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SCALING LIMITS & COSTS REGARDING WT BLADES

Connecting WP3 with WP1B4

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Abstract: This document focuses on the identification of the scaling limits and the costs associated with the wind turbine blade structure. The work has been conducted by CRES in the frame of Task 3.4 of work-package WP3 “Rotor Structure and Materials” of the UPWIND project. The purpose of the work conducted was to facilitate information exchange with WP1B4 “Upscaling” of the UPWIND project.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released			**R0**	General public			Private web site	X
S1	Reviewed	X		**R1**	Restricted to project members	X		Public web site	
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for commends			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

The objective of Task 3.4 “Up-scaling - Cost factors” of work-package WP3 “Rotor Structure and Materials” of the UPWIND project is to identify the major technological and economic barriers associated with the development of future wind turbine blade technology. Within the frame of this task following questions were posed to work package WP3 partners by partners of work package WP1B4 “Up-scaling”:

- What is the limit for increasing the thickness of the laminates, assuming a linear increase with the blade length, denoted R?
    - Would it be better to increase the number of layers or the thickness of the individual layer?
- Is it possible to use alternative (enhanced) materials or lamination sequences in order to mitigate loads and/or reduce the weight of the blade?
- Would it be possible to reduce the safety factors on the materials for wind turbine blades? Where upon not only the possibility should be investigated but also quantification should be provided.
- Would it be possible to formulate a cost model for the blade?
    - If yes, would a cost factor of 2.4, in correlation with the weight factor, be still valid for the blades?

The current document is prepared in order to cover both the scaling limits of the wind turbine blades, as well as cost factors associated with the blade structure. The issues addressed in this document range from material aspects (including enhanced and alternative materials), structural solutions and the associated costs and safety factors.

As a first step the structural constraints of the wind turbine blade are addressed.

2. Structural design constraints

2.1 Geometry

The external geometry of the blade is a constraint regarding the structural design of the blade. The geometry is driven by aerodynamic constraints, which in turn are prescribed by an optimized solution taking into account the loads and the power output of the wind turbine and it is assumed in this Task that the external blade geometry is given for a specific rotor diameter.

Therefore, the following assumptions have to be adopted when up-scaling the wind turbine blade: the blade planform characteristics scale-up proportionally to the blade radius, the twist distribution and the airfoil types remain the same. Table 1, taken from [1] summarizes the size dependency of the blade geometry to obtain aerodynamic rotor similarity and assuming geometric similarity rules.

Table 1: *Size dependency of external blade geometry [1]*

Symbol	Defining Formula	Description	Size-Dep.
R		Blade Radius	*R*
r		Local Radius	*R*
L	$L = R - r_0$	Blade length	*R*
x	$x = r / R$	Non-dimensional spanwise distance, $[x_h, 1]$. *h=hub*	*I*
$c(r)$		Chord distribution	*R*
$t(r)$		Max-Thickness distribution of airfoils	*R*
$c^*(x)$	$c^*(x) = c(r)/R$	Non-dimensional chord distribution	*I*
$t^*(x)$	$t^*(x) = t(r)/c(r)$	Non-dimensional Max-Thickness distribution	*I*
$twist(x)$		Twist distribution	*I*
$airf(x)$		Airfoil type	*I*

R: denotes linear dependency on blade radius.

I: denotes size independency.

Translating Table 1 into geometrical constraints for the wind turbine blade, one can clearly see that the length of the blade and the geometry of the aerodynamically active part of the blade, are completely fixed.

2.2 Operational characteristics

For the smooth operation of the wind turbine as a system, operational characteristics of the blade form also constraints of the blade structure. These include the natural frequencies of the blade, especially the first flap and edge bending natural frequencies. As a general rule of thumb the first natural frequency of the blade (in the flap direction) should be between 4p and 5p, with p being the rotational frequency of the rotor, while the first natural frequency of the blade in the edge direction should be close to 6.5 - 7p, to comply with requirement of good first-frequency separation. The abovementioned requirements hold also in the case of pitch regulated and variable speed wind turbines, although Campbell diagrams should be used instead of point estimates.

Regarding the natural frequencies of the blades, one interesting point to note in the development over time of blades is that for older wind turbines (3-bladed upwind, usually stall regulated ones) the first flap and edge natural frequency of the blade were fixed at 5p and 7p respectively. For modern wind turbines (and larger blades) this requirement is more relaxed (see above), while there are also design concepts with closer spaced natural frequencies, that is, close to 4p for the flap and close to 5.5p for the edge frequency [2].

In any case the requirements for specific natural frequencies are strong drivers of the whole wind turbine blade structure due to the direct connection of stiffness requirements and mass properties.

Additional constraints on the structural design are posed through the limits on the blade's deflection, the strength under extreme loading and of course the strength under alternating wind loading conditions during the operational lifetime of the blade (fatigue).

Obviously the tip deflection limits are controlled through stiffness constraints, while the load carrying capacity of the blade is controlled through strength constrains (ultimate and fatigue). Yet, strength constraints do entail also buckling limitations, which are also affected by the (local) stiffness of the blade.

Therefore, to comply with the operational constraints following should be considered:

- Deflection: controlled through stiffness
- Natural frequencies: controlled through stiffness and mass distribution
- Buckling: controlled through (local) stiffness and strength
- Extreme Load carrying capacity: Controlled through ultimate strength
- Variable load carrying capacity: Controlled through fatigue strength

2.3 Additional constraints

Finally, constraints on the structural design are imposed through manufacturing constraints. These might include constraints set as a precaution for reducing manufacturing uncertainties, e.g. over sizing of gluing areas between adherent parts of the blade, or constraints set as limits on the manufacturing procedure, e.g. minimum thickness of composite material layer.

Additional analysis has to be performed on the cost reduction achieved in the final wind turbine blade product if the optimization is leading to extremely detailed reinforcement drawings. The subject is given a lot of attention in the case of aerospace products. Through expensive optimization software, especially suitable for composite materials, solutions are found where each structural part includes differences in fibre orientations depending on the local loading conditions.

In the low cost driven wind turbine industry however we should be aware that for a series production line, cumbersome manufacturing sketches might increase the manufacturing time so as to keep the level of the manufacturing quality.

3. Review of trends in blade characteristics

In the present section some trends in blade characteristics are reviewed, in order to enable a quantified extrapolation of these properties for very large blades and provide answers to the questions posed, with respect to the thickness of the laminates and the weight of the blade.

3.1 Thickness of laminates

To answer the first question regarding the thickness of the laminate as a first step, a review on available laminate thickness data was performed. In [3] structural analysis results are presented for blades of 30m, 50m and 70m length, using a beam section analysis methodology and loading conditions corresponding to IEC Class I. In [4] the lamination sequence of the UPWIND reference blade, a 61.5m blade for a 5MW wind turbine, is presented, estimated by using a representative laminate distribution by WMC and the OPTIMAT material properties database. Since both these documents contain results stemming only from design scenarios, a third blade was used for which data were available to CRES. This blade, denoted “Real” complies with specifications for IEC class I, yet it is suitable for smaller than 1MW class wind turbines. Due to the involvement of proprietary data, no further information will be given for this blade.

Analysis performed within WP1B4 of the UPWIND project [1], was based on the assumption that thickness is linearly increased with the blade length when blades going from smaller to larger blade sizes (and wind turbine capacities). Therefore, if the thickness on a section of the blade was normalized against the length of the blade, this parameter could be compared for various blades. In Figure 1 the normalized thickness along the spar of the wind turbine blade is shown for the three blades, where data were available. Denoted by “Ref.” the 50m blade of the blades reported in [3] is indicated, while the reference 5MW UPWIND blade is denoted as “5MW”. It can be seen that the data compare quite well for the three blades in the aerodynamic part of the blade, stations from 20% to 100% of the total blade length. The difference at the tip of the blade (section 100%) is due to the fact that the manufacturing constraints are pronounced on the smaller blade. The differences observed around the station at 20% of the blade length should be attributed to the start of the aerodynamic part of the blade and the handling of the transition area between the aerodynamic part and the root of the blade. Finally, the large differences observed in the root of the blade, should be probably attributed to the data provided, i.e. real data, incorporating all manufacturing and design constraints for the “Real” blade, design data for the “Ref.” blade, and representative laminate distribution for the 5MW blade.

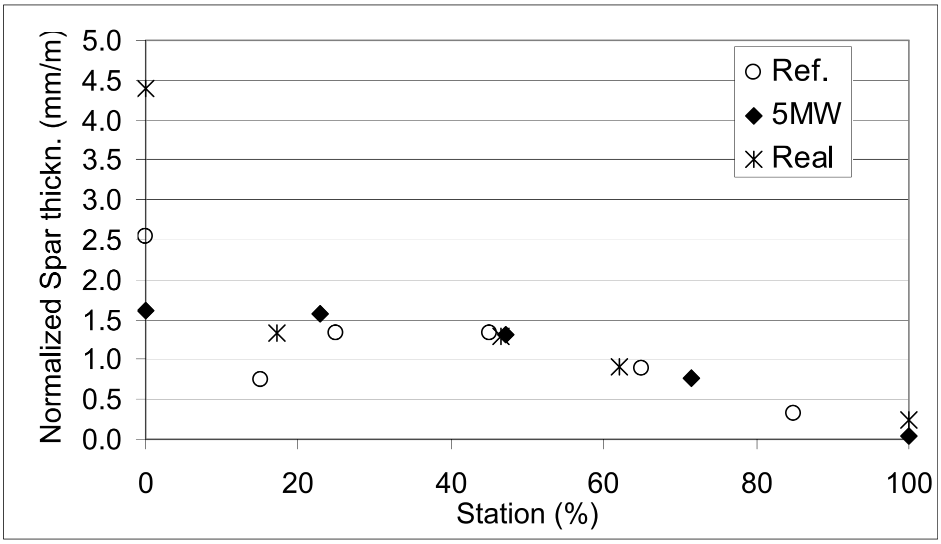

Figure 1 Spar thickness normalized with respect to blade length

However, excluding the differences in the root section thickness, the assumption that thickness increases linearly with the blade length is judged as reasonable. In Figure 2 the trend in thickness increase with respect to blade length is shown, using the data of [3]. Therefore, putting things in perspective, a thickness of more than 200mm is expected for blades of 10MW wind turbines and 300mm for the 20MW wind turbines.

The increase of the thickness of a single layer has limitations regarding the microstructural efficiency of such a layer, issues regarding the fibre impregnation and the curing cycle and is therefore not recommended.

On the other hand, the increase of the number of layers used in a laminate might pose manufacturing problems, in relation with the curing cycle and the achievement of proper fibre impregnation. However, manufacturing solutions for optimizing these aspects are already considered by the manufacturers.

The behaviour of very thick laminates has not been studied extensively, with indicative efforts available from the OPTIMAT BLADES project [5] and from a Dutch national project, Innwind, [6]. It is possible that scaling effects will be observed. This issue might be solved through safety factors accounting for these effects. Additionally, the modelling level used in the analysis might be important to be increased when dealing with such thick laminates. Therefore, it is not expected that increasing the number of layers in the laminate will impose limitations for future blades.

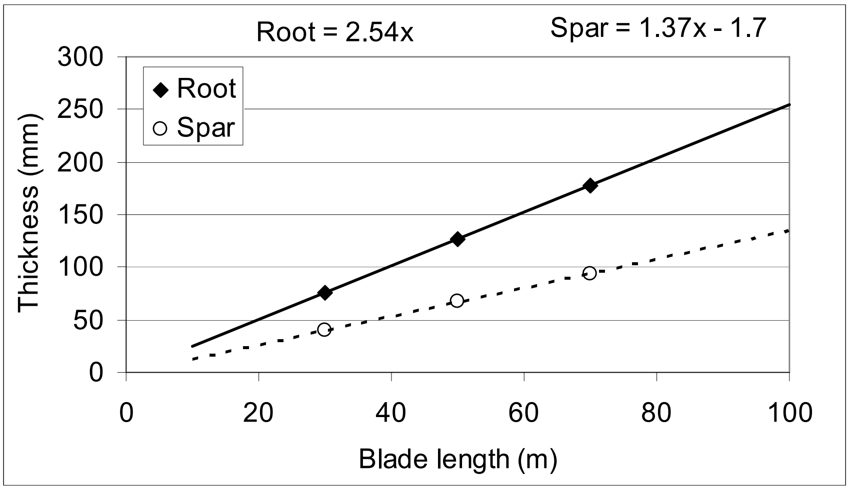

Figure 2 Spar thickness normalized with respect to blade length

3.1.1 The root

The connection of the blade to the hub is performed through a bolted joint. Previous studies on the parameters for the specification of the root were based on scaling trends of available commercial wind turbines [7]. However, limitations regarding the local geometrical parameters cannot be addressed. Therefore, a more detailed analysis was performed focusing on the parameters that might pose constraints in the up-scaling to larger sizes of blades. The analysis was performed following the line of thinking introduced in [1]. Therefore, the main scaling factor is the rotor radius.

The constraints affecting the design of the joint are following:

- The bolt hole circle diameter is limited by the diameter of the hub at the root of the blade and the pitch line of the blade. Figure 3 shows a sketch of the blade joint to the hub, with following parameters: D_{BHC} is the bolt hole circle on the blade root, r_o is the distance of the blade root to the hub centre, D_P is the distance of the pitch line relevant to the leading edge of a characteristic aerodynamic section of the blade (usually the maximum chord section) and by L_N a clearance distance is denoted that should be kept in order to be able to join the blade to the hub.

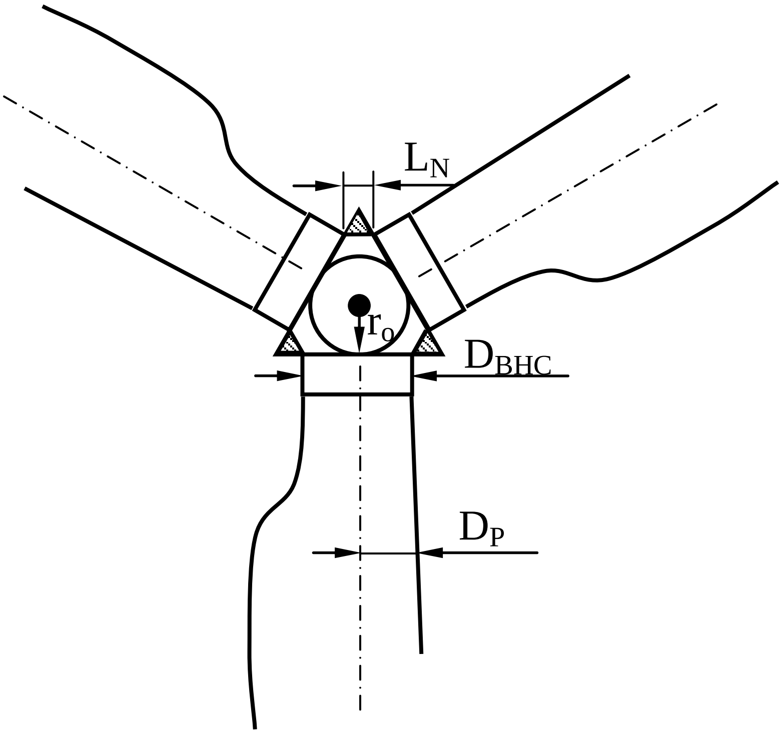

Figure 3 Basic parameters affecting blade joint

Obviously, based on Figure 3 the external diameter of the blade, $D_{B,}$ containing the bolt hole circle diameter, D_{BHC}, cannot be larger than the side of the circumscribed equilateral triangle. The inscribed circle has a radius of r_o, namely the distance of the blade root to the hub centre. The trend analysis on commercial wind turbine data shows that this distance is between 2% and 3% of the rotor radius, R. Therefore, taking the larger of the two possible r_o:

$$D_B \le \frac{2r_o}{\tan(30)} = 2\sqrt{3}\,(0.03R) \tag{1}$$

The external diameter of the blade on the root is connected to the bolt hole circle and the thickness of the blade root through: $D_B = D_{BHC} + H$

In order to be able to tighten the bolts, a distance from the triangle corner should be foreseen. Although this distance strongly depends on the specifications of the root joint, for simplicity it is assumed that this distance is a linear function of the bolt diameter. Therefore, the bolt hole circle diameter cannot be larger than:

$$D_{BHC} \le \frac{2r_o}{\tan(30)} - 2\frac{L_N}{\sin(30)} = 2\sqrt{3}\,(0.03R) - 4a_{tight}d_{BOLT} \tag{2}$$

where a_{tight} is simple the multiplier of the bolt diameter to define the required space.

A further limitation of the blade root diameter is connected with the pitch line of the blade. The pitch line should pass through the centre of the cylindrical root. The pitch line of the blade, which is connected to the aerodynamic design of the blade, is usually given as a percentage of the chord on each section. For older designs this corresponded to ¼ of the chord, while for newer aerodynamic sections, having thicker trailing edges this might be increased. Assigning L_P the distance of the leading edge of the characteristic chord to the pitch line one has:

$$D_{BHC} \leq 2L_P = 2a_P c \tag{3}$$

where a_P is the proportion of the chord where the pitch line lies and c the maximum chord of the blade. One of eq.(2) or (3), the smallest, will show the limit for the D_{BHC}.

- A further constraint for the geometry of the root joint limits the distance between the bolts on the root. This can be expressed by:

$$3d_{BOLT} \leq \frac{\pi D_{BHC}}{N_{BOLT}} \tag{4}$$

where N_{BOLT} indicates the number of bolts. Therefore, an upper limit for the number of bolts on the joint can be assigned through Eq.(4).

At this point, it should be noted that the current analysis focuses on the solution of having one row of bolts on the joint, which is used in the majority of the commercial blades. For example Enercon has introduced a solution having a double-row bolt connection [8], a solution which allows a larger number of bolts to transmit the loading from blade to hub. However, since this engineering solution has different constraints, as well as due to the fact that for the larger wind turbine model E-126, Enercon has introduced a steel inboard part on the blade [9], indicating differences in the design concept from the majority of commercial blades, the double-row concept will be not treated in the present analysis.

- The thickness of the blade on the root is also connected to the diameter of the bolts used. The thickness should be:

$$1.5d_{BOLT} \leq H \tag{5}$$

- After setting the geometric constraints the important strength constraints should also be addressed. The maximum load for a bolt due to bending moments and axial loads acting on the root of the blade can be approximated by:

$$F_{max} = \frac{4(M_{AERO} + M_{WEIGHT})}{D_{BHC} N_{BOLT}} + \frac{N_{Centrifugal}}{N_{BOLT}} \tag{6}$$

while the developed stress is given by:

$$\sigma_{BOLT} = \frac{4F_{MAX}}{\pi d_{BOLT}^2} \tag{7}$$

This stress should be kept lower than the allowable stress on the bolt.

Although a layer by layer analysis is proper for the blade, following the simplified line of thinking introduced in [1] and assigning an allowable axial stress for the laminate in the root section of the blade:

$$\sigma_{all\_C} \geq \sigma_{comp} = \frac{4(M_{AERO} + M_{WEIGHT})(D_{BHC} + H)}{\pi D_{BHC} H \left(D_{BHC}^2 + H^2\right)} + \frac{N_{Centrifugal}}{\pi D_{BHC} H} \tag{8}$$

Optimizing the design of the root joint so as to minimize the linear mass of the root subject to the abovementioned constraints, it is concluded that one needs to search for the largest D_{BHC} and the smallest d_B that result in a compliant solution.

If we look at Eq.(8) and Eq.(7) it can be proven that there is a component that increases linear to the rotor radius, R. The component in question is related to the stress as a result of the bending moment due to the weight of the blade.

Therefore it is anticipated that the wind turbine blades cannot be scaled further to a limit length. Even if the strength of the composite could be improved and therefore the scaling allowed continuing, the limit would be set by the strength of the bolts joining the blade to the hub. One would arrive to similar conclusions, if instead of taking into account the bending moment due to the weight of the blade, the axial force due the weight had been considered. Possible extension to larger wind turbine sizes would be allowed through other joining solutions, as maybe the double-row bolt concept of [8].

3.2 Blade mass and technology overview

In order to investigate the trend of blade mass with increasing blade size, a review of available data was performed. Earlier reports, e.g. [10] do not have indication on the Wind Turbine Class of the blades. Yet, lower wind turbine classes result to lighter blades, a result that was extensively discussed in [11]. An indicative figure comparing the mass per unit length of commercial blades is shown in Figure 4. In this figure, care was taken that the blades of the various classes were of comparable technology for a specific wind turbine capacity, however, the data for the two capacities are not comparable.

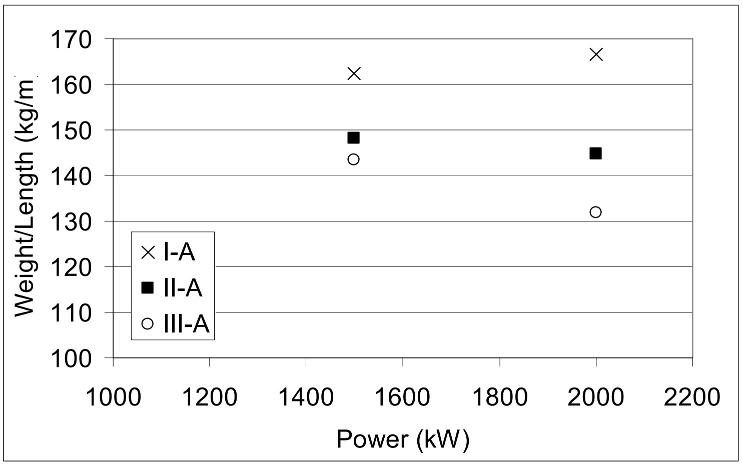

Figure 4 Blade (normalized) weight for various IEC classes

Additionally, public data for some of the blades are reported with respect to the nominal length of the blade, i.e. from the root (of the blade that will be attached to the hub) to the tip, while others are reported using the diameter of the wind turbine, i.e. including the distance from the root of the blade to the centre of the hub. Since this distance could range from 2% to even 5% of the radius of the wind turbine (not the same for all wind turbines), the difference in length might give false impression, especially on the larger blade sizes, where also available data are sparse. For example in following figure the length of the blades marked with circles corresponds to the nominal length of the blade (i.e. 0.95*rotor radius), while the length of the blade marked with squares corresponds to the half of the wind turbine diameter (i.e. equal to rotor radius).

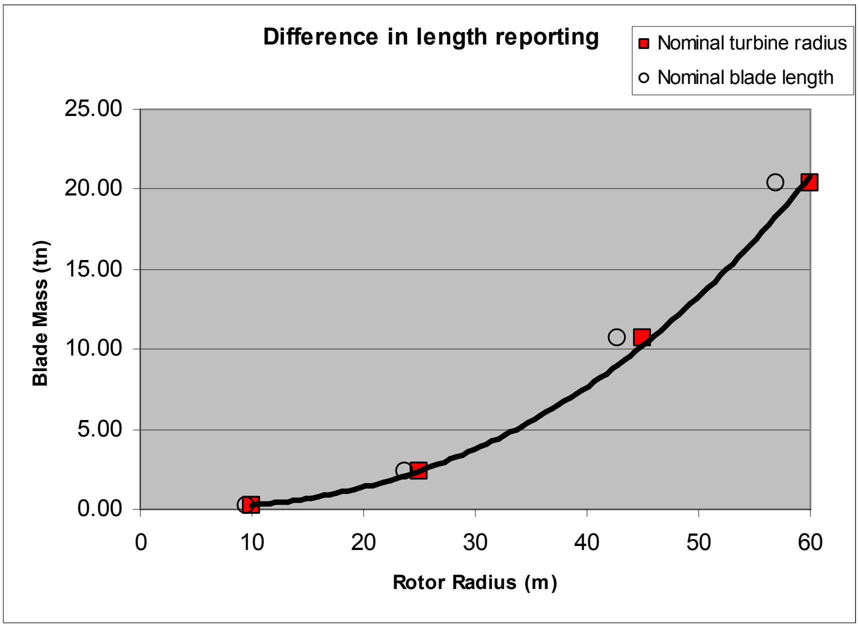

Figure 5 Differences in reporting length of blade (assuming r_o = 5% of turbine radius)

Taking into account the above Figure 6 presents mass data with respect to the length of commercial blades. The data correspond to wind turbine IEC class I-A, nevertheless, for large sizes (above 50m) the available data might correspond to lower IEC classes. Additionally, although the reported data were as much as possible converted to show the nominal blade length, there still might be data points referring to the rotor radius. Major technological trends are also shown in the figure through trend lines with an exponent factor of 3. The exponent factor is equal to 3 on all trend lines shown, while the reference blade for each technological step is as follows: A 20m blade for hand lay-up with Glass/Polyester and blades of about 40m blades for the rest of the technologies.

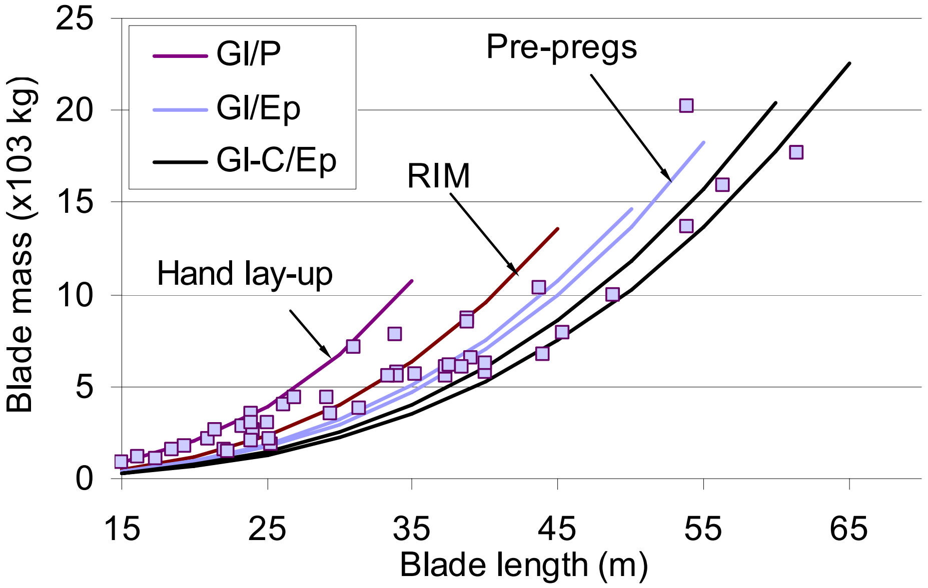

Figure 6 Blade mass trend with respect to technology

It should be noted that when applying a trend line through the data, disregarding the various technological trends, then, the outcome is an exponent factor of 2.1, or depending on the blade size range included in the fit a factor between 2.4-2.6, as also shown in other studies.

The major technological developments in the manufacturing of wind turbine blades, shown in Figure 6, correspond to material change and manufacturing process change. A general description of the technology evolution from a manufacturer's point of view can be found in [12]. During the early stages of wind turbine blade manufacturing, the material used was mainly Polyester resin reinforced with Glass fibres (Gl/P) while for the processing labour intensive hand lay-up method was used. As the size of the blade was increased, manufacturing automation was pursued and resin injection manufacturing methods were established. Epoxy resin composites exhibit better properties than polyester resin, yet the higher cost of epoxy, allowed introduction on later stages in the technology evolution of blades, with newer blades making mainly use of glass fibre reinforced epoxy (Gl/Ep). Using carbon fibres instead of glass fibres, despite the better properties of carbon composites with respect to stiffness, was discarded due to cost at even larger blade sizes, with hybrid glass-carbon blades (Gl-C/Ep) being currently in production lines. Use of pre-impregnated fibres instead of resin infusion, although resulting in better composite material properties, implies additional manufacturing costs. This, however, is also a technological step for the mass reduction of blades, which is pursued when material cost issues are overtaken by the overall product cost reduction.

Although the abovementioned major technological steps can be clearly identified on Figure 6, improvements in the design and manufacturing of the blades have resulted in further reduction of the blade mass. That is, between the initial application of the new technology for, let say, a 30m blade, and a newer generation blade, there is a learning procedure over time, which improves the design (and manufacturing). This learning procedure might simply involve the reduction of safety factors used for the older material and initially applied to the new and improved material, which is possible through building up of the material property experimental databases. But in most cases it also involves optimized use of the materials within the blade to improve the behaviour and the reliability of the blade. An exponent factor of 3 is being kept despite the stringent constraints set for blades of larger sizes. The load increase would result in an exponent of mass increase above 3, as indicated in [1]. Yet this was kept at 3 or even lower if an actual fit was performed on the available data.

In [7], written in 2001, it is indicated that for the next generation of blades, namely the 40 to 60m wind turbine blades, there would be a need to employ carbon or carbon/glass hybrid fibres, to improve the manufacturing processes in order to yield higher material properties mean values and a reduction in property scatter, as well as to introduce load-mitigation techniques. In 2005, after the production of a 60m blade, the review of the blade technology considering mainly the material aspect presented in [10] highlights potential new materials (cellulose fibres), requiring further research and stresses the need for improved understanding of the structural behaviour of composites. Within the frame of the UPWIND project efforts are aimed at the development of advanced design methods for the structural design of the blade [13], [14]. Although further research is necessary towards this direction, it is envisaged that these improvements will be the base of the next technological evolution steps.

3.3 Blade stiffness

As already mentioned, combination of the stiffness and the mass distribution along the blade affects the dynamic behaviour of the blade. In Figure 7 the 1st natural frequency in the flap and leag-lag direction of representative blade sizes is shown with respect to the rotor radius. The frequencies are normalized following [1], for possible identification of a trend. On the graph the three horizontal lines are meant to provide a rough indication of 4, 5 and 7 times the rotational frequency of the wind turbine, p, although some differences are anticipated for the data shown due to the specifications of each wind turbine. It should be noted that actual available blade data are very limited, so for sizes larger than 40m only design values are shown. From the available actual data, it is clear that the 1st flap frequency is kept slightly below 4p, with design values following the trend. The design data include results presented in [3] and [15], also incorporating hybrid carbon/glass design solution and the data for the UPWIND reference wind turbine reported in [16].

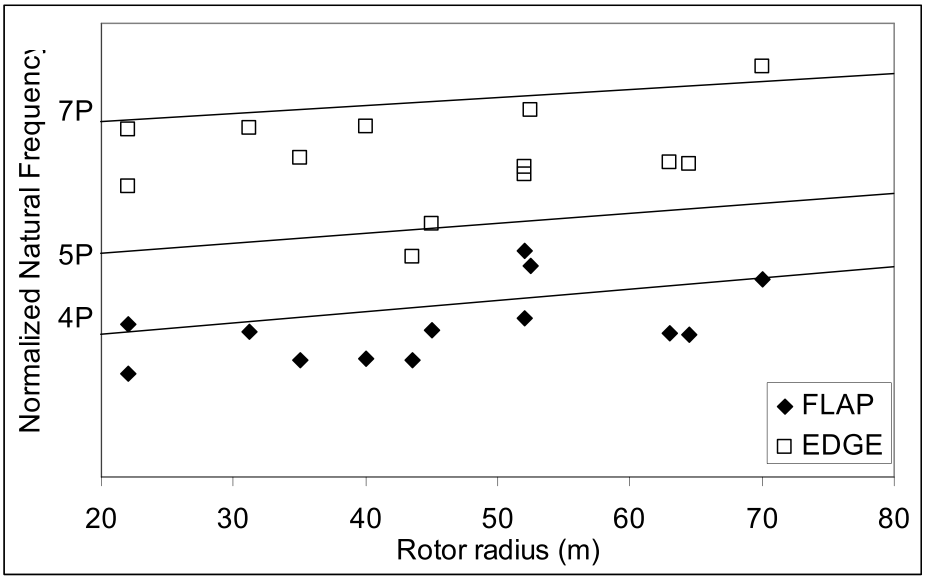

Figure 7 Trend of 1st natural frequencies with to rotor radius

Regarding the mass and stiffness distribution along the blade length, some comments are possible when comparing the normalized stiffness values along the length for various blade sizes. Bending stiffness distribution along the blade is shown in Figure 8 and Figure 9 for the flap and lead-lag direction, respectively, for various blade sizes. Both stiffness and position are normalized against the rotor radius, R, with the maximum chord section of the blade positioned at about 25% of the rotor radius. Stiffness data are normalized using the 4th power of the rotor radius, as suggested in [1]. The data for the 750kW are presented in [7], those of the 1.5MW wind turbine in [17] and those for the two cases of the 2.5MW wind turbine blades in [15]. The latter correspond to a conventional design employing Gl/Ep material only, denoted “2.5MW” and a hybrid carbon/glass fibre design, denoted as “2.5MW_C/Gl” in the graph. Data for the 5MW reference blade, not shown in this figure, fall in-between the data for the 2.5MW blades. It should be noted that available data of actual blades, not shown here, indicate quite stiffer designs than those presented in the various scaling studies.

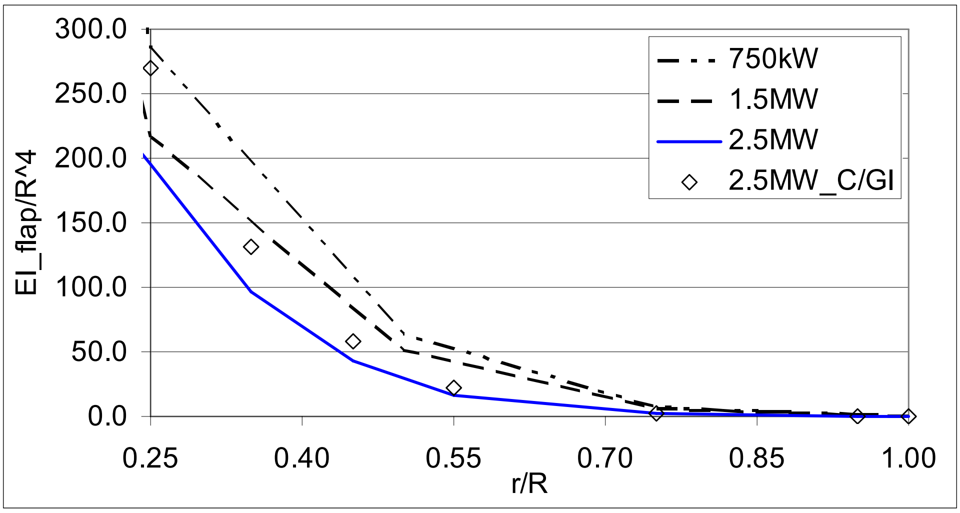

Figure 8 Stiffness distribution along the blade in flapwise direction for various blade sizes.

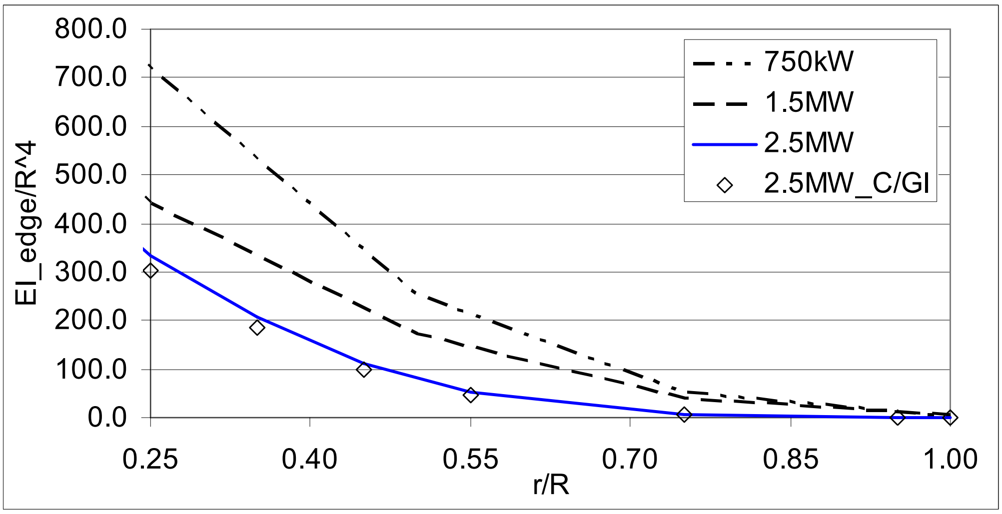

Figure 9 Stiffness distribution along the blade in edgewise direction for various blade sizes.

In [15] it is mentioned that the data result in natural frequency estimations in the flap direction close to 4.3p (with p the rotational frequency of the wind turbine) for the conventional designed blade and to 5.3p for the hybrid designed blade for the 2.5MW blade. This difference is actually indicated in the stiffness distribution in the flap direction, Figure 8, with the stiffness of the hybrid Gl/C blade being higher than that of the conventional glass fibre blade. For the edgewise direction (lead-lag) the estimation of the corresponding 1st natural frequency is found close to 6.5p for both blades of the 2.5MW wind turbine, with small differences between the stiffness distribution of the two blades.

An indicative distribution of the mass along the blade is shown in Figure 10. However, since the presented stiffness and mass distribution data refer to preliminary blade designs it is not clear whether additional masses, which do not have a pronounced effect on the strength and stiffness of the blade (during the structural design) but are indispensable on the actual structure, such as the mass of the adhesive, the mass of the lightning protection system, etc., have been included in the analysis. This additional mass is called “parasitic mass” in [7] and [3] and as indicated in [7], if this mass is not adjusted, then the results regarding mass estimations should be considered as a minimum.

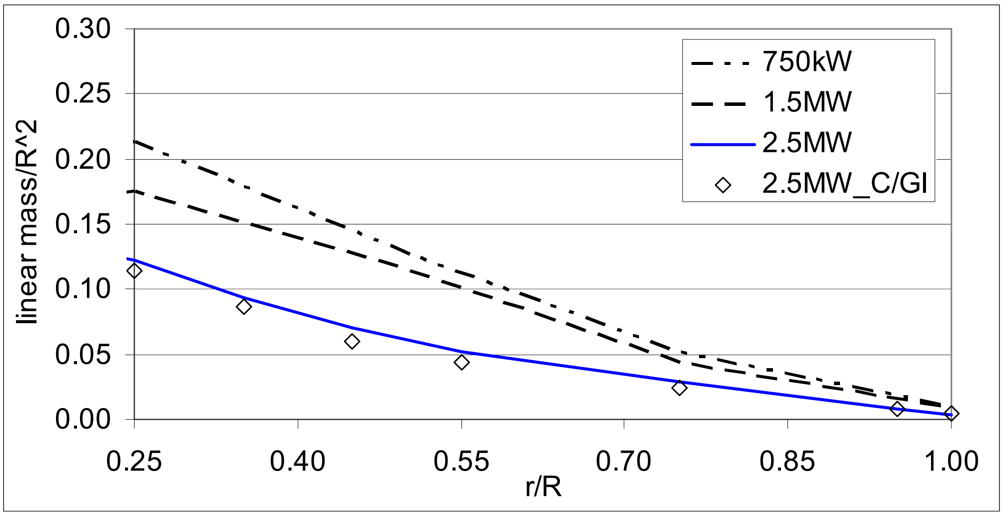

Figure 10 Mass distribution along the blade for various blade sizes.

Yet, these masses, although not having an effect on the stiffness distribution as presented, but rather on the mass distribution, they would in turn affect the estimated natural frequencies of the blade (lowering them). Similar is the case also for the UPWIND reference blade.

3.4 Improved use of materials and mass reduction

Specifically on the question set by WP1B4 members regarding the use of enhanced materials or laminate sequence and load reduction, it should be clarified that the structural design of the blade cannot lead to load mitigation other than via mass reduction, and thereupon gravity induced loading reduction.

Use of carbon fibre composite materials, as suggested, is already applied for the wind turbine blade manufacturing. It is further anticipated that material research results allowing improved properties will be continued as the issues of cost will be outbalanced by weight reduction achieved. Not only static strength, but stiffness and fatigue strength properties will be on the focus of attention, as well as other parameters affecting the final blade product behaviour such as scatter in properties, which needs to be contained through improved manufacturing control processes from the material level to the blade level and the effect of temperature variation on properties, especially fatigue.

Scaling and trend analysis performed within the USA WindPACT research project, [18], reveals a shift of loading design drivers from static and fatigue loading in the flapwise direction to fatigue loading in the trailing edge (lead-lag direction). The analysis presented in the previous sections shows that stiffness in the lead-lag direction (and the flap direction) is playing a more pronounced role as blades grow in size. To keep the mass increase confined, focus in the structural design details is anticipated.

Simple scaling will not be enough, as “parasitic mass” will come to play a more pronounced role for increasing blade sizes. It is expected that enhanced and integrated design methods, such as [13] and [14] will allow for better and optimized use of the material to permit production of larger blade sizes.

4. Safety factors on blades

To address the issue of the possibility of reducing the safety factors applied during the design of the wind turbine blade, as a first step it is important to recognize the failures exhibited during the testing of wind turbine blades and more important during operation of the wind turbines. This has not been systematically performed so as to conclude on the effectiveness of the safety factors with respect to the achieved reliability.

Following this in the present section a review of the safety factors introduced during the design of the blade is performed. Finally the potential of safety factors reduction is discussed.

4.1 Blade failures

To accommodate the scope of the present document, information on the root cause of blade failures is sought, in order to link possible adjustments of design specifications with the failure of blades. In other words if statistics show that blade failures due to e.g. fatigue loading are higher than what would be acceptable, design safety factors related to fatigue can in no way be reduced.

To do that, a review of the relevant information regarding reliability and failure reports specifically for the blades was performed. Most of the studies addressing the issue of wind turbine component reliability in general, e.g. [19], [20], provide data on blade failure rates in the best case (usually the blade failures are combined with pitch system failures, e.g. [21]) not indicating the type of failure observed or the root cause of failure, e.g. lightning strike, fatigue cracks, etc. This is due to the fact that the main interest of such studies lays on the operation and maintenance costs related with the operation of the wind turbine. Realizing the need for improved failure reports, research including the formation of enhanced databases is underway, both in the EC and USA, [22] and [23], respectively, but with data specifically regarding blade failure analysis not yet available.

In [23] a blade reliability survey conducted, revealed following issues regarding blade failures:

- Manufacturing issues – waviness and overlaid laminates
- Bad bonds, delamination, and voids
- Leading edge erosion
- Trailing edge splits
- Lightning – comments:
    - At one plant every blade has been struck at least once
    - Many repairs and replacements
    - Scorching and splits
    - Manageable problem (relative to gearboxes)

Need for the replacement of blades is included along with information on cost and time, yet no information on relative frequency is provided, especially regarding manufacturing and possible design subjects, such as bad bonds and delaminations.

In [24] an analysis of the blade failure modes in field is presented, were damage due to lightning accounts for 20% of the failures and damage due to foreign objects hit on the blade account for an additional 16%. Although lightning strikes, depending on the lightning characteristics, the lightning protection system and the blade structure itself, may cause substantial damages on the blade, these failures fall outside the design issues addressed within WP3 of the UPWIND project and therefore will not be treated in the present document. Foreign object impacts will also not be treated, since these are falling outside the scope of the document. For completeness, it should be mentioned that lightning protection issues are addressed under the newly released IEC 61400-24 [25], while informative directions for the evaluation of impact damage during the design phase of blades are provided in DNV-OS-J102 [26]. In summary from [24], the following types of failures are encountered in the field:

- Lightning (20%) & Foreign Object impacts (16%)

- Tip hits the tower (13%)
- Adhesive Bonding failures (20%)
- Voids in skin and core (18%)
- Improper Cure (13%)

As stated in [24] these data are the results of an analysis of 45 blades, therefore, the figures should be treated with caution. Nevertheless, these seem to fit also with the results of the blade reliability survey [23]. The failures of interest to the present study are the deflection related failures (tip hits the tower), which is the result of either overestimation of the blade stiffness or underestimation of the load imposed on the blade, the adhesive bonding failures and the manufacturing related failures of voids presence and improper cure.

A different source which might improve the understanding of failures observed in wind turbine blades are the failures exhibited during the performance of laboratory tests on blades. Towards this direction the data on failures during testing of blades presented in [27] could improve understanding. The test data population includes Megawatt scale wind turbine blades, with design representative of current in-field designs and tests performed according to the relevant IEC/TS 61400-23. Following summarizes the causes of catastrophic or functional failures exhibited during static and fatigue tests presented in [27]:

- Design/material; including design deficiencies, panel stability and ply drops: 10%
- Laminate defects; including waves, voids and dry spots: 40%
- Bondlines; including bondlines in shear webs, leading and trailing edge: 40%
- Root fixing failures; including T-Bolts, Barrel Nuts and Flanges failures: 10%

Of these failures the majority of failures (95%) have been observed during fatigue testing. Moreover, in [28] it is noted that 75% of the cases are observed early during the testing procedure, with the substantial amount of 25% of the cases occurring in the later stages of fatigue tests based on damage equivalent loads.

Within WP3 it was requested to confirm on a qualitative basis the data reported in [27] and [28] by relevant project participants, however, this was not performed due to intellectual properties rights protection issues raised. These issues are also recognized in studies involving assessments of wind turbine components failures in general, but also specifically for blades, e.g. [27] and [28].

In a more detailed analysis, operational failures can be classified as birth failures (or initial failures), which are usually failures that are observed during the commissioning period of a wind turbine. For this case the available data are very scarce, since they are treated immediately by the manufacturer. However, these are raising usually issues of manufacturing quality. An independent study should be undertaken to address this issue. Answers should be provided on whether these manufacturing quality issues should be taken into account within the design specifications of the blade in question, or whether the quality inspections after the finishing of the blade and before its shipment should be improved.

4.2 Possibility of reduction of safety factors

The design of wind turbine blades should be performed based on the current edition of IEC 61400-1 standard [29]. The IEC standard distinguishes between safety factors that are to be applied on wind turbine loads and those applied on material properties in order to achieve the required reliability for the wind turbine. However, the standard provides limited guidelines with respect to the wind turbine blades and the design thereof, as is recognized by the new work that will be performed within the relevant IEC committee [30]. Meanwhile, the blades are designed following design guidelines issued by wind turbine certification bodies, essentially GL [31] and DNV [26].

Within the present document only the material safety factors will be discussed, since load safety factors fall outside the scope of the work and partial uniformity on the relevant treatment of load cases and safety factors has been achieved through the IEC 61400-1. A short summary of the partial safety factor for fibre reinforced plastic materials is shown in Table 2 for the IEC 61400-1, where for cases where the characteristic value, R_k, is not clearly defined a question mark is shown, and in Table 3 and Table 4 for material partial safety factors according to GL and DNV, respectively. In these tables, where more than one partial safety factor is required depending on details of the design to account for a specific effect, these are shown on the respective tables through indication of the range or the alternatives mentioned in the guidelines.

Table 2: *Material safety factors according to IEC 61400-1 [29]*

Partial Safety Factor	**Deflection**	**Buckling**	**ULS**	**Fatigue**
	Reduction of γ_m allowed if deflection is verified by test	Description connected to ULS analysis Elastic buckling allowed		
R_k	(?,?)	(?,?)	95%, 95%	95%, 95%
γ_n	1.0	1.0	1.0	1.15
γ_m	1.1	1.2	1.3 (1.1 if ductile, redundant)	1.2

Table 3: *Material safety factors according to GL [31]*

Partial Safety Factor	**Notes**	**Deflection**	**Buckling**	**ULS**	**Fatigue**
		Assigned through distance limits	γ_3 For linear analysis	C_{IFF} applied for inter-fibre failure analysis	γ_5 for trailing edge depending on analysis type
R_k		50%, (?)%	50%, (?)%	95%, 95%	
γ_{m0}	Base	1.05	1.35	1.35	1.35
γ_{1x}	Aging		1.1 (E-modulus scatter)	1.35	$N^{1/m}$
γ_{2x}	Temperature		1.1	1.1	1.1
γ_{3x}	Manufacturing		1.25	1.1/1.2	1.0/1.1/1.2
γ_{4x}	Curing			1.0/1.1	1.0/1.1
γ_{5x}	Local effect				1.0… 1.2
C_{IFF}				1.25	

Table 4: *Material safety factors according to DNV [26]*

Partial Safety Factor	**Notes**	**Deflection**	**Buckling**	**ULS**	**Fatigue**
		If using mean value in analysis	Connected to ULS and progressive failure analysis (Post-buckling)		
R_k		50%, 95%		95%, 95%	95%, 95%
γ_n		1.0		1.0	1.15
γ_{1x}	Base	1.1		1.3	1.2
γ_{2x}	Correction factor for different R_k				
γ_{3x}	LCF			1.1	--
γ_{4x}	Environmental			1.1/1.2	1.1/1.2
γ_{5x}	Manufacturing			1.0… 1.3	1.0… 1.3
γ_{6x}	Curing			1.0… 1.1	1.0… 1.1

Clearly, IEC 61400-1 prescribes only the minimum partial safety factors to be applied during the structural design of the wind turbine blade. Moreover, differences are observed between GL and DNV partial safety factors. This, however, has to do with the inter-connection of the various partial safety factors and the analysis and testing requirements that have to be fulfilled for each described design and manufacturing procedure. For example, GL regulations [31] set fewer requirements for testing on the material level and the calculation of the characteristic property value, than those prescribed by the DNV standard [26]. These differences are taken into account by increasing safety factors to achieve a target reliability level.

Analysis was performed comparing probabilistic (with a probability of failure, $P_F = 10^{-3}$) and deterministically obtained failure locus for a [±45/0_4/±45] laminate, which is characteristic of the lamination sequences considered for the wind turbine blade manufacturing, as shown in Figure 11. In this figure the curve denoted as FORM_EXP corresponds to the prediction of the failure locus if the mean values and the corresponding standard deviations of the strength parameters are employed, using test results presented in [33]. The variability is taken into account both for the strength properties, as well as for the elastic properties in the probabilistic analysis. The same experimental data are used for the determination of the characteristic values and the design values of the material parameters employed for the calculation of the deterministic failure loci, following IEC 61400-1 (IEC), the DNV guidelines (DNV) and the GL regulations (GL). For the probabilistic prediction denoted FORM the characteristic values for the material mean properties have been used instead of the experimental mean values. Although the probabilistic prediction does not contain any partial safety factors to account for temperature effects or aging effects, some general remarks might be allowed. The first is that partial safety factors suggested as minimum by IEC 61400-1 might result in overestimation of the load carrying capability, as seen in the regions were the probabilistic curve falls inside the IEC curve. The failure locus predicted through the GL determined design values is the most severe one, although as already noted, this is the effect of having relaxed material testing requirements. In this case for which the testing matrix was rather extensive, comprising multiple batches, etc. the differences are pronounced.

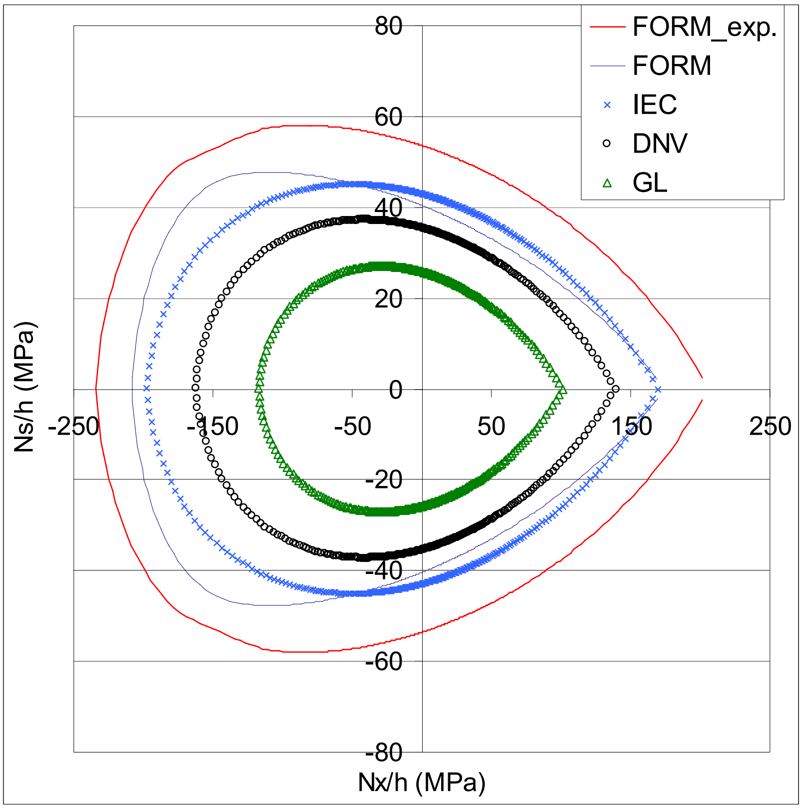

Figure 11 Probabilistic (FORM & FORM_Exp) and deterministic failure loci on the Nx-Ns stress plane for a [±45/0_4/±45] laminate

So from this point, a reliability analysis employing partial safety factors to account for the effect of temperature, aging and differences between the material within the blade and the coupons might result in some alleviation in the strength properties requirements of DNV and GL.

Yet, more insight is necessary to account for all possible reductions or increases of partial safety factors. This is more pronounced if the design drivers for large and very large blades are not ultimate loads (ULS) or fatigue loads but rather deflection and buckling modes of failure. At this time, safety factors to account for temperature effects and aging effects are a combination of empirical factors from other industries, e.g. aerospace industry, adjusted for the wind turbine blade manufacturing industry. General (or base) safety factors are used to account for manufacturing induced uncertainties in material properties, such as waves and voids. Nevertheless, more in depth research is necessary, first to identify the possible manufacturing induced tolerances, especially for very large blades, and secondly to develop design methods properly taking into account these differences. This is quite important, if one considers the failure modes observed in field, described in previous section. Raising or lowering the partial safety factor on strength for example, would not prohibit adhesive bonding failures, if the latter are not properly designed and accounted for.

5. Blade Cost model

From a literature review performed within the frame of the UPWIND WP3 Task 3.4, it was found that there are several cost models available for composite material structures in general but also specifically for wind turbine blades. General cost models for composite material structures date back to 1976 for structures used in the aircraft industry, e.g. [34] with a relevant review of such models presented in [35]. More relevant to the wind turbine blades initial approaches to cost estimators can be found in [36], where only material and labour costs are considered, and [37], where a simplified cost model was used to approach the overall wind turbine cost.

A more complete cost model for composite wind turbine blades was developed within the USA WindPact project, presented in [38], which summarizes the results of the individual studies. Within the frame of that project, cost analysis specifically for the wind turbine blades is presented in [3], where costs of materials, labour, development, plant, tooling and transport are taken into account.

The presented cost in [3] is considered as suitable for the purposes of cost modelling in an up-scaling study for wind turbines, as that performed within WP1B4 of the UPWIND project. Therefore, an attempt to develop a new cost model within the frame of WP3 of the UPWIND project seems not necessary.

The analysis in [3] concludes that for up-scaling a growth exponent of 2.96 is anticipated in terms of weight, with a growth exponent of 2.7 to 2.8 regarding the cost of the blades for increasing wind turbine sizes. Thus, it is concluded that the overall blade cost scales at a rate slightly less than the rate in the weight. That is some cost saving is anticipated through increasing the size of the blade. This however, strongly depends on the underlying assumptions regarding the cost drivers, not so much the labour and material costs, but more the hidden costs, such as tooling costs, facilities costs, and the cost of rejecting a product found defected during a quality control process, etc.

In the following the relative cost increase as a result of use of different materials or manufacturing procedures is discussed in a little more detail.

5.1 Cost differences between various technologies applied in the wind turbine blade manufacturing

The technology development cases which are described are indicative of the technology evolution. Changes resulting in small additive improvements are not mentioned, as e.g. structural design improvements, change from woven to stitched fibres (reduction of safety factors and improved material properties), changes from room temperature cure (~25°C) to higher temperature cure (~60°C) using heated moulds (improving the material properties), changes due to moving from stall to pitch controlled wind turbines, including the removal of the tip-brake.

5.1.1 Cost change from Polyester to Epoxy Resin

The cost ratio of an epoxy resin blade, $\mathrm{Cost}_{\mathrm{EP\text{-}blade}}$ to a polyester resin blade, $\mathrm{Cost}_{\mathrm{P\text{-}blade}}$ is estimated in the range of:

$\mathrm{Cost}_{\mathrm{EP\text{-}blade}}/\mathrm{Cost}_{\mathrm{P\text{-}Blade}} = 1.05\ldots\ 1.18$

The indicated range corresponds to differences in the cost per kg (or lt) of the epoxy resin with respect to polyester. This market driven cost is not easy to be estimated. Indicative prices found on the internet of, e.g. 17.7$/kg for Epoxy over 5.4$/kg for the polyester as found in the internet, resulting in the rate of epoxy to polyester cost of 3.2, and 8 $/kg for Epoxy over 2 $/kg for the polyester reported in [17], corresponding to a rate of epoxy to polyester cost of 4, reveal the differences.

In any case, this cost modification will affect the material cost which ranges from 30.7% (for a 30m blade) up to 37.9% (for a 70m blade) of the total blade cost according to [3]. The resin weight corresponds to the 19% of the total blade weight [3]. Assuming that the pass from polyester to epoxy refers to blades close to 30m in length rather than 50m or 70m, that is, the material cost is close to 30.7% of the total blade cost we have:

$Cost_{EP\text{-}Blade}/Cost_{P\text{-}Blade} = 0.693 + 0.307*0.81 + 0.307*0.19*(C_{EP/P})$

with $C_{EP/P}$ the rate of epoxy to polyester cost.

5.1.2 Cost change from Glass to Hybrid Glass/Carbon

The cost ratio of a hybrid carbon-glass blade, $Cost_{Hybrid\text{-}blade}$ to a conventional glass fibre blade, $Cost_{Gl\text{-}blade}$ is estimated in the range of:

$Cost_{Hybrid\text{-}blade}/Cost_{Gl\text{-}blade} = 1.05... 1.19$

Again this ratio depends on the difference in the cost of Carbon fibres to the Glass fibres. From a search prices found range from 15 $/kg for carbon fibres and 4.5 $/kg for glass fibres as reported in [17] up to 7 $/kg for Carbon fibres and 0.7 $/kg for Glass fibres found in the internet.

As in the case of the resin change, in this case also the modification enters in the material cost, which ranges from 30.7% (for a 30m blade) to 37.9% (for a 70m blade) of the overall blade cost according to [3]. The percentage of fibres within the blade is 60% of the total blade weight according to [3]. The weight percentage of UD fabrics within the blade corresponds to 33% of the total weight of the layers, while it is assumed that the unidirectional (UD) Glass layers replaced by UD Carbon layers represent the 30% of the UD layers, which means that there are still a 23% (of the total weight of the layers) of UD Glass layers in the blade. This is a rough approach using data from [32].

Therefore, assuming that the technology step from conventional Glass fibre blades to Hybrid blades will be taken for blades close to 50m rather than 30m or 70m, we have:

$Cost_{Hybrid\text{-}Blade}/Cost_{Gl\text{-}Blade} =$
$0.65 + 0.35*0.4 + 0.35*0.6*0.67 + 0.35*0.6*0.23 + 0.35*0.6*0.1*(C_{C/Gl})$

with $C_{C/Gl}$ the cost ratio of Carbon over Glass.

In [32] the cost of the Hybrid Carbon/Glass blade is estimated at 1.88 $/lb, while the cost of the full glass blade is 1.50 $/lb, using the same manufacturing technology. Therefore, the cost ratio is 1.25 for the shell materials only, which should be then adjusted by estimating the labour costs, etc. for the blade product.

Differences in the labour cost to account for challenges in handling carbon reinforcement were ignored in the present study, assuming that the same manufacturing technology is applicable to both reinforcement types, as e.g. [3].

5.1.3 Cost change from Hand lay-up to Resin injection

In the case of change of the production method from hand lay-up to resin injection, apart from the rough assumptions involved in the cost estimations there is a possibility that the technology change results in a cost reduction instead of increase. This is due to simultaneous requirements set to manufacturers for improving the air conditions in the working environment, resulting from the handling of open moulds and due to reductions in the labour costs because of application of a more automated process.

In more detail, the labour rate is assumed 5.5 $/kg for the hand lay-up and 5 $/kg for VARTM (vacuum assisted resin transfer moulding) following [17]. Moreover, in the same reference [17] an increase in the resin waste from 2% for the hand lay-up process to 5% for the VARTM process is estimated. In addition to that, the cost of low temperature heated moulds (60-65^{o}C) as 1.25 of the non heated moulds should be added. Taking into account the data given in [3] the following terms should be estimated for the cost ratio of resin injection to hand lay-up cost, $C_{RI/HL}$:

- Assuming that the material cost corresponds to 30.7% of the total blade cost, having as a reference a 30m blade and that the resin corresponds to the 19% of the total blade weight, we have an increase in the resin waste from 2 to 5%, i.e. $C_{resin} = 5/2$, and the effect of the material cost on the technology innovation is:
  $0.307*0.81 + 0.307*0.19*C_{resin}$

- Assuming that the labour cost is 36.8% for the 30m blade and that this cost reduces from 5.5 \$/kg to 5 \$/kg for the hand lay-up procedure to the resin injection procedure, respectively, then we have $C_{labour} = 5.5/5.0$. Then, the effect of labour cost on the technological development will be:
  $0.368*C_{labour}$

- The cost terms “other” (of 4.3%) and “transportation” (of 6.7%) described in [3] are not affected by the technological change:
  0.043+0.067

- In the term “overhead” costs, which corresponds to the 21.6% of the total blade cost, the term involving the profit and the facilities cost remain unaffected, while the tooling cost should be modified. Assuming that the facilities and profit cost is the 60.5% of the overheads cost, while the rest refers to the tooling cost, the overhead cost term is affected as follows for the passing from Hand lay-up to resin infusion process:
  $0.216*0.605 + 0.216*0.395*C_{tool}$

If we assume that C_{tool}, that is the cost change referring to the tooling, is 1.25, the final ratio of the cost of the technology development is:

$Cost_{RI}/Cost_{HL} = 1.077$

Of course if we assume that the cost of the consumables used in the resin injection process is much higher than that used during hand lay-up, e.g. $C_{tool} = 2.0$ then:

$Cost_{RI}/Cost_{HL} = 1.14$

It should be noted that in [17] the cost ratio estimated is 1.039, taking into account, however, the lower mass of the final blade. Moreover, it should be noted that potential cost savings from the reduction of requirements for working area ventilation, etc. when applying the hand lay-up method were ignored in this estimation.

5.1.4 Cost change from Resin Injection (RI) to Pre-impregnated fibres technology (PREPREG)

This modification with respect to the cost is difficult to estimate. It depends on various manufacturing parameters for which there are no data available. From a preliminary bibliographic research there are two trends. The first recommends the application of resin injection methodologies, instead of use of pre-impregnated fibres (Prepreg) using autoclaves for aeronautical parts and materials, which would lead to cost savings. It is suggested that these savings are due to cost reductions in tooling of the order of 62%, in the capital cost by 62%, in the lay-up & curing labour by 25% and in energy consumption by 80% referring, however, to a production of 10 thousand parts per year. The other trend applicable to structures closer to blades suggests the passing from RI to PREPREG, stating faster curing process, reductions in the mould costs by 10% due to using less expensive resins and coatings. In addition to that there are storage issues in the case of use of Prepregs, which are hard to estimate in terms of cost.

To enable comparison, available costs of composite material parts using RTM and Autoclave PREPREG indicate values of 108.70 $\$/ft^2$ for the PREPREG solution and 69.75$\$/ft^2$ for the RTM, that is, $\text{Cost}_{\text{PREPREG}}/\text{Cost}_{\text{RI}} = 1.55$. In other cases the ratio is close to ~2000/1000, that is, $\text{Cost}_{\text{PREPREG}}/\text{Cost}_{\text{RI}} = 2.0$. In [17] the cost of a carbon stitched (VARTM) blade is 14.81 $/kg, while the corresponding PREPREG blade has a 15.62 $/kg cost. This results to a ratio $\text{Cost}_{\text{PREPREG}}/\text{Cost}_{\text{RI}} = 1.055$.

Assuming that this change would follow somehow the change from hand lay-up to resin injection, it is suggested that a ratio of $\text{Cost}_{\text{PREPREG}}/\text{Cost}_{\text{RI}} = 1.06\sim1.15$ would be reasonable.

5.2 Proposal for cost ratios to be used in the UPWIND cost model

The purpose of this analysis is to provide the relevant input for the UPWIND cost model, following [39]. For that, the cost of the up-scaled component having weight denoted as W(s,t) is expressed through the following linear weight based model including two terms a fixed one and a variable one with weight expressed through functions a(t) and b(t) which are assumed to scale independent (but, evidently, technology dependent) [39]:

$$\text{Cost}(s,t) = a(t) \cdot W(s,t) + b(t) \qquad (9)$$

Following the analysis presented in [39], of interest in the study is not the actual function of a(t) but rather the ratio of the function over the function describing the previous technological step a(t-1), i.e. the ratio a(t)/a(t-1).

Therefore, based on the above described analysis, regarding the technological steps and the relevant cost for the manufacturing of wind turbine blades, following cost ratios, a(t)/a(t-1), are suggested to be applied within the UPWIND WP1B4 cost model:

Gl-P HLU = 1.00 (glass/polyester blade manufactured by Hand lay-up) – Base technology

Gl-P RI = 1.08 (glass/polyester blade manufactured by RESIN INJECTION)

Gl-Ep RI = 1.08 (glass/EPOXY blade manufactured by Resin Injection)

Gl-Ep Prep = 1.10 (glass/Epoxy blade manufactured by use of PREPREGs)

Gl-C Hybrid = 1.10 (glass-carbon HYBRID blade manufactured by TECHNOLOGY 1)

Gl-C Hybrid 2 = 1.00 (glass-carbon hybrid blade manufactured by TECHNOLOGY 2)

At this point it should be noted that during manufacturing technologies can be combined for the production of different blade parts, e.g. use of resin injection method to produce the skins of the blade and use of prepreg for the main spar if this is prefabricated. The same goes for the introduction of Carbon fibres in the blade structure. Carbon parts may be introduced in a blade manufactured through resin injection, or can be introduced in a prepreg blade. To accommodate the needs of the WP1B4 study, under the “Technology 1” step in the introduction of carbon fibres in the blade is denoted, where the material cost increase is taken into account. The next step termed “Technology 2” takes into account manufacturing procedure improvements, assuming no effect on the cost.

6. Conclusions

Up-scaling of composite material wind turbine blades was investigated in the present report, considering various aspects of the structural design of blades including cost issues. It was shown that assumptions made within the UPWIND WP1B4 work package, described in [1] regarding mass increase and major geometric parameters trends during conventional up-scaling procedures are reasonable and could be effectively used within cost studies.

Major technological barriers for up-scaling of the blade structure using the currently applied technology involve following issues:

- Bonding design & technology
- Production – Manufacturing Issues
    - Production time, reproducibility, quality control
- Material stiffness/strength

These have to be tackled through extensive research within the relevant areas.

An economic barrier highlighted within the WindPACT research project, [40], is the transportation costs of blades. This, however, is being dealt with through development of split blades, such as the one developed within UPWIND project WP1B1 and others developed in previous research projects. Besides that blades for offshore application could be manufactured close to harbour facilities so that on land transportation is no issue.

In any case, it is the opinion of the author that in order to investigate a potential up-sizing of wind turbine blades, failure issues observed in the field have to be investigated and solved, since these are only going to be more pronounced in larger sizes. Moreover, damage assessment and repair methods have to be improved and further developed so as to reduce probability of failure after an identification of damage and repair in the factory, as well as recurring failures on site.

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