DEVELOPMENT OF A LARGE ROTOR BLADE WITH NEW FIBRE COMPOSITES

"BLADE of NEW FIBRES"

JOR3 – CT96 – 0108

Publishable Report

PARTNERS:

LAGERWEY WINDTURBINE BV
THE NETHERLANDS

THE NETHERLANDS ENERGY RESEARCH FOUNDATION
THE NETHERLANDS

A TOUT VENT
FRANCE

PREPARED BY:

A.J.P. van der Wekken [Lagerwey]
J.J. Heijdra [ECN]
L. Torres [ATV]

NOVEMBER 1998

TABLE OF CONTENTS

1. INTRODUCTION TO "BLADE OF NEW FIBRES"

Starting from the early nineties a small number of wind turbine manufacturers applies carbon epoxy blades for their wind turbines. The main reason for using carbon-fibre-reinforced-epoxy is the demand for both light and very stiff blades. Mainly as a result of those requirements Lagerwey Windturbine applies carbon fibre for the rotor blades of the wind turbines LW18/80, 80 kW and 18 meter rotor diameter, and LW30/250 which is equipped with 30 meter rotor and 250 kW nominal power.

The carbon-epoxy blades are manufactured from expensive high strength (HS) fibres. The HS fibres itself have a modulus of elasticity somewhat higher than steel, i.e. E=230 Gpa. In general the fibres may be loaded in tension up to approximately 1% strain before breakage occurs. As a consequence of micro-buckling the compression strength is about half the tensile strength.

In case a laminate is built up from 60% (volume) uni-directional carbon fibre and 40% epoxy resin the modulus of elasticity of the laminate is approximately 140 Gpa which is much higher with regard to uni-directional glass-fibre-epoxy or Polyester laminates (GRP).

According to the carbon fibre manufactures the high material price of HS carbon fibre is mainly due to the heat treatment of the during the production process.

From the same manufactures in known that less costly carbon fibre is recently available which has been subjected to less intensive heat treatments. This is called general-purpose (GP) carbon fibre. Depending on the production process the stiffness is decreased with approximately 20% or the strength will be lowered with the same percentage

Aim of the project

The main objective of the project is the development of a rotor blade from new fibres, e.g. general purpose (GP) carbon fibre, and matching manufacturing technique in order to build large cost effective high quality rotor blades. Depending on the savings in production costs it is envisaged that the cost reduction for a blade will be up to 20%.

It is aimed that after some material tests a blade of of the LW30/250 wind turbine will be manufactured from GP material.

Participants

The work will be carried out in co-operation by the following three partners:

- Lagerwey Windturbine BV, The Netherlands **[LW]** (co-ordinator);
- The Netherlands, Energy Research Foundation **[ECN]** (partner)
- A Tout Vent Enterprise, France **[ATV]** (partner)

Time period

The work was carried out in the time period Juli 1st, 1996 and June 30th , 1998

2. MATERIAL TESTS

Carbon/glass epoxy coupons

From the start of the project it was clear that GP carbon weavings were only available as uni-directional or 0° fabrics and not as ±45° fabrics. Therefor it was decided to apply glass fibre material for the ±45°. Test specimen gave been produced with both HS and GP uni-directional carbon fibres.

For the material investigation coupon specimens were cut on-axis from a 0°, ±45,90° glass and carbon fibre epoxy plate (5.5 mm thickness). The plate contains two 650 g/m^2 layers of ±45° glass, two 1200 g/m^2 layers of 0/±45/90 glass and 3 layers of 800 g/m^2 uni-directional carbon fibre in a symmetical lay-up. Two types of carbon have been used: a high strength type HS and a cheaper general purpose type GP. The plates were produced under industial conditions at ATV by hand lay-up.

The specimens had the following dimensions: length 160 mm, width 40 mm, width in waist 21 mm, thickness about 5.5 mm.

For laminates containing angle-plies it is often observed that damage is initiated at the free edges. This will give conservative fatigue data, because damage may not occur as early in edge-free components or in components where the edge are at a lower stress level.

Materials

Material epoxy + fibre	Lay-up, symmetrical about mid-layer /s
Glass/carbon coupon HS	±45g//±45/0/90g//1½0c/s
Glass/carbon coupon GP	±45g//±45/0/90/1½0c/s

Fabrics

Type	Mass [g/m^2]	Warp [g/m^2]	Weft [g/m]	Process	Manufacturer
Carbon HS 12K	815	808	7 glass	woven	Toray T300
Carbon GP	880	800	80 glass	Woven	
Glass ±45/0/90	1200				
Glass ±45	650				

Ultimate strength tests

In a previous investigation the HS material was tested in a full 0/±45 carbon fibre laminate, also produced by ATV. The mean ultimate tensile strength (UTS) and ultimate compression strength (UCS) were respectively 809 and 445 Mpa, and the E-modulus 80.8 Gpa [Wekken and Bach, 1993]

Materials static data

Material Epoxy + fibre	Lay-up, symmetrical about mid-layer /s	E-modulus [Gpa]	UTS [Mpa]	UCS [Mpa]
Glass/carbon coupon HS	±45//±45/0/90g//1½0c/s	69.6	669±29	-336±13
Glass/carbon coupon GP	±45g//±45/0/90g//1½0c/s	62.8	636±15	-296±22

Fatigue tests

In order to obtain fatigue endurance curves (σ-n) tests up to about 3million cycles were conducted.

Especially with the HS material several specimens failed untimely by shear in the clamped part.

Although only a few specimens failed correctly, this figure indicates that the use of GP carbon gives only a negligible reduction in the fatigue strength.

Based on levels of 95% survivability and 95% confidence, both for HS and GP carbon fibres the fatigue curve for reversed loading (R=-1) can be expressed as follows:

$$\varepsilon_{amplitude} = 0.506 * N^{-0.059} \quad [\% \text{ strain}]$$

or

$$N_{allowable} = 1.07 * 10^{-5} * \varepsilon_{amplitude}^{-16.8} \text{ [cycles]}$$

The formula shows that carbon fibre material is nor very sensitive to fatigue loading.

On a logarithmic scale for the strain ε and the number of cycles N the slope is very flat: 1 to 16.8. For most glass fibre materials this fatigue slope is in the range 1:10 and 1:12.

Change in project objective

Already at a very early stage in the project, after some three to four months, it turned out from the 2D material testing at ECN that the general purpose (GP) carbon fibre is not so cost effective as expected in first instance.

The GP carbon material is only about 15% less expensive compared to high strength (HS) carbon material and the mechanical strength properties reduce at least with the same percentage. Another disadvantage is that the GP material is only available in uni-directional fabrics. Most of the applied layers in a rotor blade are built up from both uni-directional fibres and fabrics consisting from ±45° material, mostly the applied quantities are about equally.

Also because ±45° fabrics are more expensive than uni-directional material, it has been decided unanimously between the three partners in the summer of 1996 to stop investigating the material properties of general purpose carbon and continue with high strength carbon (HS) material in combination with ±45° glass material.

The stiffness and static strength of this hybrid material is some 15 to 20% less compared to the full carbon material, however, compared to only glass material it has promising material properties.

It has been decided to manufacture a LW30/250 blade from glass-carbon material. For the uni-directional or 0° layers high strength carbon fibre will be applied. The function of the ±45° glass layers is to transfer the shear loads in the structure, specially in the root connection where the load has to be transferred from the aerodynamic profiles to mostly cylindrical shaped blade root and hub structures.

3. TEST PROGRAM LW30/250 BLADE

Background

The windturbine Lagerwey LW30/250 is equipped with a rotor having two blades and a rotor diameter of 30 meter. The nominal power of the wind turbine is equal to 250 kW.
Currently the blades are manufactured from carbon/epoxy material. The carbon material lay-up is built up from approximately 50% 0° and 50% ±45°. The mass of the blade is in the range 295 to 310 kg.
In order to produce in the near future more cost effective blades, at Lagerwey's it has been decided to replace the carbon ±45° carbon layers for glass layers with the same fibre layout.
Because the mass density of glass is somewhat higher compared to carbon the total blade mass will be increased. The blades manufactured from glass-carbon/epoxy will result in a total mass of 315 to 330 kg. In principle the ±45° carbon layers are replaced by glass without adding additional glass layers.
Both the flapwise and edgewise frequencies depend mainly on the fibres in spanwise or 0° direction. Because the material and geometry of UD lay-up has been unchanged the bending frequencies will change a little. As a result of the less stiff glass fibres compared to carbon the torsion frequency will decrease a little.
For the LW30/250 blade the change from carbon to hybrid material resulted in a lowering of the first flapwise and edgewise natural frequency of less than 5%.

The full carbon blade has been designed in such a manner that the ultimate load, without load factor, results in a material strain of less than 2510με. By means of a full scale experiment has to be investigated for the glass-carbon blade if the strains at ultimate load will not exceed the 2510με. The blade has to be able to withstand 1.50 times the ultimate load. Coupon test as well as full-scale tests showed that the failure load of carbon laminates on compression loading is 4500 to 5000 με.

In first instance a fatigue test will be performed followed by a residual strength test. During the residual strength test the blade will be loaded up to ultimate load and subsequently to 1.5x ultimate load.

Design and test loads

In the test the load application point is: 8.0 meter from the blade root or 9.6 meter from the rotor hub centre. The design loads and test loads are equal to each other at 1.5 meter from the blade root.

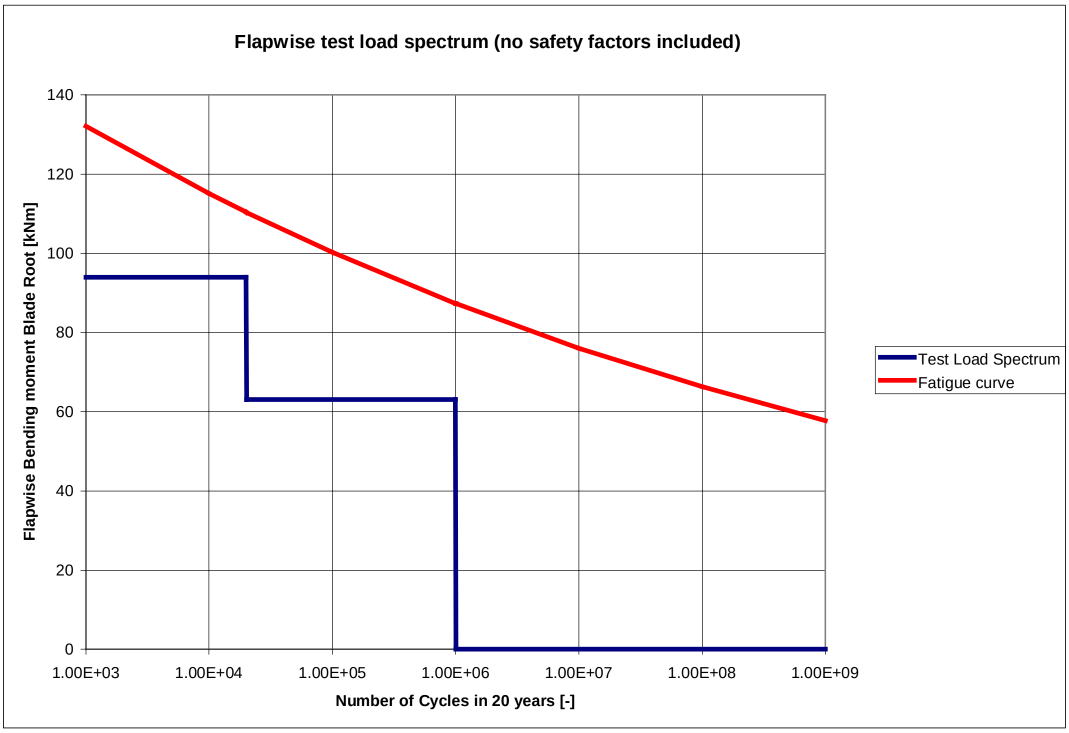
Fatigue loading

Only the flapwise loading will be applied during the fatigue test.
For the fatigue design calculations the following safety factors are considered:

- Consequence of failure	1.25;
- Material (moisture and production tolerances)	1.375;
- Load	1.0.

The result is a safety factor of 1.72
Based on the flapwise blade load spectrum a simplified test load spectrum has been derived. The fatigue damage contents of the test and design spectrum based on the strain – cycle formula given in the previous chapter is the same.
The test spectrum contains only two load levels, first all lower load cycles (10^6 cycles) will be applied and secondly the higher levels ($2*10^4$).

In the following figure the nominal test load spectrum (no safety factors) and the fatigue damage formula are shown.



According to the fatigue strain – cycle formula the limited number of cycles and the higher load level cause most damage.

Static load

For the residual strength test only the flapwise loading will be applied, the edgewise loading due to mass and torque is less than 50% of the spanwise loading.

The blade has been designed with a safety factor for ultimate strength of 1.5.

Loadings

- Extreme flapwise load: 158,6 kNm in the blade root;
- Test load is 19.8 kN applied at 8.0 m from the root.
- Including the safety factor of 1.5, the test load becomes 29.7 kN.

During the residual strength test the blade will be first loaded up to ultimate load of 19.8 kN and after good results up to 150% of this value.

4. THREE DIMENSIONAL TEST RESULTS

Introduction

A fatigue test of a Lagerwey 30/250 Wind turbine blade is reported. The load carrying laminate of the blade consists of UD carbon fibre layers combined with +/- 45 ° cross ply glass fibre layers bonded with epoxy resin. The blade has been loaded in flapwise bending using an actuator at a section 8 m from the blade root. Under assignment of ECN the tests have been performed in the Stevin Laboratory of the Delft University of Technology, faculty of civil engineering, in Delft, The Netherlands.

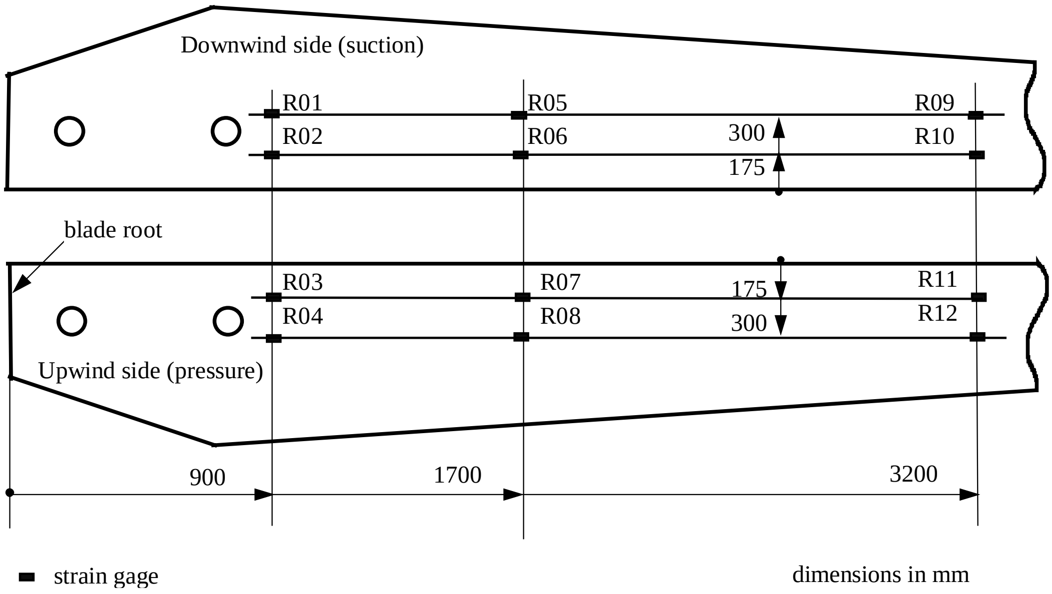
Blade specimen

The blade to be tested was manufactured from a hybrid laminate, consisting of unidirectional carbon fibre layers in spanwise direction and +/- 45 degrees glass fibre cross ply fabric.
The main characteristics of the blade are as follows:

Blade serial number	XXXX
Length	13.4 m
Maximum chord	1.2 m
Maximum thickness	0.264 m
Tip chord	0.5 m
Thickness at the tip	0.075 m
Mass	315 kg
Twist	15°
Tip angle	1°
Root angle	16°

Instrumentation

Strain gages were mounted to the blade at 3 spanwise positions both on the aerodynamic suction and on the aerodynamic pressure side.
In the figure below the gages for both sides of the blade are given.



Fatigue loads

The test spectrum has been derived from the design load spectrum for flapwise bending of the blade. Since the experiment is done with displacement steering of the actuator, the force is a derived quantity and the actual force and corresponding root moment may deviate from the specified testing moment. The specification as prepared by Lagerwey is attached as Appendix A.
The actual loads have been as follows:

blade root bending moment		number of cycles
Average kNm	Range kNm	
43.0	88.4	$1.0 * 10^6$
69.4	123.2	$2.0 * 10^4$

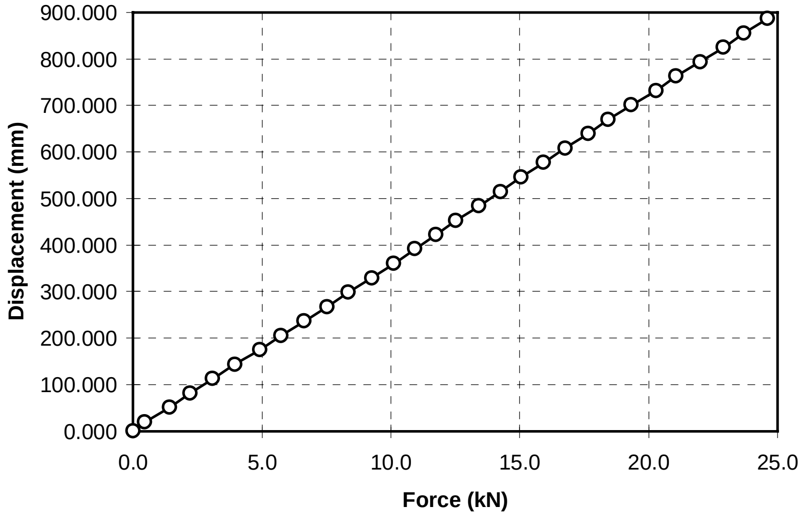
Results fatigue test

During the first 200000 cycles the strains show a slight tendency to increase. This is in line with the stiffness that shows a slight decrease. For the remainder of the test period the strains remain constant. Only at the higher loading in the last 20000 cycles the highest loaded gage show some scatter in the results, although a clear degradation cannot be observed.
A gradual decrease in stiffness can be noted during the testing.

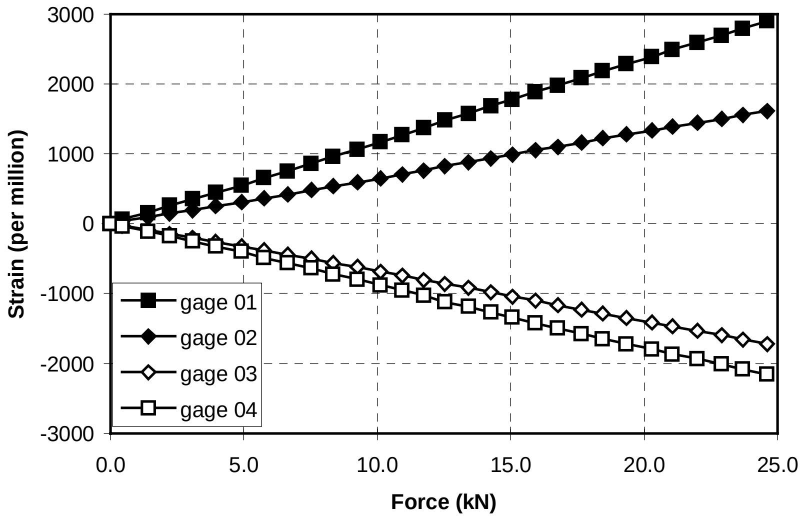
Visual inspection of the blade after the fatigue test showed no damage or degradation.

Residual strength test

For the residual test load the extreme design load has been used which corresponds to 19.8 kN in flapwise direction applied on a distance of 8 m. from the blade root.
At the residual strength test, the blade had to be loaded up to 150 % of nominal design load. The blade collapsed, however, at a load of 24.6 kN, equivalent to a root bending moment of 198.4 kNm, being 125 % of the nominal design load. The force deflection diagram of the residual strength test is given in the following figure.

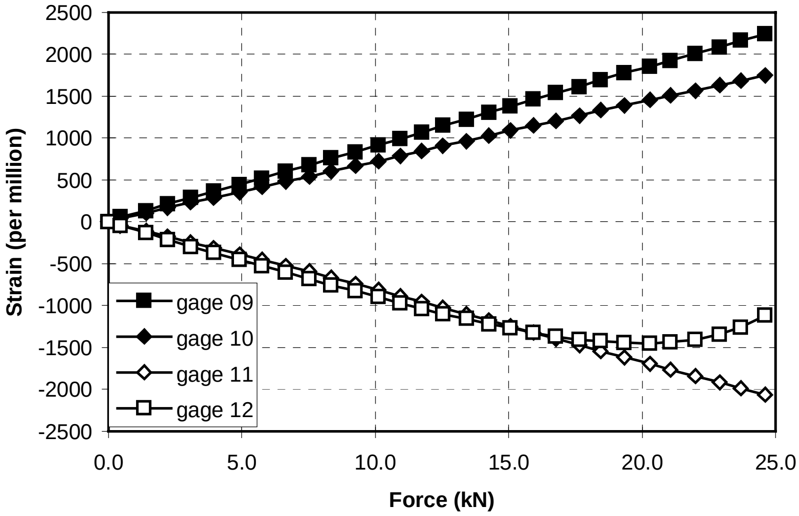


Force defection diagram at the load introduction point



Strains in section 900 mm from blade root

The strain of the gage at 3200 mm from the blade root and 300 mm from the nose shows non-linear behaviour prior to collapse. The strain of the gage shows a significant decrease above 17 kN. The non-linear behaviour will be caused be the development of buckles in the shell surface. The position and inward/outward movement of these buckles is more or less arbitrary and hence the non-linear strain development will show an arbitrary sign.

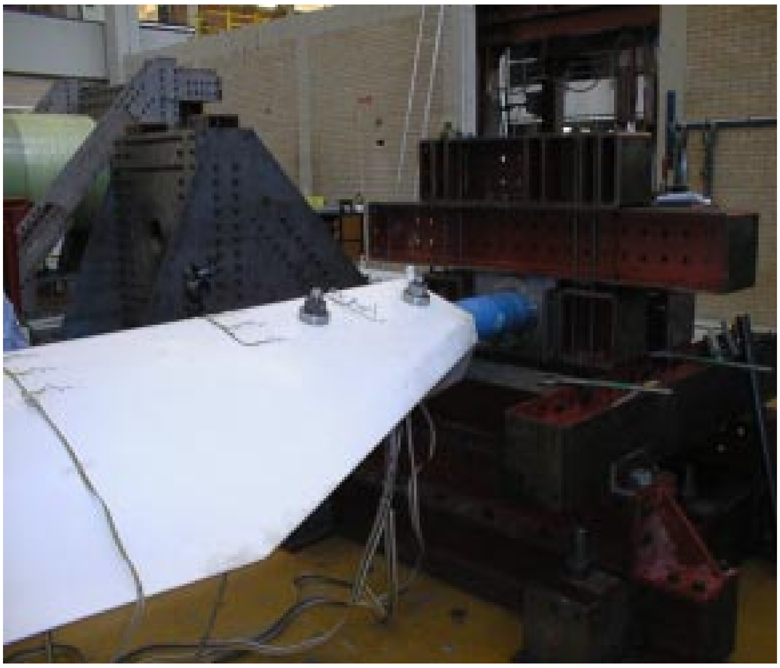


Strains in section 3200 mm from the blade root.

Summary of the results
Fatigue test
The blade has been loaded with a root bending moment with an average value of 43.0 kNm and a range of 88.4 kNm, for 10^6 cycles and subsequently with a root bending moment with an average value of 69.4 kNm and a range of 123.2 kNm, for $2*10^4$ cycles. No serious reduction in stiffness, strain non-linearity's or other or other deterioration of properties was noticeable.
Residual strain test
After the fatigue test a residual static strength test has been performed. In this test the blade collapsed at 125 % of the nominal design load in flapwise direction, due to buckling.

Conclusions
The blade could withstand a representative fatigue loading without any noticeable degradation of the structure. This is not very surprising for carbon material is known as very well resistant against fatigue loading.
However the blade could not withstand the extreme loading taking into consideration the required safety factor of 1.5. The blade failed at a low strain level due to buckling of the skin. By changing the carbon ±45º fibres for glass the material becomes more sensitive to buckling. Due to a lower E-modulus and Poisson ratio glass material is less resistant with regard to buckling stability.
For the blade manufacturer this is a subject of attention but it falls outside the scope of the project

Photographs of the test set up



Root connection of the LW30/250 blade, instrumented with strain gages

The LW30/250 blade loaded during the fatigue test

Blade failure at 125% loading during residual strength test

5. COST EVALUATION HYBRID BLADES

Introduction

In this chapter an overview is given of the mass a purchase costs of wind turbine rotor blades made of carbon and/or glass fibre material. For the overview only existing blades have been use. The information requested consisted of weight and price series of 50 to 100 blades.

The blade mass has been translated in a trend line to ease further evaluation. Typical blade costs have been calculated, based on typical blade costs and the blade mass trend line.

For a large blade, the blade mass and costs of glass fibre blades have been compared to the present costs of Atout Vent carbon and glass/carbon (hybrid) blades.

Overview blade mass of GRP blades

An overview will be presented of the blade masses of the currently available wind turbine rotor blades. The blades taken into consideration are built from glass fibre reinforced polyester or epoxy, known as GRP materials.

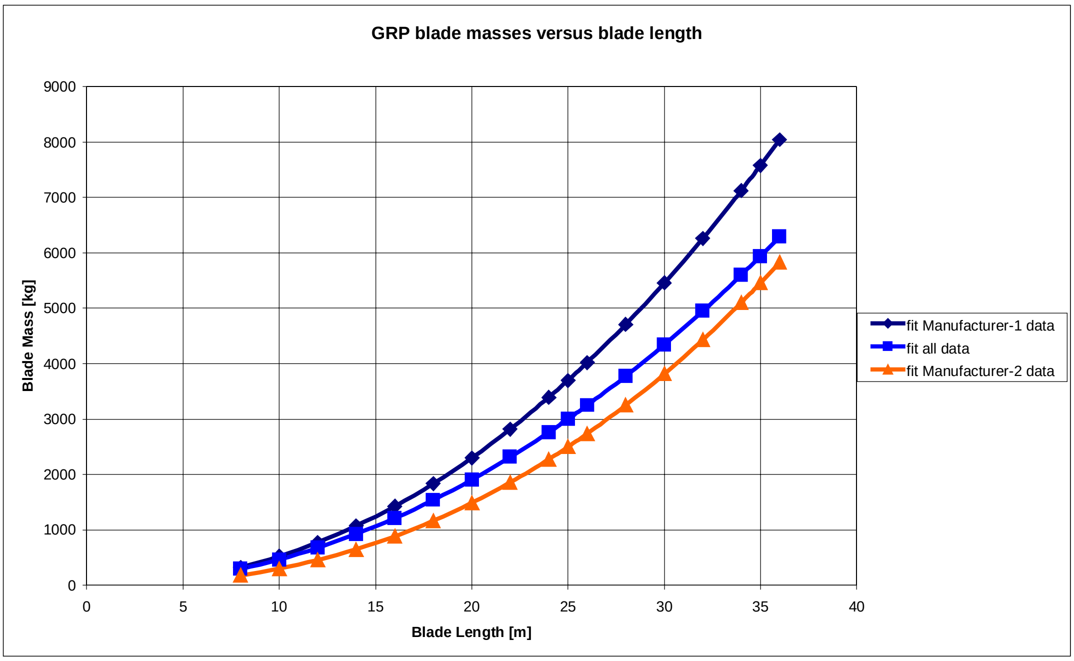
Manufacturer-1 is a large independent blade manufacturer and can deliver blades with different blade lengths for both pitch, active stall and stall regulated wind turbines. Manufacturer-1 uses glass polyester for their blade production.

The blade mass of Manufacturer-2 blades is known to be low in comparison to other manufacturers. The material used by manufacturer-2 is glass epoxy.

Information has been received from six blade manufacturers in total. The blade manufacturers are from the countries The Netherlands, Germany and Denmark.

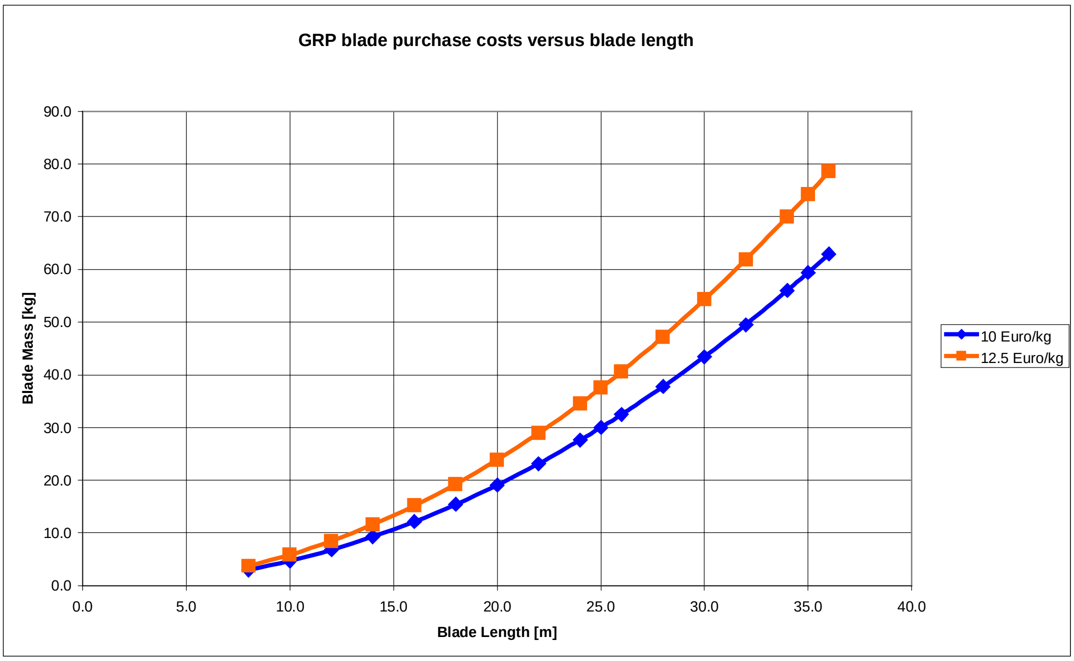
In the following figure are shown the results of curve fitting through the data points.

The results are presented as power law functions for that meets the original data most. Manufacturer-1 data shows an exponent of 2.13, the exponent of Manufacturer-2 is 2.32 and all data meets most closely the exponent 2.03. In the figure containing all data besides Manufacturer-1 and Manufacturer-2 data also the other manufacturers blade data is used.



When the relation between the weight and the length is given in a power law the exponent of the different populations ranges between 2.0 and 2.5.
Based on physical reasons an exponent would be expected of 2.7 to 2.9 being somewhat lower than the square cube law would imply. This difference is due to changes in the geometry, e.g. larger thickness to chord ratio and taper.
The exponent found here is significant lower than that. The reason for this can be found in different field: more knowledge and confidence on materials and aerodynamics, improved blade root connections and higher production quality.

Overview blade costs of GRP blades
For the blades the purchase costs have been requested. These costs are mostly based on a series of 50 to 100 blades. Because of commercial sensitivity not all manufacturers were willing to provide the requested information.
Typical blade costs are 10 Euro/kg for glass polyester and 12.5 Euro/kg for glass epoxy blades.
For large blade lengths the 10 Euro/kg is too optimistic, the blade costs increase more rapidly than the trend line suggests. For blades less than 25 meter the costs of 10 Euro/kg are most close to the current costs and for larger blades the higher costs of 12.5 Euro/kg. In the following figure the costs of GRP blades, based on all data, are presented both wit respect to 10 and 12.5 Euro/kg.



Mass and costs of Carbon epoxy blades.

Currently only two types of Atout Vent carbon epoxy blades have been produced for Lagerwey in large numbers. Those blades are specialities, i.e. the specifications are deviate from rather unusual design conditions and hard to meet. The most important constraints are the low weight and required position of the centre of gravity in chordwise direction. For reasons of aero-elastic stability the centre of gravity has to be located before the ¼ chord line. Experience shows that these requirements are very hard to meet using standard glass fibre material.

The blade for the LW18/80 wind turbine (two bladed 18 meter rotor and 80 kW rated power) has a mass of approximately 80 kg and a length of 7.9 meter. The two bladed wind turbine LW30/250 (30 meter rotor and 250 kW) is equipped with blades of 13.4 meter and a blade mass of 300 kg.

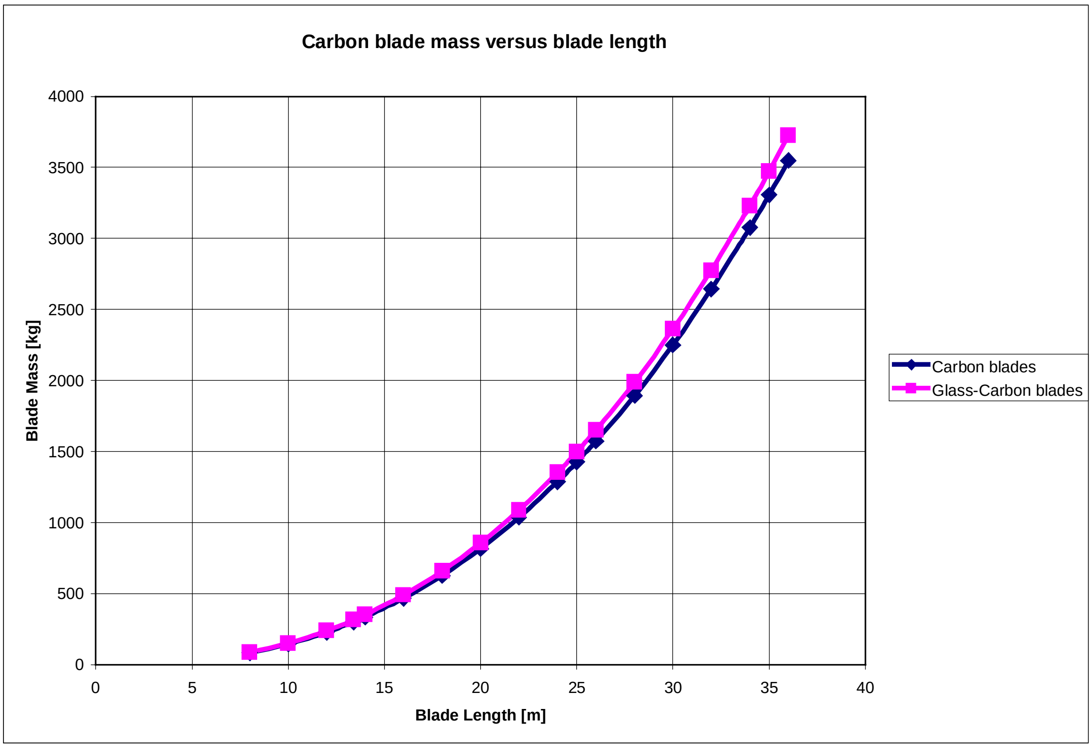
Both blades have a special root connection design and a considerable balance nose weight. For example, the LW30/250 blade is built with a balance weight of about 50 kg. For this reason comparison with the GRP blades is rather complicated.

The cost per kilogram are close to 37.5 Euro/kg for the large blade.

The number of carbon/epoxy blade designs, only two is far too small to find a reliable exponent for the power law. As a first approximation it can be expected that the power law for carbon blades will be comparable with those for glass matrix blades. Mainly based upon the two blades the exponent can be set at 2.5.

For the hybrid blade glass the expensive carbon layers with the same fibre orientation replace layers of ±45º lay-up. The ±45º carbon layers are roughly half of the total mass of total carbon amount. Since glass fibre material is 10 to 15% heavier than carbon fibre material an increase in blade mass may be expected. For the blades produced and tested within the project the increase in total blade mass of the hybrid blade is 5%.

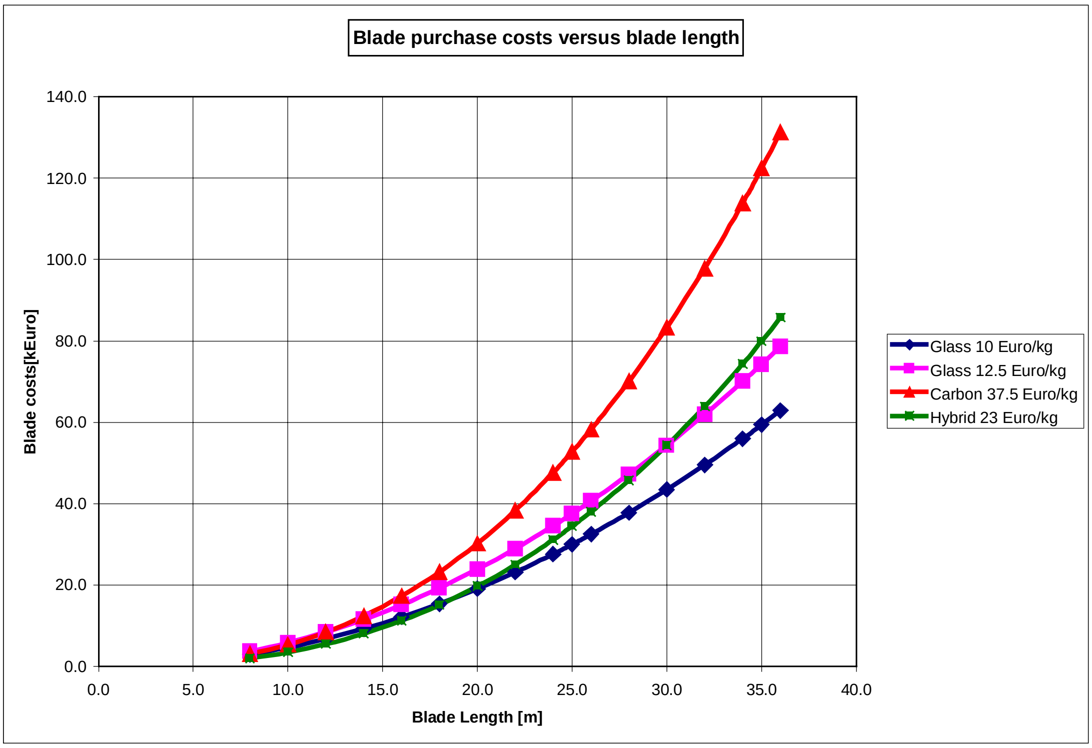
The material cost is estimated from the blade costs of the components: 23 Euro/kg.



The carbon and hybrid blades are significantly lower in mass compared to the GRP blades, even the Manufacturer-2 blades. As example a Manufacturer-2 blade of 25 m length has a mass of approx. 2200 kg and a carbon or hybrid blade weighs only 1500 kg.

Evaluation of blade costs

In the following figure the costs of glass matrix blades are compared to carbon and glass-carbon or hybrid blades.



The figure shows that carbon blades are for all blade lengths more expensive than GRP blades. Hybrid blades, however, show that the costs are very well comparable to GRP blades. Up to a blade length of 20 m the hybrid curve follows the GRP 10 Euro/kg line and only starting from 30 m length the hybrid blade becomes more expensive than the blades of 12.5 Euro/kg.

Conclusions

Wind turbine blades of fully carbon epoxy material are for any length much more expensive than glass matrix blades. For blade lengths between 15 and 25 meter carbon blades are about 50% more expensive compared to glass blades.
Carbon blades have to be considered as special design blades, needed if the design demands heavy constraints with regard to weight, stiffness or centre of gravity.
Blades with a hybrid lay-up show to have a high potential: the blade weight is comparable to carbon blades whereas the blade costs are equally or below the weight of conventional GRP blades.

6. CONCLUSIONS

From the project “Blade of new fibres ” the following conclusions may be drawn:

1) Carbon general-purpose fibres (GP) are not cost effective to the generally applied high strength fibres (HS). Although the costs of GP fibres are less also the material properties decrease with the same amount. During the time of the project the GP fibres were only available as uni-directional or 0º fabrics.
2) The combination of carbon HS material and glass matrix material, also mentioned as hybrid material, is a promising material layout. The material properties are only slightly less compared to full carbon HS laminates and the costs are significantly lower.
3) A blade cost evaluation showed that carbon blades are for any blade length more costly compared to glass blades. Carbon blades are only applied in case the design specifications are very strict with regard to low weight and high stiffness.
4) Hybrid (combination of carbon and glass) material seems to be a cost effective alternative for carbon and glass blades. As example, changing the carbon material for glass material the costs of the rotor blade of the LW30/250 decrease with approximately 15 to 20%. The hybrid LW30/250 blade is of the same cost level as comparable glass blades, however, the weight is significantly lower and the stiffness higher.