) |
|---|---|
| 0 - 0.9 | 90.24 |
| 0.9 - 1.2 | 32.2 |
| 1.2 - 3 | 34.2 |
| 3 - 5 | 19.16 |
| 5 - 7 | 53.88 |
| 7 - 9 | 94.36 |
| 9 - 12 | 93.42 |
| 12 - 16 | 91.54 |
| 16 - 20 | 85.9 |
| 20 - 24 | 80.26 |
| 24 - 29 | 72.74 |
| 29 - 32 | 60.99 |
| 32 - 36 | 51.12 |
| 36 - 37 | 33.73 |
| 37 - 41 | 20.1 |
| 41 - 47.97 | 12.11 |
| 47.97 à48 | 12.11 |

## *C. Mesh Part*

For the 5 developed models, shell elements of type S4R were used. Below, are the characteristics of the 5 models with a 200 mm mesh element size. Solid elements C3D8R were used to mesh the adhesive (models 4 and 5). Fig. 9 shows an example of the mesh carried out for model 3. The difference between the two cases of materials assignment affects the mass of the intrados/extrados face and webs (see Table 5). The overall assets of the blade are almost the same for the two types of modelling.

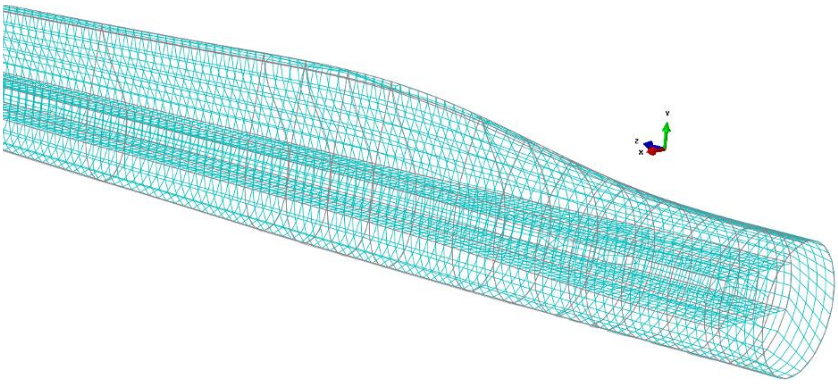


Fig. 9 High fidelity finite element model of a wind turbine blade, mesh of model 3

TABLE 5 CHARACTERISTICS OF THE MODELS

| | Model | Masse (T) | Number of elements | Number of nodes | Element type | Element size (mm) |
|---|---|---|---|---|---|---|
| case 1 | Blade without spar | 11.19685 | 14336 | 14307 | S4R | 200 |
| | 1 | 12.91847 | 10200 | 9926 | S4R | 200 |
| | 2 | 13.78327 | 11636 | 11086 | S4R | 200 |
| | 3 | 14.25972 | 12480 | 11703 | S4R | 200 |
| case 2 | Blade without spar | 6.31685 | 24344 | 24582 | S4R | 200 |
| | 4 | 12.91637 | 21993 | 26088 | S4R+C3D8R | 200 |
| | 5 | 13.77408 | 24336 | 28108 | S4R+C3D8R | 200 |

The mass of the various components of the blade enables us to target the optimizable zones of to save on the materials used. One can see the distribution of the mass of the blade for each portion in Table 6. It is clear that the heaviest part of the blade is in its first 10 meters. It is the critical zone where the damage and the failure of the blade are, in general, localized. It is always necessary to reinforce the structure at this location. It also shows that the sensitivity of this zone is related to the variation thickness of the blade, therefore there is an abrupt fall in the mass and thickness.

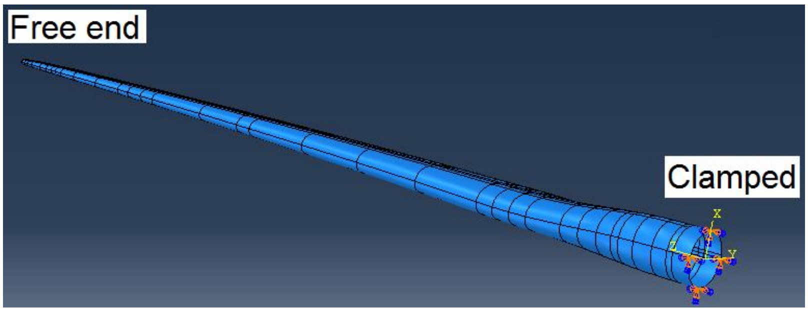
Note that, as the shear-web spacing increases, the blade mass grows significantly. This is because in the particular layup used, the composite stack applied in the outer skin in-between the two shear-webs is significantly heavier than that applied near the leading and trailing edges. In terms of blade stiffness, one can see that the increase in shear-web spacing also brings higher stiffness values, both in terms of linear and angular displacements. Although the analysis results presented here are valid, they raise the question of cross-coupling between the various design parameters, and it emerges that parameter that sweeps with cross coupling of several independent parameters would be necessary. Alternatively, and perhaps more comprehensively, optimization graphs could be produced from the script where iso-parameter contours can be interpolated, improving the understanding of the interdependency between various design parameters.

TABLE 6 EXAMPLE OF THE BLADE MASS DISTRIBUTION FOR MODEL 1, 2 AND 3

| | Model 1 | Model 2 | Model 3 |
|---|---|---|---|
| **r(m)** | $m_1$ | $m_2$ | $m_3$ |
| 0 - 10 | 4.98625 | 5.28053 | 5.41147 |
| 10 - 15 | 1.99579 | 2.11253 | 2.17563 |
| 15 - 20 | 1.73363 | 1.83743 | 1.89523 |
| 20 - 25 | 1.45289 | 1.54405 | 1.59631 |
| 25 - 30 | 1.14438 | 1.22373 | 1.26947 |
| 30 - 35 | 0.78333 | 0.85035 | 0.89086 |
| 35 - 40 | 0.45732 | 0.51200 | 0.54795 |
| 40 - 45 | 0.26461 | 0.30575 | 0.33611 |
| 45 - 48 | 0.10027 | 0.11690 | 0.13669 |
| **Total mass** | 12.91847 | 13.78327 | 14.25972 |

## IV. MODAL ANALYSIS

To estimate the mode shapes and natural frequencies, a modal analysis is performed by using Abaqus computational code. The blade structure properties are approached by neglecting the elasticity (but not the weight) of the tip brake mechanism and by assuming the root part to be fully clamped (Fig. 10). Furthermore, the material damping properties are not taken into account. Basically, the blade model is a shell model. The defined surface area is subsequently subdivided into 8-nodes quadrangular and 6-nodes triangular shell elements with quadratic interpolation functions. The performed modal analysis gives estimates of all natural frequencies and mode shapes, for the investigated blade up to, and including, the first torsional natural frequency. The estimated natural frequencies and mode shapes for the five models obtained from a FE model of the investigated blade have been compared. The natural frequencies, obtained from modal analysis, are presented in Table 7. This study is done in order to evaluate the state-of-the-art blade modelling capacity and in addition to gain inspiration for further improvements.



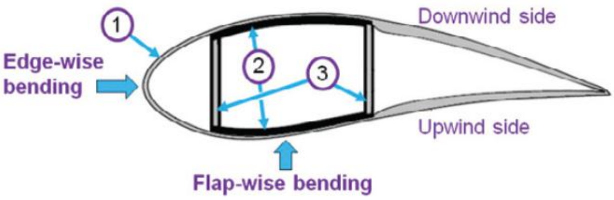



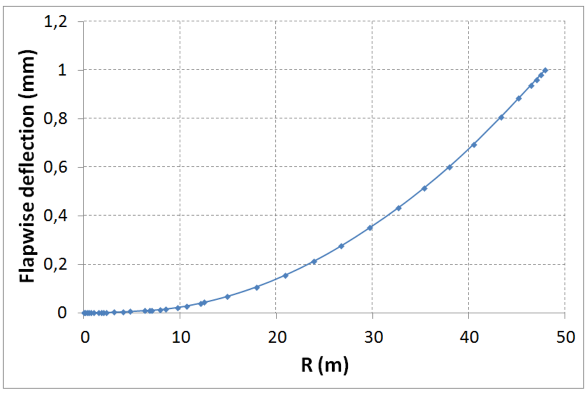

Fig. 10 Boundary conditions of the modal study

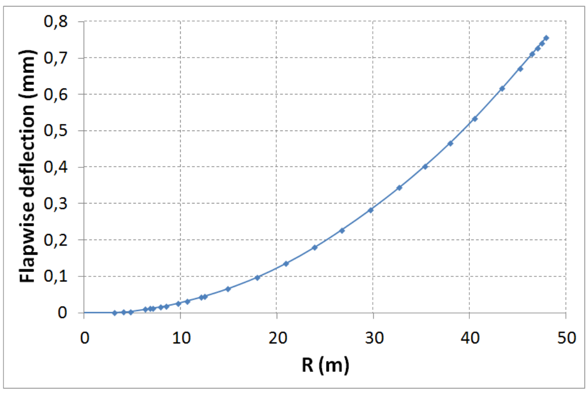
TABLE 7 MODES AND DEFLECTIONS

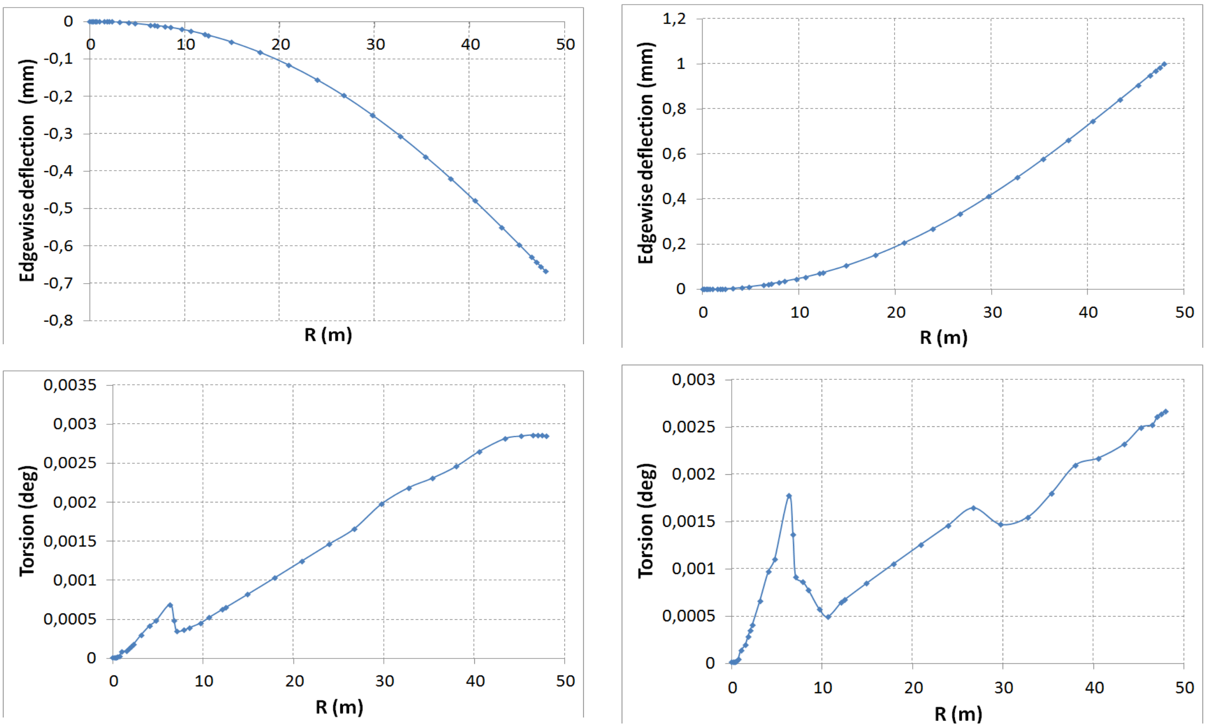
| Model | 1st mode (flap-wise) | 2nd mode (edge-wise) | 3rd mode (flap-wise) |
|---|---|---|---|
| 1 | 0.76632 | 0.88886 | 2.2711 |
| 2 | 0.68936 | 0.82776 | 2.1051 |
| 3 | 0.66633 | 0.80179 | 2.0397 |
| 4 | 0.71308 | 0.8521 | 2.1566 |
| 5 | 0.69261 | 0.83065 | 2.1157 |
| **Model** | | **Deflection (mm)** | |
| 1 | 1.338 | 1.239 | 1.124 |
| 2 | 1.205 | 1.259 | 1.101 |
| 3 | 1.202 | 1.253 | 1.102 |
| 4 | 1.217 | 1.274 | 1.107 |
| 5 | 1.198 | 1.249 | 1.101 |

## *A. Mode Shapes*

The mode shape results, associated with the lowest 2 blade natural frequencies, are illustrated in Fig. 11. For each particular mode, the modal deflection has been resolved in a flapwise, an edgewise and a torsional deflection. For each deflection component, an example of the eigenforms obtained from the FE-modelling of model 3 is done for illustration. In order to facilitate the interpretation, the cross section displacement and rotation, associated with the FE-modelling, is defined as displacement and rotation of a line connecting the leading edge with the tailing edge for a given cross section. In analogy, the bending deflection is defined as the deflection of a radial spline, along which the longitudinal web is attached to the blade surface. A mode shape is uniquely determined apart from amplitude.





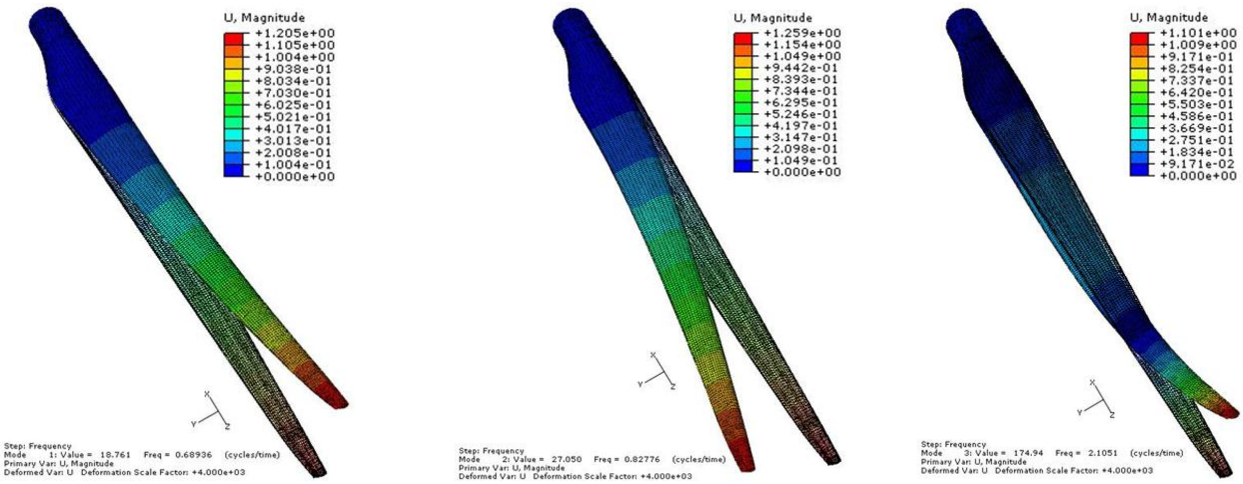

*(a) Mode 1* *(b) Mode 2*

Fig. 11 First and second blade mode, model 3

## *B. Discussion*

The structural coupling, between the dominating deflection and the two remaining (secondary) deflection components, is identified for all the analysed mode shapes. The coupling between bending deflection and torsion requires special attention due to the direct implications for the aerodynamic loading. This coupling is of course especially important for the mode shapes associated with the lower and most important natural frequencies.

Aeroelastic calculations are traditionally based on a Timoshenko beam modelling of the wind turbine blade. Although the bending torsion couplings usually are included in the beam representation, the correct specification of these structural couplings is a delicate matter. The magnitude of the observed bending/torsion coupling effects suggests that these may significantly affect the aerodynamic load characteristics of the wind turbine blade. This emphasizes the need for careful specification of such coupling effects in the aeroelastic computations. In addition, the structural coupling between the two bending components is essential for the correct modelling of aerodynamic damping [17]. For illustration, the mode shape results, associated with the lowest 3 blade natural frequencies are illustrated in Fig. 12.




*(a) 1st Mode* *(b) 2nd Mode* *(c) 3rd Mode*

Fig. 12 Eigen-frequencies, model 2

## V. PHENOMENON OF RESONANCE

According to standard GL Wind2003 (Germanischer Lloyd Wind Energy GMBH, 2005), the condition below must be checked to avoid the phenomenon of resonance:

$$F_r / F_{0,n} \leq 0.95 \tag{1}$$

where:

$F_{0,n}$ is the *n-th* natural frequency of the structure

$F_r$ is the loading frequency, $F_r = 0.26 Hz$.

One applying this condition for the first two modes, one concluded that the effect of resonance does not occur for the 5 models, Table 8.

TABLE 8 COMPUTATION RESULTS OF THE RESONANCE EFFECT

| Effect of resonance for the 1st mode (Flapwise) & 2nd mode (Edgewise) | | |
|---|---|---|
| **Model** | **$F_r/F_{0,1}$** | **$F_r/F_{0,2}$** |
| 1 | 0.339 | 0.292 |
| 2 | 0.377 | 0.314 |
| 3 | 0.390 | 0.324 |
| 4 | 0.364 | 0.305 |
| 5 | 0.375 | 0.313 |

## VI. CONCLUSIONS

Composite laminated plate structure has been widely used in wind turbine blade. In this chapter, combining composite laminated plate blade's characteristics of hierarchical structure, based on finite element analysis software ABAQUS, laminated shell and solid element are used to create finite element model, and the finite element modal analysis is made to obtain modal parameters and the natural frequency spectrum of blade.

A fibreglass blade was designed for the 48m wind turbine blade through the use of finite element analysis techniques with special consideration given to the minimisation of manufacturing complexity and cost. The modal analysis performed in this study gives estimates of 3 lower natural frequencies and mode shapes, for the 48m blade investigated. The results are based on a finite element method performed in different cross sections along the blade. The estimated natural frequencies and mode shapes have subsequently been compared to check that the resonance mode of the system is not reached. Natural frequencies and mode shapes, obtained from a FE model of the investigated blade, are performed in order to evaluate the state-of-the-art blade modelling capacity and in addition, to gain inspiration for further improvements.

The present investigation has demonstrated that essential dynamic properties of wind turbine blades, like natural frequencies and mode shapes, can be numerically determined by use of the modal analysis technique. Blades with different spar geometry have been considered and the most appropriate of these has been selected. Although the comparison is based only on FE results on a 48m blade, the recommendations given are believed to be valid also for other types (sizes, designs ...) of wind turbine blades. The results have laid a foundation for further study of the wind turbine blade's vibration, structural dynamics and other issues.

## ACKNOWLEDGMENTS

The work, presented in this report, has been funded by the WinFlo consortium. NASS & WIN, DCNS, IFREMER and VERGNET are gratefully acknowledged for assisting in performing this PhD work.

## REFERENCES

[1] K. Malawi, Special issues on design optimization of wind turbine structures. In: Al-Bahadly.2, I. (Ed.) Wind Turbines. Intech. I, 2010.

[2] G. C. Larsen and A. Kretz, Experimental Determination of Stiffness Distributions and Mode Shapes of Wind Turbine Blades. Risø-R-773(EN), 1995.

[3] D. A. Peter, M. P. Rossow, K. Timothy, Design of helicopter rotor blades for optimum dynamic characteristics, J. Comput. Math. Appl. 12A (1) 85–109, 1986.

[4] J. I. Pritchard, H. M. Adelman, Optimal placement of tuning masses for vibration reduction in helicopter rotor blades, AIAA J. 28 (2) 309–315, 1990.

[5] R. B. Taylor, Helicopter vibration reduction by rotor blade modal shaping, 38th Annual Forum of the American Helicopter Society, Paper A-82-38-09-3000, Anaheim, CA, pp. 90–101, 1982.

[6] M. W. Davis, Optimization of helicopter rotor blade design for minimum vibration, NASA CP-2327, 609–625, 1984.

[7] T. Burton, D. Sharpe, N. Jenkins, E. Bossanyi, “Wind Energy Handbook,” John Wiley & Sons, Chichester, England, 2001.

[8] A. Maheri, S. Noroozi, J. Vinney, “Combined analytical/FEA-based coupled aero structure simulation of a wind turbine with bend–twist adaptive blades” Original Research Article Renewable Energy, vol. 32, iss. 6, pp. 916-930, 2007.

[9] A. Maheri, S. Noroozi, J. Vinney, “Application of combined analytical/FEA coupled-aero-structure simulation in design of wind turbine adaptive blades.” J Renew Energy, doi:10.1016/j.renene.2006.10.012, 2006.

[10] A. Maheri, S. Noroozi, J. Vinney, “Combined analytical/FEA-based coupled-aero-structure simulation of wind turbines with bend-twist adaptive blades.” J Renew Energy; 32 (6): 916–30, 2007.

[11] H. J. Lin, W. M. Lai, Y. M. Kuo, “Combined analytical and finite element beam model for wind turbine blades.” J Reinf Plast Comp; 29 (16): 2422–37, 2010.

[12] Y. J. Lee, Y. T Jhan, C. H Chung, “Fluid–structure interaction of FRP wind turbine blades under aerodynamic effect” Composites Part B: Engineering, vol. 43, iss. 5, pp. 2180-2191, 2012.

[13] G. Li, S. S. Pang, Y. Zhao, S. I. Ibekwe, “Local buckling analysis of composite laminate with large delaminations induced by low velocity impact.” Polym Composite; 20 (5): 634–42, 2009.

[14] Dayton A. Griffin, “Evaluation of design concepts for adaptive wind turbine blades,” SANDIA report 2002 (SAND2002-2424).

[15] B. Yang, D. Sun, “Testing, inspecting and monitoring technologies for wind turbine blades” Renewable and Sustainable Energy Reviews, vol. 22, pp. 515-526, 2013.

[16] Jinshui Yang, Chaoyi Peng, Jiayu Xiao, Jingcheng Zeng, Suli Xing, Jiaotong Jin, Hang Deng, “Structural investigation of composite wind turbine blade considering structural collapse in full-scale static tests.” Composite Structures, vol. 97, pp. 15-29, 2013.

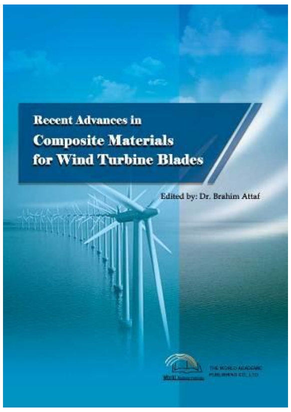
[17] J. T. Petersen, H. A. Madsen, A. Björk, P. Enevoldsen, S. Øye, H. Ganander and D. Winkelaar. “Prediction of dynamic loads and induces vibrations in stall.” Risø-R-1045(EN), 1998.

**Mostapha TARFAOUI** was born in BenSlimane, Morocco in December, 18 1967. Ph.D. Engineering Science: Mechanics and Materials, 1999. Professor: Mechanics and Materials at ENSTA Bretagne, Brest, France, 2010. Main research topics: Naval and Offshore structures - composite materials - mechanical behaviour - static and dynamic response - finite element analysis - residual strength - damage modelling - fracture behaviour - interlaminar fracture toughness - correlation of structure & properties, computer modelling and data bases - Renewable Marine Energies.

M. TARFAOUI is professor specialized in structural mechanics. His main expertise is focused on the composite materials behaviour. This includes the static and dynamic responses involved in the shipbuilding structures to finite element analysis. He has expertise in Dialogue test/calculation in the heterogeneous structures relationships and numerical modelling. He obtained his Ph.D. of Engineering Science (Faculty of Science, University Haute Alsace, France) in 1999 (dissertation: “Finite element analysis of mechanical behaviour of plain and twill fabrics”) and M.S. Physics and Applications (Faculty of Science, University Haute Alsace, France) in 1993. He participated in many congresses (CanCOM, HIPER, ICCM, CFM, IMAC, ESMC, CST, JNC…). He is member of Organization committee and Scientific committee of the international Congress (ACMA, JET…), he was chairman and co-chairman of different congress sessions for example: “Impact and Dynamic Response I and II” session in ICCM 14. Some references:

- M. TARFAOUI, S. CHOUKRI and A. NEME, Dynamic Response of Symmetric and Asymmetric E-glass /epoxy Laminates at High Strain Rates. Key Engineering Materials vol. 446, pp. 73-82, 2010.
- G. MOHAMED, M. TARFAOUI and V. BERTRAM. FEA of dynamic behaviour of Top hat bonded stiffened composite panel. Key Engineering Materials vol. 446, pp. 137-145, 2010.
- M. TARFAOUI. Experimental Investigation of Dynamic Compression and Damage Kinetics of Glass/Epoxy Laminated Composites under High Strain Rate Compression. Book: Advances in Composite Materials. Chapter 16, pp. 359-382, 2011.

Professor TARFAOUI is a membership of AFM (French Association of Mechanics), AMAC (Association for Composite Materials) and AF3M (Association Franco-Maghrebian of Mechanics and Materials). He is reviewer of international scientific journals: Journal of Composite Materials, Advanced Materials Research, Computational Materials Science, Applied Mechanics and Materials, Journal of Reinforced Plastics and Composites, Mechanics of Advanced Materials and Structures, Mécanique & Industries, Matériaux et Techniques…




**Recent Advances in Composite Materials for Wind Turbine Blades**
Edited by Dr. Brahim Attaf

ISBN 978-0-9889190-0-*6

Hard cover, 232 pages

**Publisher:** The World Academic Publishing Co. Ltd.

**Published in printed edition:** 20, December 2013

**Published online:** 20, December 2013

This book of science and technology provides an overview of recent research activities on the application of fibre-reinforced composite materials used in wind turbine blades. Great emphasis was given to the work of scientists, researchers and industrialists who are active in the field and to the latest developments achieved in new materials, manufacturing processes, architectures, aerodynamics, optimum design, testing techniques, etc.. These innovative topics will open up great perspectives for the development of large scale blades for on- and off-shore applications. In addition, the variety of the presented chapters will offer readers access to global studies of research & innovation, technology transfer and dissemination of results and will respond effectively to issues related to improving the energy efficiency strategy for 2020 and the longer term.

**How to cite this book chapter**

Tarfaoui M. and Rahman Shah O. (2013). Spar Shape Optimization of a Multi-megawatt Composite Wind Turbine Blade: Modal Analysis, *Recent Advances in Composite Materials for Wind Turbines Blades*, Dr. Brahim Attaf (Ed.), ISBN 978-0-9889190-0-6, WAP-AMSA, Available from: http://www.academicpub.org/amsa/chapterInfo.aspx

## World Academic Publishing - Advances in Materials Science and Applications

World Academic Publishing