STRUCTURAL ANALYSES OF BLADES FOR SMALL WIND GENERATORS REINFORCED WITH NATURAL FIBERS

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1. Introduction

Global demand for energy is increasing at a breathtaking pace and this is particularly true in developing economies. This sharp increase in world energy demand will require significant investment in new power generating capacity, especially in the developing world. In contrast to the uncertainties surrounding supplies of conventional fuels, wind energy is a massive indigenous power source which is available in virtually every country in the world. Regional economic development is also a key factor in economic considerations surrounding wind energy.

Ongoing innovations in turbine design include the use of different combinations of composite materials to manufacture blades, especially to ensure that the weight is kept to a minimum. The main goal of the present research was to manufacture and test blades for small wind generators using polymer composites having Brazilian natural fibers (jute fibers and a combination of jute and glass fibers) as reinforcement.

In order to achieve this goal, we have:

1. Manufactured the polymer composite blades with locally available techniques using a vinyl ester resin as the matrix and, as reinforcement, jute fibers and a combination of jute and glass fibers;

2. Determined the aerodynamic loads for nominal operation and for extreme wind gusts, adding a safety factor to compensate for aging, hidden manufactures failures;

3. Tested the structural resistance of the blades with the calculated loads.

2. Test blades (Experimental)

The following materials were used for manufacturing the test blades: Vinyl-Esther Resin RF-1001 MV; Catalyst Methyl-Ethyl Ketone Peroxide – MEK; Mold cleaner; CL Sealer 15 NEB Chem trend sealer; Demolding Agent – PMR-90; Grees Cera tec glaze (or Carnauba Wax); thinner; Jute fabric and Glass Fiber fabric $300g/m^2$.

The blades were manufactures by hand lay up on a two piece mold based on a commercial blade. The mold surface was cleaned and sealed before a demolding agent was applied. The reinforcing fabrics (hessain cloth, glass fiber as a woven fabric and non-woven down cloth) were cut out with the mold dimensions. Once the fabrics are cut out and the mold surface prepared (Fig, 1), the initiator (2% w/w Methyl-Ethyl Ketone (MEK)) was added to the resin (Vinyl-Esther Resin pre-accelerated with cobalt octoate (0.3%) and di-methyl aniline (0.2%) as a cocatalyst) with constant stirring. This provides a 30 minutes interval before curing takes place and the resin becomes too viscous to be applied on the mold and over the fibres. The catalysed resin is then applied with a brush (or spray) over the mold surface to produce the gel coat (Fig 2.).

Fig. 1: Tissue cut according to the size of the inner mold

After the gel coat is on the mold surface (Fig. 2), the chosen fabric is laid over the mold (layer by layer) and each layer separately is impregnated with the catalyzed resin. This step must be done carefully to guarantee satisfactory wetting of the fabric by the resin, and the perfect insertion into the mold piece in order to avoid bubbles or tissue folds. This blade was manufactured using two layers of jute tissue. Both parts of the mold are prepared using the same procedure.

Fig. 2: Gel coat being applied on the mold surface

After the curing, if the boundaries are not smooth and correctly filled, they must be polished in order to avoid defects that would make difficult the right joining of the two pieces (Fig. 3).

Fig. 3: Checking if the boundaries are smooth and correctly filled

When both parts of the mold are ready, the metallic insert is attached with resin (Fig. 4). Since Vinyl-Esther Resin is more expensive, unsaturated polyester resin is used instead. The “paste” is a mixture of polyester resin (matrix) reinforced with talc and calcium carbonate (proportion 70:30). The amount of the reinforcement added is that necessary to produce a high viscosity paste.

Fig. 4: Resin used to bind the metallic insert

A glass fiber strand, wetted with the resin was applied around the borders of the blade before the mold was closed. The purpose of this addition was to ensure perfect closing and adherence between the two parts of the molded blade. Once these strands are in place, care must be taken to ensure that the mold is cleaned and its borders are waxed, in order to guarantee that no demolding problems will occur. The mold was then closed and set with screws along the boundaries to guarantee a good compaction (Fig. 5).

Fig. 5: The mold is closed

The mold has two little holes (and entry and an exit hole) to allow for the injection of an expansible polyuretane resin. Once injected this resin expands and cures, filling up the empty regions left between the molded parts, imparting bending resistance to the molded blades. The part must be kept in the mold for at least 2 hours before the screws are removed and the blade is taken off of the mold.

Blades in four different configurations were manufactured this way and tested. One of them was a commercially available glass fiber reinforced blade, used as reference. The other three tested blades were manually manufactured using only jute fabric (hessian cloth) and combinations of jute fabric and glass fibers as reinforcement laminate (Figure 6).

The difference of the four blades lays merely in the material and in the fiber reinforcement orientation of the composite layers. The general characteristics are listed in Table 1. Three types of fiber lamination orientation were used.

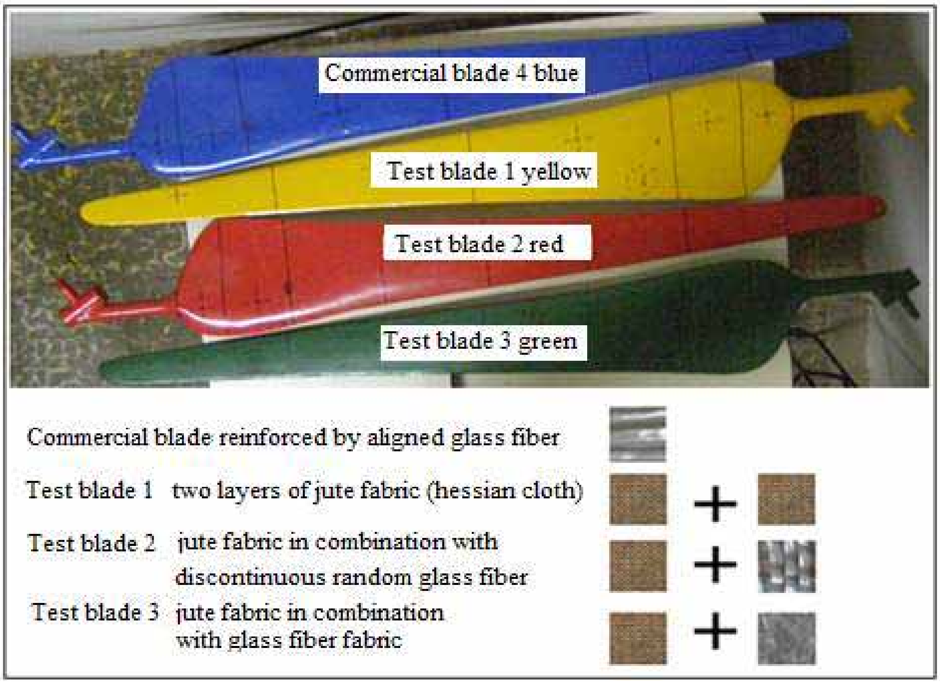

Fig. 6: Used blade configurations

Tab. 1: General characteristics of the tested blades

	Test Blades			Commercial Blade
Characteristics	1	2	3	4
Color	Yellow	Red	Green	Blue
Matrix	Polyester	Polyester	Polyester	Polyester
1st Layer	Jute Fiber	Jute Fiber	Jute Fiber	Glass Fiber
Orientation	Fiber Fabric	Fiber Fabric	Fiber Fabric	Aligned
2nd Layer	Jute Fiber	Glass Fiber	Glass Fiber	Glass Fiber
Orientation	Fiber Fabric	Random Fiber	Fiber Fabric	Aligned
Weight	1547g	1466g	1584g	1652g

3. Testing of the blades (Mechanical Performance)

Calculations were based on the operational wind speed: 12m/s and the extreme loads at maximum gust- wind speeds for wind turbine class 1 with 70m/s, class 2 with 59.5m/s, class 3 with 52.5m/s and class 4 with 42m/s (Burton *et al.,* 2008). Aerodynamic forces acting on blade elements for maximum 50 years wind gusts classes 1 to 4 are listed in table 2.

Tab. 2: Aerodynamic forces acting on blade elements for maximum 50 years wind gusts classes 1 to 4 in N (Newton)

Blade Element	Class 1	Class 2	Class 3	Class 4
5	54.47	39.36	30.64	19.61
4	89.14	64.40	50.14	32.09
3	133.71	96.60	75.21	48.13
2	56.12	40.55	31.57	20.20
1	25.42	18.37	14.30	9.15
Total	358.86	259,28	210.86	129.18

Aerodynamic forces (radial and axial forces) relative to the rotor plane acting on blade elements during nominal operation are listed in table 3.

Table3: Radial and axial components of aerodynamic forces relative to the rotor plane acting on blade elements during nominal operation in N (Newton).

Blade Element	F_r	F_{ax}
5	0.68	1.42
4	1.58	4.49
3	4.23	19.68
2	2.78	22.40
1	1.50	19.18
Total	10.77	67.17

Figure 7 below compares aerodynamic loads for nominal operation and maximum gust-wind speeds for wind turbine class 1 with 70m/s.

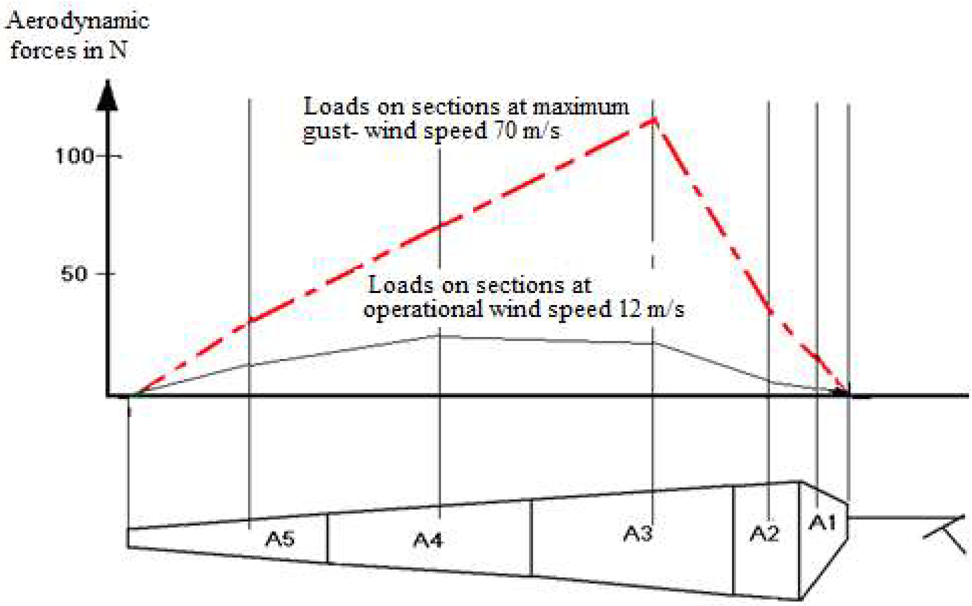

Fig. 7: Aerodynamic loads for nominal operation and maximum gust

For blade loading were used gravitational forces. So, the test rig was developed as a simple feature to fix the blade in a horizontal position and to permit gravitational loading and deflection measurements along the blade, according to Figure 8.

Fig. 8: Test rig and loading

The blades were loaded in steps, increasing the loads up to the maximum test values. In the case of nominal operational loads, the steps were 50%, 80%, 100%, 120%, 130% and 135%. In the case of maximum gust-wind speeds for wind turbine class 1 to class 4, the loads were increased from the minor values to the higher ones: 100% class 4 to 110% class 4, followed by 100% class 3 to 110% class continuing this way to the maximum load of 110% class 1.

The loading time for each step was 15 minutes. That was the time necessary to measure the deflection and to check the blade for damages visually and by tap testing. The test arrangement allowed adjusting the forces via the water volume in the test rig within a precision range of plus/minus 0.05N. The resulting deflection during the test of blade at the tip, 1 manufactured with two layers of jute fabric (hessian cloth) simulating the loads of the nominal operation (650rpm and a wind speed of 12m/s) and the tap test results are listed in table 4.

Table4: Resulting deflection during the test simulating nominal operation loads.

Load Sequence	Load Factor (%)	Deflection at Blade tip (cm)
1	0	0.0
2	50	3.2
3	80	5.8
4	100	7.7
5	120	9.7
6	130	10.6
7	135	11.3
8	0	0.0

Figure 9 shows the resulting deflection (in *cm*) of the test blade 1 for 0%, 100% and 135% loading. The maximum load was applied for a period of 15 minutes. No visual damages were detected nor any identified by the tap test.

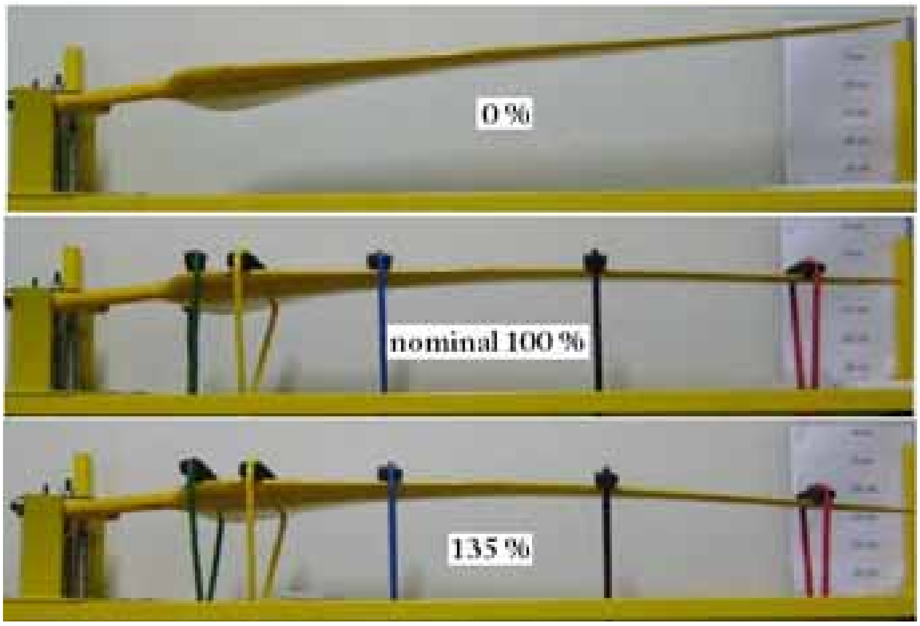

Fig. 9: Test blade 1 deflection for 0%, 100% and 135% loading

The resulting deflection of the test blade 1 simulating the loads occurring in the case of wind gusts defined for the wind classes I to IV (42 up to 70 m/s) are listed in table 5.

Table5: Resulting deflection of the test blade 1 simulating the loads occurring during wind gusts for wind classes I to IV.

Load Sequence	Wind Class	Load Factor (%)	Deflection at Blade tip (cm)
1	Initial Reference	0	0
2	4	100	9.2
3	4	110	9.5
4	3	100	12.8
5	3	110	14.2
6	2	100	16.7
7	2	110	18.7
8	1	100	25.0
9	1	110	27.3
10	Final Reference	0	1.5

Figure 10 shows the resulting deflection (in cm) of the test blade 1 for 0% and 110% loads of the wind class I, which represents the heaviest load applied during the tests. This maximum load was applied for a period of 15 minutes. No visual damages were detected nor any identified by the tap test. The resulting deflection of the blade tip was more than 25cm.

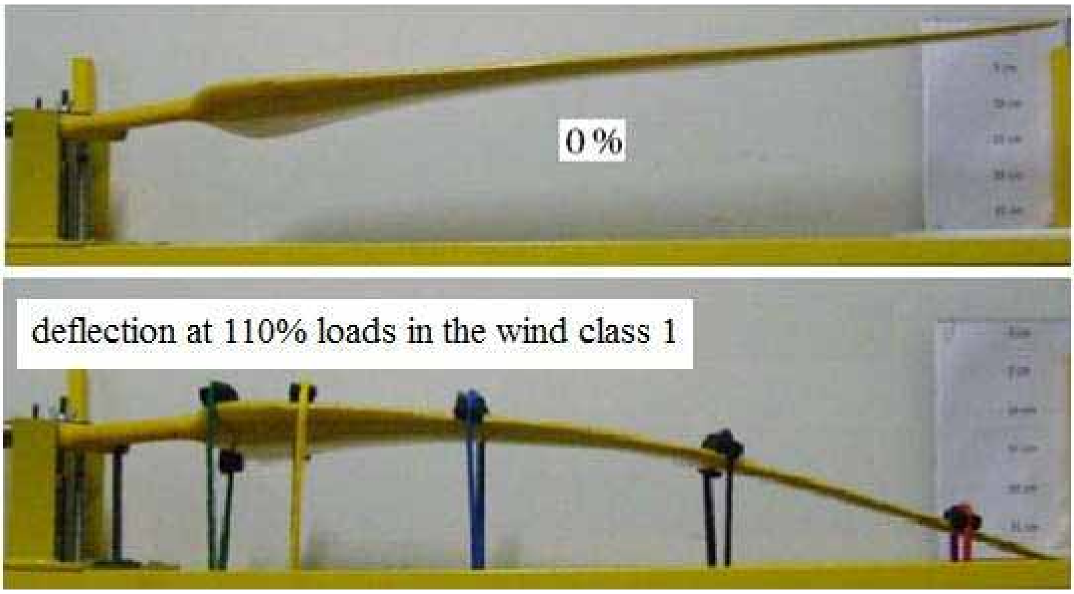

Fig. 10: Deflection of the test blade 1 for 0% and 110% loads of the wind class 1

In the following tests, the remaining test blades 2, 3 and 4 qualified as well nominal operation (plus a safety factor of 35%).

Test blade 2, reinforced with jute and glass fiber woven fabrics (plain weave, 1/1, 90° angle), failed in the harsher conditions of wind gusts defined for wind classes I (70 m/s wind speed, including a safety factor of 10%.) It is believed that the reason for not qualifying for operation in wind class I, is that Test blade 2 had a junction defect shown in figure 11.

Only the test blades 1, 3 and 4 qualified for class I.

Fig. 11: Failure in test blade 2

The different deflection levels during the tests showed that test blade 1, manufactured with two layers of jute fabric, is far more flexible than the, commercially available blade 4. The difference between the two blades is not only in the type of the reinforcing fibers but also in their orientation: Test blade 1 is made of a plain weave cloth, mad of orientated in continuous fibers perpendicularly crossing and inter-weaving each other while the commercial blade is made of oriented continuous longitudinal fibers.

Figure 12 shows the deflection for the test blade 1 and the test blade 4.

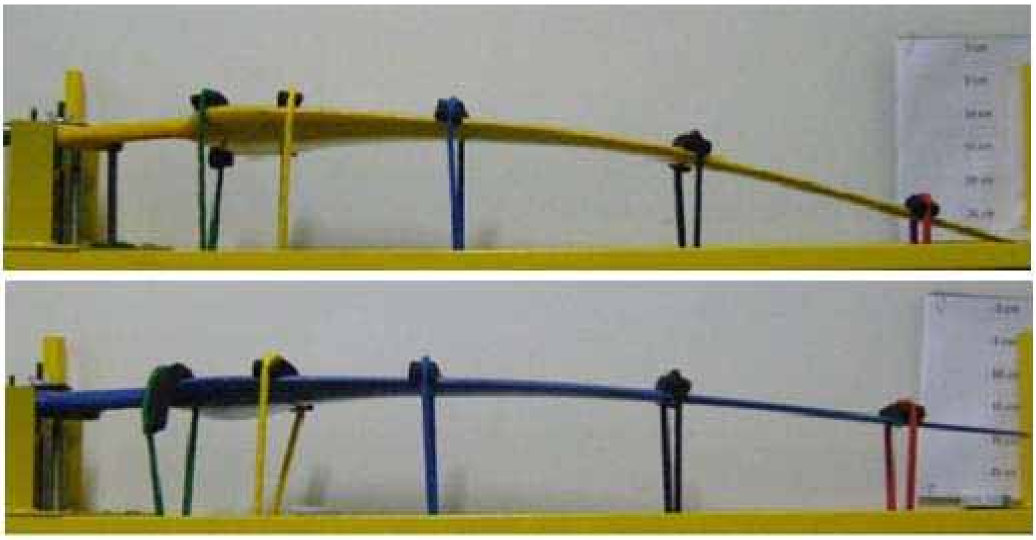

Fig. 12: Deflection for the test blade 1 and the test blade 4

The 15 minutes loading period with the heaviest load (wind class 1 with 70m/s) caused permanent deformation in all test blades, including the commercially available one, as reported in table 6. It is important to note that the 10 seconds minimum loading required by the Guideline for the Certification of Wind Turbines was surpassed by far with 15 minutes loading during the test.

Table 6: Deflection at blade tip in cm

Deflection at Blade tip	Test Blades			Commercial Blade
	1	2	3	4
Nominal Operation	11.3	8.9	7.2	7.8
Wind Class 4	9.5	8.4	8.6	6.4
Wind Class 3	14.2	12.7	14.4	9.5
Wind Class 2	18.7	16.2	19.3	12.5
Wind Class 1	27.3	Fracture	24.8	18.2
Permanent	1.5	-	1.0	1.0

4. Conclusions

All four test blades (three blades manufactured for the present project and a commercially available one) sustained the operational loads with a safety factor of 35% over the calculated loads in nominal operation with a total of 90.66N without any sign of failure and returned to their original position after reliving the load. Furthermore, the blades were tested with 110% of the calculated loads for the 50 years period maximum wind gusts defined in wind classes IV to I (42 to 70m/s) of the IEC 61400-1. The results obtained were the following:

A. Test blade 1 – with laminates exclusively in jute fibers

The blade sustained all up to the heaviest calculated one for 70m/s wind gust (wind class I) plus a 10% safety factor which totaled 394N. The test blade 1 withstood all trails without any sign of structural failure. It is important to note that after the load trails the tip of the blade did not return to the initial zero position, which resulted in a permanent deformation (deflection) of 1.5cm below the initial zero position. During the load tests the blade showed high flexibility with a maximum deflection of the blade tip reaching 27cm in a total blade length of 127cm.

B. Test blade 2– with laminates in jute fibers and glass fiber cross woven laminates

The blade sustained all up to the calculated to wind class 2 with 59.5m/s one plus a 10% safety factor, but failed to the heaviest calculated load with 70m/s wind gust (wind class I) plus a 10% safety factor which totaled 394N. This failure was attributed to a structural damage (a split at the blade junction) presented by this blade.

C. Test blade 3 – with laminates in jute fibers and short non-orientated glass fiber laminates

The blade sustained all up to the heaviest calculated one for 70m/s wind gust (wind class I) plus a 10% safety factor which totaled 394N. The test blade 3 withstood all trails without any sign of structural failure.

D. Commercial test blade 4 – with laminates exclusively in glass fiber

The blade sustained all up to the heaviest calculated one for 70m/s wind gust (wind class I) plus a 10% safety factor which totaled in 394N. The test blade 4 withstood all trails without any sign of structural failure.

After the tests all blades, including the commercial blade, did not return to the original position, with a difference of 10 to 15mm at the tip. The deformation was not considered a failure and disqualification since the loading time of 15 minutes exceeded by far the 10 seconds required. The high flexibility of the jute reinforced blade (test blade 1), which caused a high degree of reflection, has to be considered in the project of wind energy converters since this could occasionally cause a collision of the blade with the tower.

5. Acknowledgements

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6. References

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